

METHOD OF AND APPARATUS FOR MATCHING A LOAD TO A SOURCE

FIELD OF THE INVENTION

The present invention relates to the field of r.f. delivery systems, and more particularly, to the field of multivariable network control systems for match networks of r.f. power delivery systems.

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BACKGROUND ART

Vacuum plasma processing chambers are employed for processing workpieces, typically glass, semiconductor or metal substrates, so the workpiece is etched and/or has materials deposited thereon. Significant amounts of r.f. power must be supplied to the vacuum plasma processing chamber to excite ions in a gas in the chamber to a plasma and to maintain the plasma in a discharge state. The impedance of a load of the vacuum plasma processing chamber, including the plasma discharge and an excitation circuit component for it, usually a coil or one or more electrodes, varies non-linearly and unpredictably. For example, the quality factor (Q) of an excitation coil prior to ignition of the plasma is typically quite high, about 100-400. After ignition, the Q of the coil and its plasma load drops to about 10-20. Properties of the plasma also cause the reactive impedance seen looking into the matching network to decrease as a power matched condition is approached and reached. The resistive impedance results, to a large extent, from the charged carriers in the plasma. Hence, matching to a plasma presents particular problems due to these variations in the resistive (real) and reactive (imaginary) impedance components of the load seen looking into the matching network driving the excitation circuit element and plasma of a vacuum plasma processing chamber.

The matching network is intended to (1) maximize power supplied to the load, for efficiency, and (2) minimize power reflected from the load to a relatively high power r.f. excitation source, for efficiency and prevention of possible source damage. The matching network is connected between the excitation circuit components and an output terminal of a



relatively long cable (e.g., greater than 10 feet) driven by the source. The source has a specified output impedance, such as 50 ohms resistive, and zero ohms reactive. The source output impedance equals the cable characteristic impedance. The matching network is supposed to match the impedance of the load to that of the source by adjusting the impedance
5 seen by the source so it equals the source resistive impedance.

Typically, the matching network includes two variable reactances, one for primarily controlling the resistive impedance component ($|Z|$) seen looking into the matching network and a second for primarily controlling the reactive impedance component (ϕ) seen looking into the matching network. In one prior art arrangement, the variable reactances are
10 automatically simultaneously adjusted in an attempt to minimize reflected power. The most commonly used technique for controlling the values of the variable reactances involves detecting the phase and magnitude of the impedance seen looking into the input terminals of the matching network. The automatic simultaneous adjustment according to the prior art, however, is imprecise and relatively slow to achieve a matched condition, for the reasons
15 discussed below.

In general, the control surfaces of $|Z|$ and ϕ in the space of the match network variables are complicated such that there is not a one-to-one correspondence between $|Z|$ and ϕ and the two match variables. In other words, changing one of the match network variables so that, for example, $|Z|$ is made to equal 50 ohms, will also have an effect on the value of ϕ .
20 The same holds true when changing a match network variable to make ϕ equal to 0° , since there is not a one-to-one correspondence between $|Z|$ and ϕ and the two match variables. Hence, attempting to adjust both match variables simultaneously in the prior art was difficult, since a change in one match variable would have an effect on the other match variable. This lack of correspondence leads to slowness in matching and a failure to match due to
25 ambiguities in the surface shapes of $|Z|$ and ϕ .

SUMMARY OF THE INVENTION

There is a need for a method and apparatus for independently adjusting the match variables of a match network so that precise and fast matching of the variable load is accomplished.

5 This and other needs are met by embodiments of the present invention, which provides an arrangement for matching a load to a power source. The arrangement includes a match network coupled between a power source and a load, the match network having at least two controllably variable electrical characteristics. A sensor is provided that senses at least two parameters of the load. A drive controller responds to the sensed parameters of the load
10 to independently control varying a first one of the electrical characteristics of the match network as a function of one of the parameters of the load and a second one of the electrical characteristics of the match network as a function of another one of the parameters of the load until the power source and the load are matched.

 Since the drive controller independently controls the varying of first and second
15 electrical characteristics as respective functions of first and second load parameters, fast and precise matching is accomplished. This is an advantage over the prior art in which the match variables (the variable electrical characteristics) of the match network do not have a one-to-one correspondence with the load parameters, which makes matching relatively slow and ambiguous.

