[56] To complete impedance matching at the shortest distance from the position P1, it is advantageous to decrease a frequency when the position P1 is disposed above a line passing through the origin on the Smith chart and the center of a characteristic circle of the position P1 and to increase a frequency when the position P1 is disposed below the line.

[57] To easily find a shortest trajectory, when an angle φ is provided to the conductance circle with g=1, a line, passing through the center of the circle and the center of the Smith chart, matches an X axis (an axis of the real part of the reflection coefficient). Accordingly, an optimal trajectory direction may be determined depending on whether an imaginary component of the reflection coefficient Γ' is positive or negative. The reflection coefficient of the position P1 is multiplied by a complex number having a phase of φ and a size of 1. Accordingly, it is advantageous to increase the driving frequency in the P3 position where an imaginary component of the reflection coefficient Γ' is positive. In addition, it is advantageous to decrease the driving frequency in a position P2 where the imaginary component of the reflection coefficient Γ' is negative.

[58] FIG. 6 is a circuit diagram of a pulsed variable frequency RF generator and a load according to another example embodiment of the present disclosure.

[76] Equation 1

[77] $\Gamma' = \Gamma i\, e^{j\varphi}$

[78] $\varphi = \omega d/c$

[79] where φ denotes a phase difference, d denotes a length of a transmission line, ω denotes a driving angular frequency, and c denotes speed of an electromagnetic wave on a transmission line. The transmission line 120 may be a coaxial cable. The phase-shifted reflection coefficient Γ' is a reflection coefficient when viewing the load 140 at the input N2 of the impedance matching network 130.

[80] The impedance processing unit 111 may convert the phase-shifted reflection coefficient Γ' into phase-shifted admittance y'. The phase-shifted admittance y' may be given as follows:

[81] Equation 2

[82] $y' = g' + jb'$

[83] where g' denotes conductance and b' denotes susceptance.

[84] The driving frequency control unit 113 may receive the phase-shifted reflection coefficient Γ'. The driving frequency control unit 113 may divide the ON-time period T_ON into a plurality of unit time Δt to vary the driving frequency every unit time Δt. The unit time Δt may be about 1 usec as on operating time of a control loop. Thus, the total number of control loops (q) is T_ON/Δt (q being a positive integer greater than or equal to 3).

【CLAIMS】

【Claim 1】

A control method of a driving frequency of a pulsed variable frequency RF generator providing RF power to a load as a pulse of an ON-time period T_ON and an OFF-time period T_OFF, which are alternate, and including a control loop varying a driving frequency in the ON-time period T_ON, the control method comprising:

varying a driving frequency f(n,m) in an ON-time period T_ON(n) of an n-th pulse;

predicting a driving frequency of an ON-time period T_ON(n+1) of an (n+1)-th pulse

using a plurality of phase shifted admittance values y' and corresponding driving frequency values obtained in the step of varying the driving frequency in the ON-time period T_ON(n) of the n-th pulse ; and

providing an RF output of the pulsed variable frequency RF generator as the predicted driving frequency f(n+1,1) in the ON-time T_ON(n+1) of the (n+1)-th pulse,

wherein f(n,m) is the driving frequency in an m-th processing number in the ON-time period T_ON(n) of the n-th pulse,

n denotes a sequence number of a pulse,

m is a positive integer of 1 to q, and

m denotes an index indicating the processing number of the control loop for varying the driving frequency in the ON-time period T_ON,

wherein q is the last processing count of the ON-time period T_ON of the n-th pulse and is a positive integer greater than or equal to 3.

【Claim 2】

The control method as set forth in claim 1, wherein the varying a driving frequency f(n,m) in an ON-time period T_ON(n) of an n-th pulse comprises:

a first step of measuring an RF current signal I and an RF voltage signal V at an output terminal of the pulsed variable frequency RF generator in the ON-time period T_ON(n) of the n-th pulse;

a second step of calculating impedance Zi and a reflection coefficient Γi at the output terminal of the pulsed variable frequency RF generator by using the RF current signal I and the RF voltage signal V in the ON-time period T_ON(n) of the n-th pulse, a phase-shifted reflection coefficient Γ' reflecting a phase caused by a transmission line, and phase-shifted admittance y'; and

a third step of selecting an increasing or decreasing direction of the driving frequency of the pulsed variable frequency RF generator depending on a sign of an imaginary part Im(Γ') of the phase-shifted reflection coefficient in the ON-time period T_ON(n) of the n-th pulse and varying the driving frequency, and

the first step, the second step, and the third step are repeated until the ON-time period T_ON(n) of the n-th pulse is finished.

【Claim 3】

The control method as set forth in claim 2, wherein the predicting a driving frequency of an ON-time period T_ON(n+1) of an (n+1)-th pulse using admittance of the ON-time period T_ON(n) of the n-th pulse comprises:

linearly fitting an imaginary part of the phase-shifted admittance y' in an n-th ON-time period T_ON(n) with respect to the driving frequency; and

setting a frequency corresponding to a point, in which the imaginary part of the phase-shifted admittance y' is zero (0), as a predicted driving frequency f(n+1,1) of an ON-time period T_ON(n+1) of an (n+1)-th pulse.

