Impedance Matching for One Atmosphere Uniform Glow Discharge Plasma (OAUGDP) Reactors

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***Abstract*—A characteristic one atmosphere uniform glow discharge plasma (OAUGDP) reactor requires a power supply capable of delivering a few kilowatts at a frequency of 1–10 kHz, and an rms voltage up to 20 kV. The OAUGDP reactor with the plasma energized can be modeled as a capacitor in parallel with a resistor. In addition, the nonideality of the transformer between the radio frequency (RF) power supply and the plasma reactor 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 overrated power supply. All the impedance matching networks in the existing literature are for the RF or microwave plasma applications under low pressures, and they cannot be applied to the applications of the OAUGDP, which is operated at much lower frequencies and much higher voltages. In this paper, the design theory and experimental results of two types of impedance matching circuits that match OAUGDP reactors to their power supplies will be presented.**

***Index Terms*—Impedance matching, OAUGDP, one atmosphere uniform glow discharge plasma, RF power supplies.**

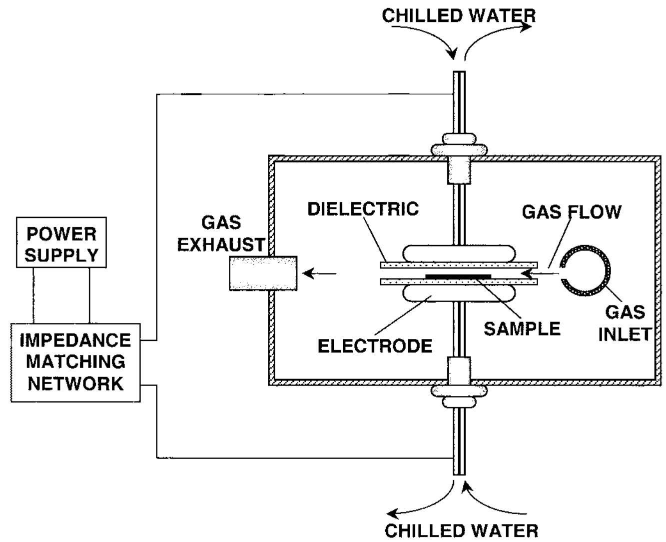

Fig. 1. Schematic of the MOD IV OAUGDP parallel plate reactor system.

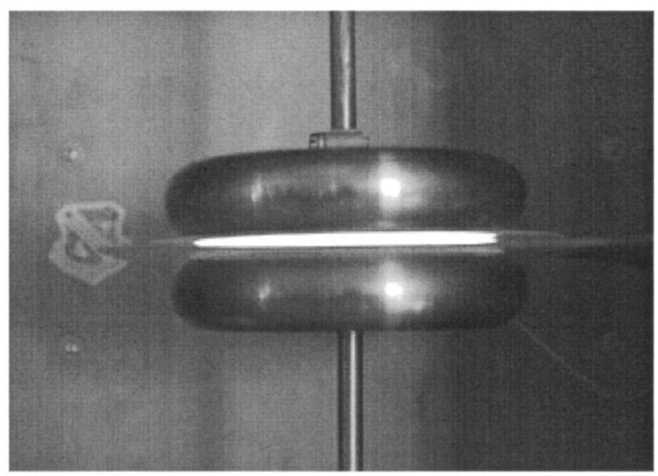

Fig. 2. Photograph of the MOD IV OAUDGP parallel plate reactor in operation.

I. Introduction

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. An OAUGD reactor characteristically requires a power supply capable of delivering a few kilowatts at a frequency of 1–10 kHz, and an rms voltage of up to 20 kV. Fig. 1 shows a schematic of the Mod. IV OAUGDP parallel plate reactor and Fig. 2 shows a photograph of it in operation. Fig. 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 [4]–[7].

An OAUGDP reactor 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 overrated power supply. In addition, the nonideality of the transformer between the RF power supply and the plasma reactor also con-

Manuscript received October 2, 2001; revised September 10, 2002. This work was supported in part by the UTK Center for Materials Processing (CMP) and by United States Air Force under Contract AF F49620-01-1-0425ROTH.