20 The earlier stated needs are also met by another embodiment of the present invention which provides a method of matching a load to a power source with a match network having a primary circuit and a secondary circuit. This method comprises the steps of establishing a resonant condition in the primary circuit and measuring at least two parameters of the load. A control variable is calculated from at least one of the two parameters. It is then determined
25 whether a first one of the load parameters is equal to a first specified value based on the value of the control variable. A first match variable of the match network is adjusted to drive the control variable such that the first load parameter is equal to the first specified value. It is then determined whether a second one of the load parameters is equal to a second specified value.

A second match variable of the match network is adjusted to drive the match variable such that the second load parameter is equal to the second specified value, wherein the first match variable has a one-to-one correspondence with the first load parameter and the second match variable has a one-to-one correspondence with the second load parameter.

- 5 The earlier stated needs are also met by another embodiment of the present invention which provides a method of matching a load to a power source with a match network having a primary circuit and a secondary circuit, comprising the steps of measuring at least two parameters of the load, transforming the two parameters of the load into first and second orthogonal functions, and simultaneously and independently adjusting a first match variable
10 of the match network to drive the value of the first function to the first specified value, and a second match variable of the match network to drive the value of the second function to the second specified value.

- The foregoing and other features, aspects and advantages of the present invention will become more apparent from the following detailed description of the present invention when
15 taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic depiction of a match network constructed in accordance with an embodiment of the present invention.

- 20 Figure 2 is a flow chart of a method of matching a load in accordance with an embodiment of the present invention.

Figure 3 is a schematic depiction of a control system for the match network of Figure 1.

- 25 Figure 4 is a flow chart of a method of matching a load in accordance with another embodiment of the present invention.

Figure 5 is a schematic depiction of a match network constructed in accordance with another embodiment of the present invention.

Figure 6 is a plot of the contours for $(|Z|)$ and ϕ for the match network of Figure 5.



Figure 7 is an enlarged view of Figure 6 in the matching region.

Figure 8 is a plot of nearly orthogonal functions for the match network of Figure 5 generated according to embodiments of the present invention.

Figure 9 is a flow chart of a method of matching a load in accordance with another
5 embodiment of the present invention.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

Figure 1 is a schematic depiction of a power delivery system with a match network employed in certain exemplary embodiments of the present invention for matching a
10 capacitive load. In other embodiments, however, systems other than that shown in Figure 1 are controlled in accordance with the present invention. In the exemplary system of Figure 1, the r.f. generator 102 produces alternating current and voltage, and transfers the voltage and current via a primary circuit 104, a match network 100, and a secondary circuit 120 to a load
130. The load 130 may be a vacuum processing chamber, for example.

15 The primary circuit 104 includes the rf generator 102, a capacitance C_1 106, a resistance R_1 108, and an inductance L_1 110 that serves as the primary side of a transformer 112. The capacitance C_1 106, resistance R_1 108, and inductance L_1 110, are measurable quantities. The transformer 112 has a controllable mutual inductance M 114 and a controllable secondary inductance L_2 122. The controllable secondary inductance L_2 122 is
20 part of a secondary circuit 120, and is in series with a secondary capacitance C_2 124 and a load impedance Z_L of a vacuum plasma processing chamber coupled to the secondary circuit 120.

The complex power provided to the load 130 and match network 100 by the arrangement of Figure 1 includes a voltage and current in a ratio Z_{in} and a phase angle of ϕ_{in} .
25 A phase/ magnitude sensor (described later) measures Z_{in} and ϕ_{in} . The impedance Z_{in} and the phase ϕ_{in} are determined by the load 130 characteristics, the primary capacitance C_1 106, the primary intrinsic resistance R_1 108, the primary inductance L_1 110, the frequency ω , the



secondary capacitance C_2 124, the mutual inductance M 114, and the secondary inductance L_2 122. The mutual inductance M 114 and the secondary inductance L_2 122 are adjustable in real time to vary Z_{in} and ϕ_{in} , while the other values of the circuit are constant over time. Exemplary values of the components in the schematic of Figure 1 are: $L_1 = 1.27 \mu\text{H}$; $C_1 =$
 5 160 pF ; $R_1 = 0.4 \Omega$; $L_2 = 1.8 - 2.8 \mu\text{H}$; $C_2 = 75 \text{ pF}$; $R_2 = 0.8 \Omega$; $0 < X_L < 100 \Omega$. The mutual inductance M and the variable inductance L_2 are adjusted using drive motors that vary the inductances. The motors are driven according to a magnitude error signal (the deviation of $|Z_{in}|$ from 50 ohms) and the phase error signal (the deviation of ϕ from zero degrees). In the
 10 Hence, a change in $|Z_{in}|$ required a change in both M and L_2 to compensate. This lack of orthogonality resulted in extensive searching of M and L_2 to obtain a matched condition and may extend the matching time required to several seconds.