【Claim 4】

The control method as set forth in claim 3, wherein a prediction driving frequency f(n+1,m=1) of the ON-time period T_ON(n+1) of the (n+1)-th pulse is given as follows:

f(n+1,m=1) = f(n,m=q) - b'(n,m=q) [df/db']

df/db'= [f(n,m=q)-f(n,m=r)]/[b'(n,m=q)-b'(n,m=r)],

where f(n,m=r) denotes a driving frequency at a predetermined r-th processing number in the ON-time period T_ON(n) of an n-th pulse,

b'(n,m=r) denotes susceptance which is the imaginary part of the phase-shifted admittance y' at the predetermined r-th processing number of the ON-time period T_ON(n) of the n-th pulse,

f(n,m=q) denotes a driving frequency at the last processing number in the ON-time period T_ON(n) of the n-th pulse, and

b'(n,m=q) denotes susceptance which is the imaginary part of the admittance y' of the last processing number q of the ON-time period T_ON(n) of the n-th pulse.

【Claim 5】

The control method as set forth in claim 4, wherein r is a positive integer of 3 to q-1.

【Claim 6】

The control method as set forth in claim 2, further comprising:

determining an optimal condition for impedance matching using the phase-shifted reflection coefficient Γ',

wherein the optimal condition is determined by an absolute value |Γ'| of the phase-shifted reflection coefficient or a magnitude of the imaginary part Im(Γ') of the phase-shifted reflection coefficient Γ',

when the determined condition is the optimal condition, the first step of measuring an RF current signal I and an RF voltage signal V at an output terminal of the pulsed variable frequency RF generator is performed after increasing an index m indicating a processing number for variation of a driving frequency, and

when the determined condition is not the optimal condition, the third step of varying the driving frequency is performed.

【Claim 7】

The control method as set forth in claim 2, wherein the third step of selecting an increasing or decreasing direction of the driving frequency of the pulsed variable frequency RF generator depending on a sign of an imaginary part Im(Γ') of the phase-shifted reflection coefficient in the ON-time period T_ON(n) of the n-th pulse and varying the driving frequency comprises:

a driving frequency is increased when the imaginary part Im(Γ') of the phase-shifted reflection coefficient has a positive value, and

a driving frequency is decreased when the imaginary part Im(Γ') of the phase-shifted reflection coefficient has a negative value.

【Claim 8】

The control method as set forth in claim 7, wherein a variation amount of the driving frequency in the n-th ON-time period T_ON(n) depends on an absolute value of the phase-shifted reflection coefficient or an absolute value of the imaginary part of the phase-shifted reflection coefficient.

【Claim 9】

The control method as set forth in claim 1, further comprising:

changing a reactance value of a variable reactance element of an impedance matching network, which is disposed between the pulsed variable frequency RF generator and the load and includes at least two variable reactance elements, to set a real part Re(Z') of the impedance in the load direction at the input terminal of the impedance matching network as characteristic impedance of a transmission line.

【Claim 10】

The control method as set forth in claim 1, further comprising:

a plasma stabilizing step, including an ON-time period T_ON and an OFF-time period T_OFF which are alternate, without

variation of the driving frequency of the pulsed variable frequency RF generator.

【Claim 11】

A pulsed variable frequency RF power system comprising a pulsed variable frequency RF generator configured to supply RF power to a load as a pulse of an ON-time period T_ON and an OFF-time period T_OFF which are alternate,

wherein the pulsed variable RF generator comprises:

an impedance sensing unit disposed at an output terminal of the pulsed variable frequency RF generator in an n-th ON-time period T_ON(n) to sense an RF current signal and an RF voltage signal;

an impedance processing unit configured to calculate impedance Zi and a reflection coefficient Γi by using the RF current signal and the RF voltage signal at the output terminal of the pulsed variable frequency RF generator, a phase-shifted reflection coefficient Γ' by a transmission line between the load and the pulsed variable frequency RF generator, and phase-shifted admittance y' converted from the phase-shifted reflection coefficient Γ' in the n-th ON-time period T_ON(n);

a driving frequency prediction unit configured to predict a driving frequency of an ON-time period T_ON(n+1) of an (n+1)-th pulse using a plurality of phase-shifted admittance values y' and corresponding driving frequency values obtained in the step of varying the driving frequency in the ON-time period T_ON(n) of the n-th pulse ;

a driving frequency control unit configured to receive the predicted driving frequency and set the predicted driving frequency as a start driving frequency of the next ON-time

period T_ON(n+1) and to control a driving frequency using the phase-shifted reflection coefficient Γ';

a pulse generator configured to generate a pulse signal and divide the ON-time period T_ON and the OFF-time period T_OFF and to provide the pulse signal to the driving frequency prediction unit and the driving frequency control unit; and

an RF amplifier configured to amplify a sinusoidal wave of a driving frequency of the driving frequency control unit.

【Claim 12】

The pulsed variable frequency RF power system as set forth in claim 11, wherein the driving frequency prediction unit linearly fits an imaginary part of phase-shifted admittance y' with respect to a driving frequency, in the n-th ON-time period T_ON(n) to set a frequency, corresponding to a point in which the imaginary part of the phase-shifted admittance y' is zero, as a prediction driving frequency.