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Digital Object Identifier 10.1109/TPS.2002.805373

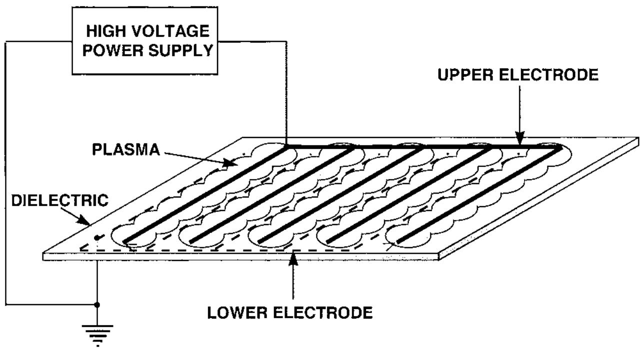

Fig. 3. Schematic of a symmetric plasma panel to generate a flat layer of OAUGD plasma.

tributes 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 generate a high-power OAUGDP efficiently.

Impedance matching is a well-studied subject in the fields of RF and microwave applications, and there are numerous books specifically studying this subject [8]–[10]. There are also numerous articles pertaining to the issue of matching a plasma to a power supply in the literature [11]–[15]. To the knowledge of the author, however, all the impedance matching techniques and the matching networks in the existing literature are for the radio-frequency or microwave plasma applications under low pressures, and they cannot be adopted to the applications of OAUGDP, which is operated at much lower frequencies from 1 to 10 kHz, and much higher voltages from 4 to 20 kV rms. Therefore, new impedance matching techniques must be developed for OAUGDP applications. The characteristics of OAUGD plasmas can be found in [2].

This paper presents two types of impedance matching circuits that match OAUGDP reactors to their power supplies.

II. Secondary-Side Impedance Matching Circuit

A. Definition of Impedance Matching

Impedance matching is the connection of an additional impedance to an existing one in order to accomplish a specific effect, such as to balance a circuit or to reduce reflection in a transmission line [16]. 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, 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.

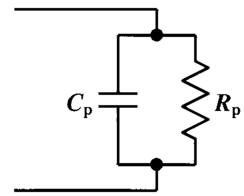

Fig. 4. Electrical model of OAUGDP reactor with plasma energized.

B. Electrical Circuit Model of OAUGDP Reactor With Plasma Energized

An OAUGDP reactor—both the parallel plate reactor and the plasma panel—is essentially a capacitor. When the plasma is energized, a resistive component that is responsible for the power dissipation in the plasma is added to the basic capacitor. Therefore, the OAUGDP reactor with plasma initiated can be represented by a capacitor in parallel with a resistor, as shown in Fig. 4, 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 [17]–[21] can actually be transformed into the form of the simple circuit in Fig. 4 by circuit analysis techniques. Therefore, for the task of impedance matching, the crude plasma model in Fig. 4 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 they may represent the real plasma more accurately.

C. Basic Impedance Matching Theory

The classical Π-type, T-type, and L-type matching networks [9], [11], [13]–[15] 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 much higher voltage (4–20 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. 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. 5. The secondary-side (of the transformer) impedance matching network is the part of the circuitry within the dashed-line frame. It is so called because it is connected to the secondary side of the transformer.

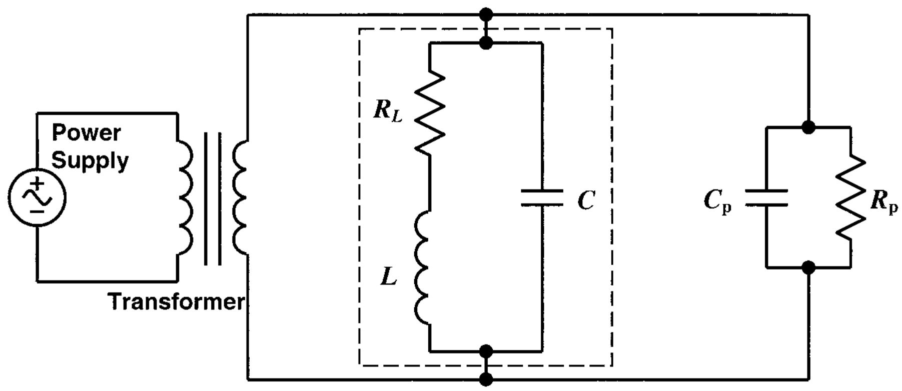

Fig. 5. OAUGDP system with secondary-side impedance matching circuit.