The present invention mitigates this problem by making the measured error signals have a nearly one-to-one correspondence with the match variables, as described below. The
 15 changes in $|Z_{in}|$ or ϕ then require compensation by the adjustment of only one of the match variables each, thereby achieving precise and rapid matching.

A first exemplary embodiment provides a method for controlling the match variables M and L_2 to drive $|Z_{in}|$ to 50 ohms and to drive ϕ_{in} to zero degrees. The first step in this exemplary embodiment is the reduction of the set of equations as described below.

20 Equations 1 and 2 provide the real and imaginary parts of the input impedance of the match connected to a load $Z_L = R_T + j \cdot X_L$, where R_T is the sum of the load impedance R_L plus the residual match resistance R_2 :

$$\text{Re}(Z_{in}) = R_1 + \frac{(\omega \cdot M)^2 \cdot R_T}{R_T^2 + \alpha^2} \quad (1)$$

$$\text{Im}(Z_{in}) = \left(\omega \cdot L_1 - \frac{1}{\omega \cdot C_1} \right) - \frac{(\omega \cdot M)^2 \cdot \alpha}{R_T^2 + \alpha^2} \quad (2)$$

where

$$\alpha = \omega \cdot L_2 - \frac{1}{\omega \cdot C_2} + X_L \quad (3)$$

The phase of the input impedance as measured by the phase/magnitude detector is given by:

$$\phi_{in} = \alpha \tan\left(\frac{\text{Im}(Z_{in})}{\text{Re}(Z_{in})}\right) \quad (4)$$

and the magnitude of the input impedance is:

$$|Z_{in}| = \sqrt{(\text{Re}(Z_{in}))^2 + (\text{Im}(Z_{in}))^2} \quad (5)$$

These equations define two components (either $\text{Re}(Z_{in})$ and $\text{Im}(Z_{in})$, or $|Z_{in}|$ and ϕ_{in}) of input impedance and an intermediate variable α that are dependent on various constants (R_1 , ω , L_1 , C_1 , and C_2) and four variables (M , R_T , L_2 , and X_L).

Thus, in the first step of the exemplary embodiment of the invention, equation (1) and equation (2) are reduced to a set of two equations in four unknowns (M , L_2 , R_T , and α). Since α is a function of L_2 and X_L , equations (1) and (2) can be reduced to a set of two equations in four variables (M , L_2 , R_T , and X_L). However, as is evident from the reduced equations, the quantities $\{|Z_{in}| - 50 \text{ ohms}\}$ and $\{\phi_{in} - \text{zero degrees}\}$ are not orthogonal to the match variables M and L_2 . In other words, if either $|Z_{in}|$ or ϕ_{in} alone were to change, then both M and L_2 would require adjustment.

The first exemplary embodiment of the invention solves this problem by making the primary circuit 104 resonant. Ordinarily, resonance in the primary is avoided, since resonant circuit elements store and return power in a way that causes current to increase rapidly, potentially damaging the circuit elements. However, modern r.f. generators are able to detect an overcurrent condition and prevent damage to sensitive circuit elements, so that resonance

no longer presents a significant danger. If C_1 106 in the circuit of Figure 1 is changed from 160 pF to 108.5 pF, as in certain exemplary embodiments of the present invention, a resonant condition is reached in the depicted circuit. This is exemplary only, however, as other values for the circuit elements will also create a resonant condition. The tangent of the phase angle

5 ϕ_{in} is given by combining equations (1), (2), and (4):

$$\tan(\phi_{in}) = \frac{\left(\omega \cdot L_1 - \frac{1}{\omega \cdot C_1} \right) - \frac{(\omega \cdot M)^2 \cdot \alpha}{R_T^2 + \alpha^2}}{R_1 + \frac{(\omega \cdot M)^2 \cdot R_T}{R_T^2 + \alpha^2}} \quad (6)$$

Equation (6) demonstrates that the $\tan \phi = 0$ contour is clearly dependent on both match variables M and L_2 (through α). However, according to the present invention, the primary circuit is made to be resonant. As a result, $\tan \phi = 0$ is then independent of M and L_2

10 since:

$$\omega \cdot L_1 - \frac{1}{\omega \cdot C_1} = 0 \quad (7)$$

and

$$\alpha = \omega \cdot L_2 - \frac{1}{\omega \cdot C_2} + X_L \quad (8)$$

15 Accordingly, the match variable M is determined solely by the condition that $|Z_{in}| = 50$ ohms.

From equation (1), this leads to the condition:

$$\frac{(\omega \cdot M)^2}{R_T} = 50 - R_1 \quad (9)$$

By making the primary circuit resonant, the $\phi = 0$ contour is made independent of match variable M . Thus, the matched condition can be reached by varying L_2 alone to make

20 $\phi = 0$, and then varying M alone to make $|Z_{in}| = 50$ ohms. Since both match variables M and

L_2 have a one-to-one correspondence with ϕ and $|Z_{in}|$, matching is accomplished very quickly and reliably.

An embodiment of a method of adjusting the match network according to the present invention in accordance with the equations described above is depicted in Figure 2. In step 5 200, a resonant condition in the primary circuit of a match network is established. This step involves providing components whose values establish a resonant condition. Once the resonant condition is established in the primary circuit, the match variables are adjusted to match the resistive and reactive impedances of the input as the output. First, in step 202, the value of α is determined. If α has a value such that ϕ is not equal to zero, as determined in 10 step 204, then L_2 (the secondary inductance) is adjusted to drive ϕ to zero (step 206). This is done, in exemplary embodiments, by driving a motor that adjusts L_2 . Once L_2 has been adjusted, then it is determined in step 208 whether $|Z_{in}| = 50$ ohms. If not, then the mutual inductance M is adjusted (by driving another motor, for example) to drive $|Z_{in}|$ to 50 ohms, in step 210. When $|Z_{in}| = 50$ ohms, then the match condition is achieved. Control returns to 15 step 202 and the process is repeated, in order to maintain the matched condition.

An exemplary embodiment of the match network and control system is depicted in Figure 3. In addition to the components already depicted in Figure 1, the control system includes a sensor 310 and a drive impedance controller 320. The phase/magnitude sensor 310 determines the values of the resistive and reactive impedances, $|Z_{in}|$ and ϕ . These values are 20 provided to the drive impedance controller 320, which drives the motors to adjust the mutual inductance M and the secondary inductance L_2 , so that $|Z_{in}|$ is made equal to 50 ohms and ϕ is made equal to zero.

Another embodiment of the present invention also employs the physical structure of Figure 3 to adjust and match the resistive and reactive impedances. However, in this alternate 25 embodiment, the primary is not made resonant as in the embodiment of Figure 2. Instead, the measured phase and magnitude values are converted by a transformation into quantities which have a one-to-one correspondence with match variables. An advantage of this



embodiment, described more fully below, is that the two match variables may be changed simultaneously to reach the matched condition. This is in contrast to the first embodiment of Figure 2, in which one match variable is adjusted, and only then is the other match variable adjusted. Hence, since both match variables are adjusted simultaneously in this alternate
 5 embodiment, an even faster matching is achieved.

In the embodiment of the method depicted in Figure 4, the measured variables of $|Z_{in}|$ and ϕ and other fixed attributes of the match network are used to generate two orthogonal functions which can be plotted in the space of M and L_2 as follows.

Equations (1) and (2) are written as:

$$10 \quad \text{Re}(Z_{in}) - R_1 = \frac{(\omega \cdot M)^2 \cdot R_T}{R_T^2 + \alpha^2} = \gamma \quad (10)$$

$$\text{Im}(Z_{in}) - X_P = \frac{-(\omega \cdot M)^2 \cdot \alpha}{R_T^2 + \alpha^2} = -\beta \quad (11)$$

where

$$X_P = \omega \cdot L_1 - \frac{1}{\omega \cdot C_1} \quad (12)$$

The quantities β and γ are therefore measured quantities.