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

$$\begin{aligned} Z &= (R_L + j\omega L) \parallel \frac{1}{j\omega(C+C_p)} \parallel R_p \\ &= \frac{R_L + j\omega[\delta L - R_L^2(C+C_p)]}{\delta^2 + \omega^2 R_L^2 (C+C_p)^2} \parallel R_p \end{aligned} \tag{1}$$

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

From (1), the impedance characteristic of the whole load is determined by the sign of the function

$$\begin{aligned} f(\omega) &= \delta L - R_L^2(C+C_p) \\ &= L - \omega^2 L^2 (C+C_p) - R_L^2(C+C_p). \end{aligned} \tag{2}$$

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 $f(\omega) = 0$

$$\omega_r = \sqrt{\frac{1}{L(C+C_p)} - \frac{R_L^2}{L^2}}. \tag{3}$$

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 secondary/primary turns ratio (characteristically 20:1) and range of operating frequency encountered in OAUGDP applications make it difficult to avoid nonideal 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.

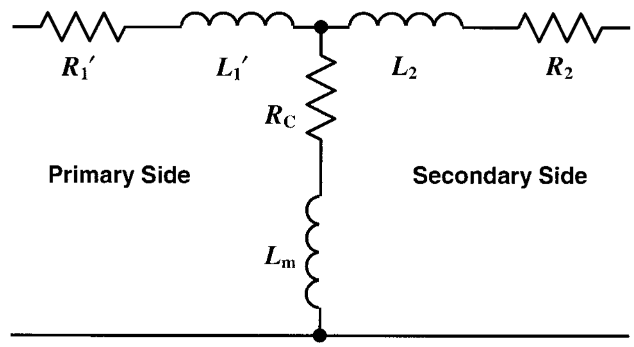

Fig. 6. Equivalent circuit of a nonideal transformer.

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 nonideal transformer is worthwhile. In Section II-D, a refined matching theory is investigated.

D. Refined Impedance Matching Theory

1) Equivalent Circuit of a Nonideal Transformer: The equivalent circuit of a nonideal transformer referred to the secondary side is shown in Fig. 6. 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 larger than that of the other components in the OAUGDP system. Therefore, the branch of L_m is neglected in the following circuit analysis to simplify the task. Fig. 7 shows the schematic of the electrical system of the OAUGDP reactor with

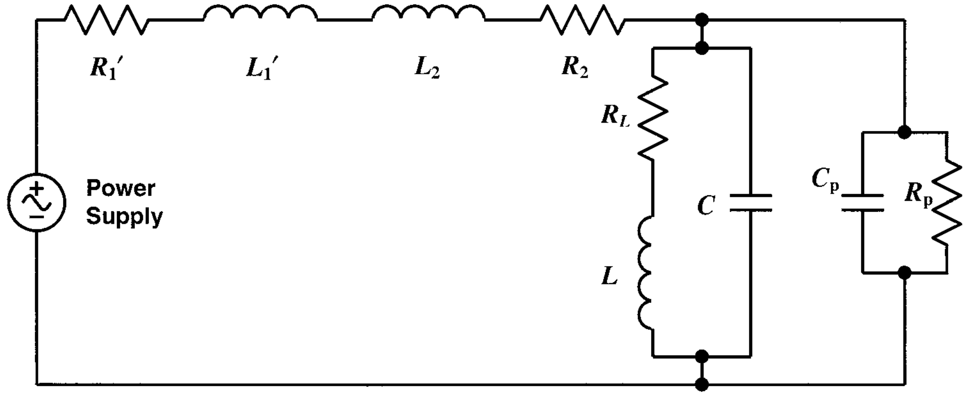

Fig. 7. Equivalent circuit of the OAUGDP system with secondary-side impedance matching circuit.

the nonideal transformer replaced by its simplified equivalent circuit.

2) 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 as in (4) shown at the bottom of the page 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 (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 (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 (3).