15 From the measurements of magnitude and phase:

$$\text{Re}(Z_{in}) = |Z_{in}| \cdot \cos(\phi) \quad (13)$$

$$\text{Im}(Z_{in}) = |Z_{in}| \cdot \sin(\phi) \quad (14)$$

The quantities R_1 and X_P are network constants which can be experimentally determined. The quantities on the left sides of equations (10) and (11) are therefore known
 20 during the matching process and the right sides appear to contain three unknowns M , α and R_T . However, in this particular case, there are only two independent variables since, if:

$$p = \frac{(\omega \cdot M)^2}{R_T} \quad \text{and} \quad q = \frac{\alpha}{R_T} \quad (15,16)$$

one has:

$$\operatorname{Re}(Z_{in}) - R_1 = \frac{p}{1+q^2} = \gamma \quad (17)$$

$$\operatorname{Im}(Z_{in}) - X_p = \frac{-p \cdot q}{1+q^2} = -\beta \quad (18)$$

- 5 Equations (17) and (18) can be treated as two simultaneous equations in two unknowns, p and q, which are independently related to the match variables M and L₂. Thus, from the measured magnitude and phase the transformed control variables p and q can be used to independently control the match variables M and L₂. Solving (17) and (18) for p and q yields:

$$p = \frac{\beta^2 + \gamma^2}{\gamma} = \frac{(\omega \cdot M)^2}{R_T} \quad (19)$$

$$10 \quad q = \frac{\beta}{\gamma} = \frac{\alpha}{R_T} \quad (20)$$

By constructing the control variables p and q from the measured quantities, β and γ, one can then independently control M and α for any given load.

- When the system is in a matched condition, these two solutions (19,20) have definite numerical values which depend on the network's component values. Specifically, when
15 matched:

$$\beta = X_p \quad \text{and} \quad \gamma = 50 - R_1 \quad (21,22)$$

and hence:

$$p_o = \left(\frac{\beta^2 + \gamma^2}{\gamma} \right) = \frac{X_p^2 + (50 - R_1)^2}{50 - R_1} \quad (23)$$

and:

$$q_o = \left(\frac{\beta}{\gamma} \right) = \frac{X_p}{50 - R_1} \quad (24)$$

The numerical values of (23) and (24) can be arbitrarily subtracted from equations (19) and (20) to yield zero values of the functions when matching is achieved. The new, orthogonal functions are thus given by:

$$5 \quad F = p - p_o = \frac{\beta^2 + \gamma^2}{\gamma} - \left[\frac{X_p^2 + (50 - R_1)^2}{50 - R_1} \right] \quad (25)$$

and:

$$G = q - q_o = \frac{\beta}{\gamma} - \frac{X_p}{50 - R_1} \quad (26)$$

Thus, the controller 320 of Figure 3 is employed in this embodiment to generate values of F and G from the calibrated phase/magnitude detector signals $|Z_{in}|$ and ϕ and the match
10 constants R_1 and X_p .

The values of F and G are dependent on only one of the match variables (M or L_2) so that a zero value of F can be reached by changing M only, and a zero value of G by changing L_2 only. The matched condition is reached when F and G are both zero.

The inputs of R_1 , X_p , $|Z_{in}|$ and ϕ must be calibrated in this embodiment. The residual
15 primary resistance R_1 can be measured along with X_p at 13.56 MHz using a conventional network analyzer and $|Z_{in}|$ and ϕ are calibrated as in the prior art.

In the embodiment of the method of Figure 4, the values for the inputs R_1 , X_p , $|Z_{in}|$ and ϕ are calibrated, in step 250. In step 252, the values of $|Z_{in}|$ and ϕ are measured by the sensor 310, and provided to the driver controller 320. The measured values of $|Z_{in}|$ and ϕ are
20 transformed by the driver controller 320 into two orthogonal functions F and G, in step 254. The values of both of these functions, based on the measured quantities $|Z_{in}|$, ϕ and the known constants of the circuit components, are then compared to specified values, in steps 256, 258.

In preferred embodiments, and as depicted in Figure 4, the specified value is zero for both F and G.

When the value of either F or G deviates from zero (or another specified value), the drive controller 320 drives a motor to adjust one or both of the match variables M and L_2 , in steps 260, 262. Since both F and G are dependent on only one match variable (M or L_2), the match variables M, L_2 can be changed simultaneously to reach the matched condition. When the values of F and G are both zero (or another specified value), the matched condition has been achieved and the process returns to step 252 to monitor the values of $|Z_{in}|$ and ϕ .

The embodiment of the present invention depicted in Figure 4 may also be applied to other match networks that employ different match variables. For example, in another match network, the match variables are M and C_2 , instead of M and L_2 . However, since L_2 and C_2 are both contained in the variable α , the transformation is essentially the same as described above. Hence, a separation of variables occurs and the orthogonal control functions F and G are generated from known and measured quantities.

Another embodiment of a match network is depicted in Figure 5, this network being used to match inductive loads. In comparison to Figure 1, the resistor-inductor-capacitor (RLC) arrangement is replaced by four capacitors C_1 - C_4 . Capacitors C_1 and C_3 are variable capacitors in this embodiment. The capacitances are varied by drive motors in response to signals from the drive controller 320. In the exemplary embodiment of Figure 5, C_1 and C_3 can be varied in capacitance from 20 to 200 pF, C_2 has a value of 200 pF and C_4 has a value of 151 pF.

The change of variables described for the embodiment of Figure 3 may also be performed for the embodiment of the match network of Figure 5. However, the reduction of three apparently unknown quantities to two does not occur in this case due to the structure of the equations for the input impedance of the match. The result is that two equations emerge for the real and imaginary parts of the input impedance containing three unknown quantities.

For the match network embodiment of Figure 5, one of the match variables must be measured. In exemplary embodiments, this measurement is accomplished using some form

of encoder and capacitance calibration. The capacitors C_1 and C_3 are the load and tune components controlled by the magnitude and phase error signals. The matching range capability using the component values shown is approximately 1 to 10 ohms (real) and 200 to 500 ohms (inductive).

- 5 Despite the need to measure C_1 or C_3 , considerable simplification can be derived by transforming the measured variables, as will be seen. Typical match response contours are shown in Figures 6 and 7 for a load impedance of $R=5 + j240$ ohms. Here the magnitude error and phase error signals control C_1 and C_3 respectively. The response surface is complicated, particularly for the magnitude, which is also dual valued. The match could
- 10 search for a 50 ohm contour at high values of C_3 rather than at lower values where the match condition occurs. Figure 7 is a view of the match region of Figure 6 expanded for clarity. Note that the 50 ohm line in Figure 7 does not appear in Figure 6 as a result of the nature of the plotting algorithm. The complexity of Figure 6 may be compared to the simplicity of Figure 8, which depicts the response contours after the transformation and which corresponds
- 15 to the same load. The coordinates of C_1 , C_3 at the matched condition are the same in Figures 6-8 ($C_1 = 97.8$ pF and $C_3 = 96.6$ pF).

The input impedance of the match network and load for the embodiment of Figure 5 is given by:

$$\text{Re}(Z_{in}) = \frac{R_L \cdot x_2^2}{R_L^2 + \alpha^2} \quad (27)$$

$$20 \quad \text{Im}(Z_{in}) = (x_1 + x_2) - \frac{x_2^2 \cdot \alpha}{R_L^2 + \alpha^2} \quad (28)$$

where:

$$\alpha = X_L - x_2 - x_3 - x_4 \quad (29)$$

and:

$$x_n = \frac{1}{\omega \cdot C_n} \quad (30)$$

for the four capacitors C_1 through C_4 . Equation (27) is not dependent on C_1 but only upon C_3 (through α) and the load. Thus, using $\text{Re}(Z_{in})$ rather than $|Z_{in}|$ as one control signal would lead to linearization in the C_1, C_3 space. However, solutions for C_3 would again be dual
 5 valued due to the quadratic nature of equation 27 leading to possible searching anomalies. Equations (27) and (28) may again be treated simultaneously but for the term $-(x_1 + x_2)$ in equation (28). Although x_2 is fixed and known, the match variable x_1 is usually not known. This term prevents the reduction to two variables and the simplicity of the embodiment of Figure 3 becomes unavailable. However, in the embodiment of Figure 5, an independent
 10 measurement of C_1 is made by an encoder 350. Because of this, the $-(x_1 + x_2)$ term can be joined with the measured value of $\text{Im}(Z_{in})$ and the equations solved. Denoting:

$$RZ = \text{Re}(Z_{in}) \quad \text{and} \quad IZ = \text{Im}(Z_{in}) + x_1 + x_2 \quad (31,32)$$

then:

$$\frac{RZ}{x_2^2} = \frac{R_L}{R_L^2 + \alpha^2} \quad \text{and} \quad \frac{IZ}{x_2^2} = \frac{\alpha}{R_L^2 + \alpha^2} \quad (33,34)$$

15 from which:

$$R_L = \frac{x_2^2}{RZ} \cdot \frac{1}{\left[1 + \left(\frac{IZ}{RZ}\right)^2\right]} \quad (35)$$

and:

$$\alpha = -\frac{IZ}{RZ^2} \cdot x_2^2 \cdot \frac{1}{\left[1 + \left(\frac{IZ}{RZ}\right)^2\right]} \quad (36)$$