However, a fairly good impedance matching still could be achieved with the nonideal 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

$$\frac{\left[\delta L - R_L^2(C+C_p)\right]\left[\delta^2+\omega^2 R_L^2(C+C_p)^2\right] R_p^2}{\left\{R_L+R_p\left[\delta^2+\omega^2R_L^2(C+C_p)^2\right]\right\}^2+\omega^2\left[\delta L - R_L^2(C+C_p)\right]^2} + (L_1' + L_2) = 0. \quad (5)$$

the effect of the leakage inductance is completely cancelled, and perfect impedance matching will be achieved. 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, (5) can be simplified as

$$\frac{\delta L - R_L^2(C + C_p)}{\delta^2 + \omega^2 R_L^2 (C + C_p)^2} + (L_1' + L_2) = 0. \quad (6)$$

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, (6) can be further simplified to

$$\frac{L}{\delta} + (L_1' + L_2) = 0. \quad (7)$$

Then we can derive the matching frequency ω_r' from (7) with the help of $\delta = 1 - \omega^2 L(C + C_p)$

$$\omega_r' = \sqrt{\frac{1}{C + C_p} \cdot \left(\frac{1}{L} + \frac{1}{L_1' + L_2}\right)}. \quad (8)$$

III. Requirement on the Magnitude of Impedance of the Matching Network

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

$$\begin{aligned} Z =& R_1' + j\omega L_1' + j\omega L_2 + R_2 + (R_L + j\omega L) \parallel \frac{1}{j\omega(C + C_p)} \parallel R_p \\ =& (R_1' + R_2) + j\omega(L_1' + L_2) + \frac{R_L + j\omega[\delta L - R_L^2(C + C_p)]}{\delta^2 + \omega^2 R_L^2 (C + C_p)^2} \parallel R_p \\ =& (R_1' + R_2) + j\omega(L_1' + L_2) \\ &+ \frac{R_L R_p \left\{R_L + R_p\left[\delta^2 + \omega^2 R_L^2 (C + C_p)^2\right]\right\} + R_p\omega^2\left[\delta L - R_L^2(C + C_p)\right]^2}{\left\{R_L + R_p\left[\delta^2 + \omega^2 R_L^2(C + C_p)^2\right]\right\}^2 + \omega^2\left[\delta L - R_L^2(C + C_p)\right]^2} \\ &+ \frac{j\omega\left[\delta L - R_L^2(C + C_p)\right]\left[\delta^2 + \omega^2 R_L^2(C + C_p)^2\right] R_p^2}{\left\{R_L + R_p\left[\delta^2 + \omega^2 R_L^2(C + C_p)^2\right]\right\}^2 + \omega^2\left[\delta L - R_L^2(C + C_p)\right]^2} \end{aligned} \quad (4)$$

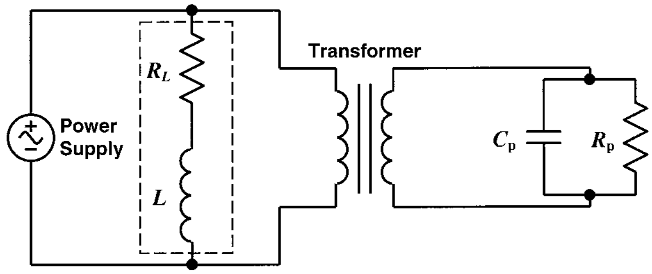

Fig. 8. OAUGDP system with primary-side impedance matching circuit.

of the matching network and the plasma reactor, they form a voltage divider. For a nonideal 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 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 reactor to generate a dense plasma. In the worst case, the voltage is not even high enough to break down the gas.

We now examine (4) again to find a way to increase the combinatorial impedance of the matching network and the plasma reactor. It can be seen that the real part of the combinatorial impedance, the third term in (4), needs to be increased. Let us still consider the simple case—plasma is off, or the equivalent plasma resistance is so large that it can be taken as infinity. Therefore, the third term in (4) can be simplified to

$$Z_{\text{real}} \approx \frac{R_L}{\delta^2 + \omega^2 R_L^2 (C + C_p)^2}. \tag{9}$$

Equation (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. Actually, when the plasma is on, especially when it is dense, its equivalent resistance R_p is quite small (on the order of 10 kΩ), and the capacitance of the plasma reactor C_p is normally fixed. Therefore, the only way to keep Z_{real} as large as possible is to increase the impedance of the matching network at the matching frequency Z_r'. This leads to the need to decrease C and increase L in the matching network. Z_r' can be calculated by (10)

$$Z_r' = \frac{R_L}{\delta^2 + \omega^2 R_L^2 C^2} = \frac{R_L}{[1 - \omega^2 L (C + C_p)]^2 + \omega^2 R_L^2 C^2}. \tag{10}$$

IV. Primary-Side Impedance Matching Circuit

We also developed another type of impedance matching circuit, called the primary-side impedance matching circuit, which is shown in Fig. 8.

The primary-side matching circuit is that part of the circuitry within the dashed-line frame in Fig. 8. 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. 9 shows the equivalent circuit of Fig. 8. R_1, L_{l1}, L_{l2}', R_2', L_m', and 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 R_2, the resistance of the secondary winding, referred to the primary winding, and $R_2' = R_2/N^2$, where N is the turns ratio of the transformer. L_{l2}' is L_{l2}, the leakage inductance of the secondary winding, referred to the primary winding, and $L_{l2}' = L_{l2}/N^2$. L_m' is L_m, the magnetizing inductance of the transformer, also 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 C_p, the capacitance of the plasma reactor, referred to the primary winding, and $C_p' = N^2 C_p$. R_p' is R_p, the equivalent resistance of the plasma, 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. 10. It is easy to recognize that Fig. 10 is similar to Fig. 5, so the same circuit analysis procedures were performed, and the matching frequency for the primary-side impedance matching circuit is found to be

$$\omega_r = \sqrt{\frac{1}{LC_p'} - \frac{R_L^2}{L^2}}. \tag{11}$$

This result is similar to (3). The only difference is that the capacitance in (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 much smaller than that for secondary-side matching, so the cost of primary-side matching is much 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 a 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.

V. 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 a high voltage 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 millihenry for the primary-side matching circuit) than that for RF or microwave plasmas, and it must also be able to handle high voltage (~10 kV, for secondary-side matching) and large currents $(\sim 10\ \text{A})$. The selection of such inductor coils commercially available is very limited, so we built the required coils at the UT Plasma

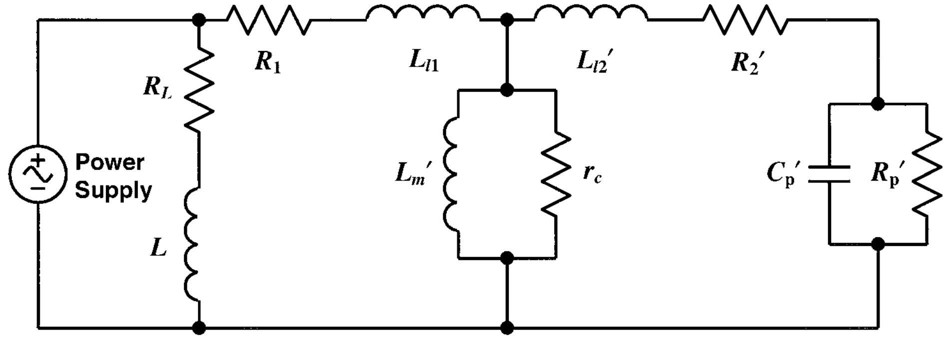

Fig. 9. Equivalent circuit of an OAUGDP system with primary-side impedance matching circuit.

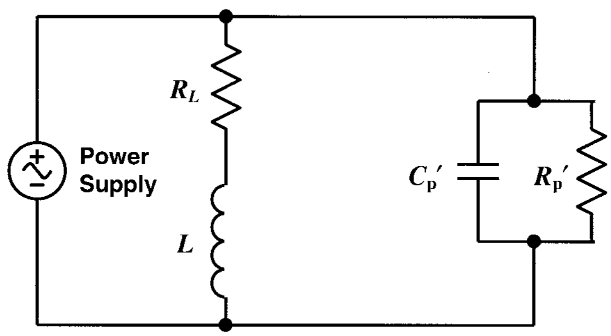

Fig. 10. Simplified equivalent circuit of OAUGDP system with primary-side impedance matching circuit.