Equations (35) and (36) form the basis of the new control variables but must first be corrected for their values when a match is achieved to assign a value of zero to those contour lines. When a match is made RZ is equal to 50 ohms and $\text{Im}(Z_{in})$ is zero so IZ equals $x_1 + x_2$. The new control variables can thus be defined as:

$$F = \frac{x_2^2}{RZ} \cdot \frac{1}{\left[1 + \left(\frac{IZ}{RZ}\right)^2\right]} - \frac{x_2^2}{50} \cdot \frac{1}{\left[1 + \left(\frac{x_1 + x_2}{50}\right)^2\right]} \quad (37)$$

$$G = \frac{IZ}{RZ^2} \cdot x_2^2 \cdot \frac{1}{\left[1 + \left(\frac{IZ}{RZ}\right)^2\right]} + \frac{(x_1 + x_2)}{2500} \cdot x_2^2 \cdot \frac{1}{\left[1 + \left(\frac{x_1 + x_2}{50}\right)^2\right]} \quad (38)$$

Hence, by making an additional measurement of x_1 (i.e., C_1), then all of the quantities on the right hand side of equations (37) and (38) are known and F and G can be computed as control variables. Figure 8 depicts the contours of F and G in the space of the match variables C_1 and C_3 . The contours of G are not parallel to the C_1 axis due to the zeroing out of the function which introduces an x_1 (C_1) dependence. However, the linearization is much improved over Figure 6. The dual values of the control function have been removed in this formulation and no ambiguity remains. Finally, changes in the real and imaginary components of the load lead to changes in the contours of F and G respectively, but not both. For example, as R_T increases, the contours of F move to the right and those of G remain unchanged. Similarly, as X_L changes only the contours of G change. This separation of variables leads to a simple and unambiguous matching procedure.

An embodiment of a method of matching for the network of Figure 5 is depicted in Figure 9. In step 270, an independent measurement of the value of C_1 is performed using an encoder, for example. The values of $|Z_{in}|$ and ϕ are measured in step 272 by the sensor 310, and provided to the driver controller 320. Based on this measured value of C_1 , a pair of

control variables (F, G) are generated as nearly orthogonal functions by the drive controller 320 in step 274. The values of both of these control variables are then compared to a specified value, in steps 276, 278. In preferred embodiments, the specified value is zero.

When the value of either F or G deviates from zero, the drive controller 320 drives a motor to adjust one or both of the match variables C_1 and C_3 , in steps 280, 282. Since both F and G are primarily dependent on only one match variable (C_1 or C_3), the matched variables can be changed simultaneously to reach the matched condition. When the values of F and G are both zero, the matched condition has been achieved and the process returns to step 270.

Another embodiment of the present invention employs a power and impedance sensor, such as are commercially available, between the match network and the plasma chamber. Such a sensor could be used in several ways to assist the matching process if an appropriate feedback control loop is also implemented. One such method uses the sensor and feedback loop to maintain the power to the plasma load at a constant level during the matching process. This would maintain the load impedance at a nearly constant level which was assumed in the calculations, for example, of Figure 8. An alternate embodiment uses the sensor to constantly monitor the real and imaginary parts of the load impedance and uses their values to determine the desired settings of the match variables necessary to achieve a matched condition. These methods could also be employed to enhance the other embodiments of the match control algorithm already described.

A number of different embodiments of a match network have been described above, as well as methods for achieving the matched condition with these networks by independent control of two control variables. As will be appreciated by one of ordinary skill in the art, the embodiments described above are exemplary only. The present invention is applicable to other types of match networks, such as networks in which other control variables are provided.

Although the present invention has been described and illustrated in detail, it is to be clearly understood that the same is by way of illustration and example only and is not to be

taken by way of limitation, the spirit and scope of the present invention being limited only by the terms of the appended claims.



CLAIMS

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REPLACED**

WHAT IS CLAIMED IS:

1. An arrangement for matching a load to a power source, comprising:
a match network coupled between a power source and a load, the match network having at least two controllably variable electrical characteristics;
a sensor that senses at least two parameters of the load;
5 a drive controller responsive to the sensed parameters of the load to independently control varying a first one of the electrical characteristics of the match network as a function of one of the parameters of the load and a second one of the electrical characteristics of the match network as a function of another one of the parameters of the load until the power source and the load are matched.
2. The arrangement of Claim 1, wherein the match network includes a primary circuit and a secondary circuit, and the primary circuit is in a resonant condition at an operating frequency of the power source.
3. The arrangement of Claim 2, wherein the match network includes a first inductor in the primary circuit and a second inductor in the secondary circuit, and the controllably variable electrical characteristics include the mutual inductance between the first and second inductors and the inductance of the second inductor.
4. The arrangement of Claim 3, wherein the parameters of the load include magnitude and phase, and the drive controller includes means for determining an amount of variance of the mutual inductance solely as a function of the magnitude and an amount of variance of the secondary inductance solely as a function of the phase.