Sciences Laboratory. The formula for designing and building practical air-core inductors is shown in (12) [22]

$$L(\mu\text{H}) = \frac{d^2n^2}{18d + 40l} \tag{12}$$

where L is the inductance in microhenry, 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. Equation (12) can be changed into SI units as shown in

$$L(\mu\text{H}) = \frac{d^2n^2}{45.7d + 102l} \tag{13}$$

where d is the coil diameter in centimeters and l is the coil length in centimeters.

Although it is said in the reference that the above formulae are for calculating the inductance of single-layer long air-core coils, we have found by experiment that they are also adequate for multilayer 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 (from middle layer to middle layer). Our inductor coils were built by winding insulated wire around a standard 4-in-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 outer layer has a tap, so different inductances are available and then different matching frequencies can be achieved. The maximum inductance of this coil is 80 mH, and its maximum resistance of the winding is 6 Ω. The coil for the primary-side matching circuit is 35 cm long, wound with AWG-10 wire. It has three layers with taps, and its maximum inductance is 2 mH.

The capacitor bank for the secondary-side matching circuit was built by connecting tens of 1 μF electrolyte capacitors in series to provide the desired capacitance, withstand high voltage, and allow us to vary the capacitance.

The capacitances of OAUGDP reactors can be measured by a capacitance meter. The capacitance of the MOD V OAUGDP remote exposure reactor (with 11 plasma panels in parallel to each other) 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 easily calculated by the formula for calculating the capacitance of a plate capacitor $C = \varepsilon A/d$. For the MOD IV parallel plate reactor at the UT Plasma Sciences Laboratory, its radius is 9 cm, dielectric plates are 1.5-mm-thick quartz, and the gap between the two dielectric plates is 2 mm. The relative permitivity of quartz is 4. Therefore, the capacitance of MOD IV is calculated to be 82 pF. The measured capacitance is larger than this theoretical value because of the parasitic capacitance of the connections.

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 in the following example.

We tried to match the MOD V OAUGDP remote exposure reactor at 15 kHz. In this case, the maximum inductance of the coil was used. One reason for this has been discussed in Section III of this paper. The other reason for this is that, because the desired frequency was relatively low, a larger inductance would be advantageous in decreasing the resonating current in the matching circuit tank to minimize the Ohmic loss in the coil. Substituting into (3) the following numbers:

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

we obtain $C = 1.377 \times 10^{-7}$ F. Since each capacitor in the capacitor bank is 1 μF, we need eight capacitors connected in series to achieve this C. Since the capacitance of eight capacitors in series is actually 0.125 μF, the actual matching frequency that would be achieved in experiment can be calculated by plugging into (3) the following numbers:

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

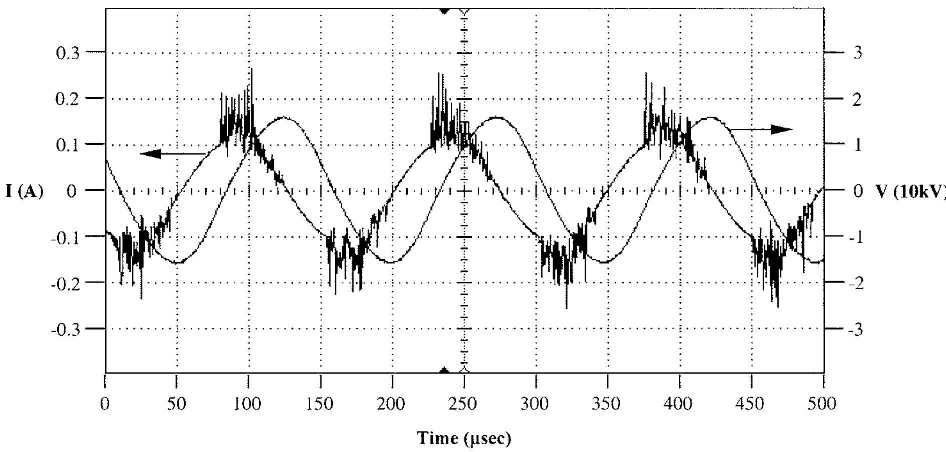

Fig. 11. Experimentally obtained voltage (sinusoidal waveform) and current waveforms (not calculated) without impedance matching.