5. The arrangement of Claim 1, wherein the match network includes a primary circuit and a secondary circuit, with a first inductor in the primary circuit and a second inductor in the secondary circuit, and the controllably variable electrical characteristics include the mutual inductance between the first and second inductors and the inductance of the second inductor.

6. The arrangement of Claim 5, wherein the parameters of the load include magnitude and phase, and the drive controller includes means for transforming the parameters into first and second control variables, the first control variable having a one-to-one correspondence with the mutual inductance and the second control variable having a one-to-one correspondence with the inductance of the second inductor.

7. The arrangement of Claim 1, wherein the match network includes a primary circuit and a secondary circuit, with a first inductor in the primary circuit and a second inductor and a capacitor in the secondary circuit, and the controllably variable electrical characteristics include the mutual inductance between the first and second inductors and the capacitance of the second capacitor.

8. The arrangement of Claim 7, wherein the parameters of the load include magnitude and phase, and the drive controller includes means for transforming the parameters into first and second control variables, the first control variable having a one-to-one correspondence with the mutual inductance and the second control variable having a one-to-one correspondence with the capacitance of the second capacitor.

9. The arrangement of Claim 1, wherein the match network includes a load capacitor and a tune capacitor, and the controllably variable electrical characteristics include the capacitance of the load capacitor and the capacitance of the tune capacitor.

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10. The arrangement of Claim 9, wherein the arrangement includes an encoder that measures parameters of the load include magnitude and phase, and the drive controller includes means for transforming the parameters into first and second control variables, the first control variable having a nearly one-to-one correspondence with the mutual inductance and the second control variable having a one-to-one correspondence with the capacitance of the second capacitor.

11. A method of matching a load to a power source with a match network having a primary circuit and a secondary circuit, comprising the steps of:

- establishing a resonant condition in the primary circuit;
- measuring at least two parameters of the load;
- 5 calculating a control variable from at least one of the two parameters;
- determining whether a first one of the load parameters is equal to a first specified value based on the value of the control variable;
- adjusting a first match variable of the match network to drive the control variable such that the first load parameter is equal to the first specified value;
- 10 determining whether a second one of the load parameters is equal to a second specified value; and
- adjusting a second match variable of the match network to drive the match variable such that the second load parameter is equal to the second specified value, wherein the first match variable has a one-to-one correspondence with the first load parameter and the second match variable has a one-to-one correspondence with the second load parameter.
- 15

12. The method of Claim 11, wherein the first load parameter is the reactive impedance of the load, the second load parameter is the resistive impedance of the load, the first match variable is a secondary inductance in the match network, and the second match variable is a mutual inductance in the match network.



13. A method of matching a load to a power source with a match network having a primary circuit and a secondary circuit, comprising the steps of:

measuring at least two parameters of the load;

transforming the two parameters of the load into first and second orthogonal functions;

5 and

simultaneously and independently adjusting a first match variable of the match network to drive the value of the first orthogonal function to the first specified value, and a second match variable of the match network to drive the value of the second orthogonal function to the second specified value.

14. The method of Claim 13, wherein the first load parameter is the resistive impedance of the load, the second load parameter is the reactive impedance of the load, the first match variable is mutual inductance in the match network, and the second match variable is secondary inductance in the match network.

15. The method of Claim 13, wherein the first load parameter is the resistive impedance of the load, the second load parameter is the reactive impedance of the load, the first match variable is mutual inductance in the match network, and the second match variable is a capacitance of a capacitor in the match network.

16. The method of Claim 13, further comprising measuring a value of a first capacitor in the match network, the steps of determining whether the value of a first one of the orthogonal functions is equal to a first specified value and determining whether the value of a second one of the orthogonal functions is equal to a second specified value incorporating the measured value of
5 the first capacitor in the match network.



17. The method of Claim 16, wherein the first load parameter is the resistive impedance of the load, the second load parameter is the reactive impedance of the load, the first match variable is the capacitance of the first capacitor in the match network, and the second match variable is the capacitance of a second capacitor in the match network.

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