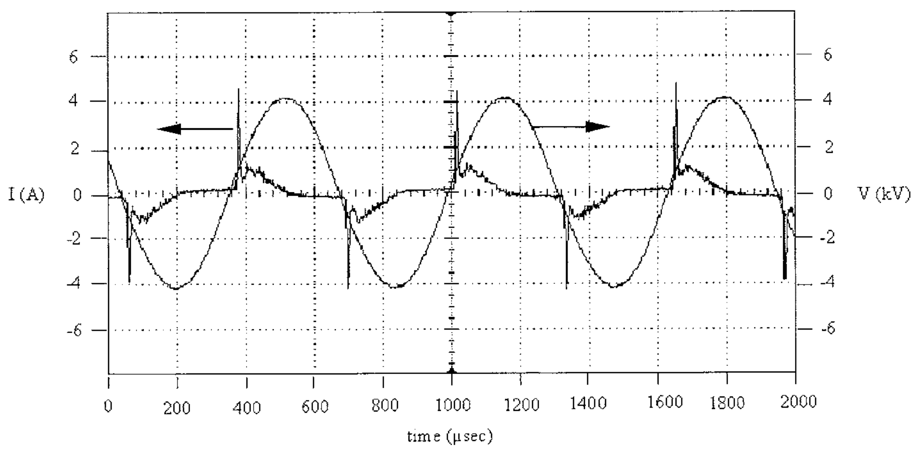

Fig. 12. Time variation over three cycles of a half of the applied voltage (sinusoidal waveform) and the discharge current in the impedance matched MOD V remote exposure reactor with 11 panels energized (the waveforms were experimentally obtained).

then we can get $f_r = 1.57$ kHz, which was exactly the resonant matching frequency that was observed. Fig. 12 shows the voltage and current waveforms of the plasma discharge for this experimental setup. 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 the Ohm's Law. In this case, $R_p \approx 5.7\,\mathrm{kV}/0.3\,\mathrm{A} = 19\,\mathrm{k}\Omega$. By (10), we can also calculate the impedance of the matching network at this matching frequency and get $Z_r' = 109$ kΩ.

Fig. 11 shows the voltage and current waveforms of a set of OAUGDP plasma panels 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.

Fig. 12 shows the voltage and current waveforms that result when operating the same set of plasma panels of Fig. 11 with secondary-side impedance matching. 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.

Fig. 13 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 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 I. 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 in-

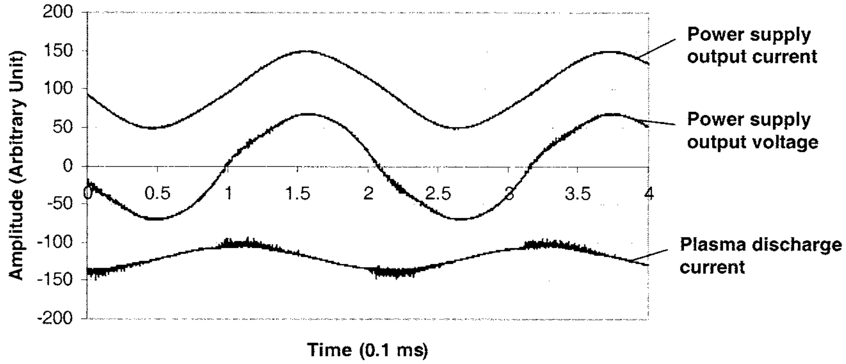

Fig. 13. Experimentally obtained waveforms of the measured power supply output voltage and current before the primary-side matching circuit, and the transformer, and the measured discharge current of the primary-side impedance matched MOD IV OAUGDP parallel plate reactor.

TABLE I
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

creased 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 plasma discharge current waveform was observed in experiments when the matching capacitance was changed.

ACKNOWLEDGMENT

The author wishes to thank Prof. J. R. Roth for his valuable suggestions and critical review of the manuscript.

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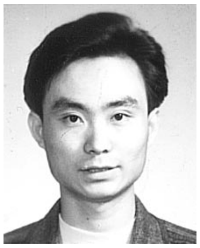

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