Optimization of Probe Numbers and Their Separation for Determination of Antenna-Plasma Coupling Impedance for Ion Cyclotron Resonance Heating

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Abstract—**This paper introduces the concept of probe numbers optimization required to plot the Voltage Standing Wave Ratio (VSWR) curve. VSWR curve formation method is used to find the antenna-plasma coupling impedance. VSWR curve can be found using the fixed probe method. The fixed probes will pick up the voltage from the transmission line which in turn will give the idea about VSWR and it will determine the antenna-plasma coupling impedance. In order to optimize the number of probes to be placed on the transmission line, their separation and the length in terms of wavelength on which the probes are to be installed, a simulation work has been done. In this simulation number of probes, separation between them and the length of the transmission line in terms of wavelength over which these probes are to be installed has been optimized with reference to a certain error. The acceptable error limit has been set as input. This paper will show the LabVIEW implementation to optimize the probe numbers, electrical length of transmission line and probe separation.**

***IndexTerms*—VSWR curve, Voltage probes, Antenna-Plasm coupling impedance.**

I. INTRODUCTION

Ion Cyclotron Resonance Heating (ICRH) has been established as one of the better heating technique for increasing the plasma temperature. But one of the major problems in ICRH is - RF power coupling to the plasma. Plasma being an ionized state of matter has very low resistive impedance. So matching the RF source impedance with the plasma impedance is necessary for ICRH. In order to match the plasma impedance, it should be known first. In conventional methods plasma impedance may be determined using Voltage Standing Wave Ratio (VSWR) curve method. In Aditya and SST-1 tokamak machines; RF power fed to the plasma is of the order of few hundreds of KW [1]. With such high power levels, VSWR curve cannot be determined using conventional technique of sliding probe. Fixed probe technique is used to determine plasma impedance. In this technique voltage probes are fixed over a section of transmission line of the length more than one-fourth of wavelength so that at least one minima is obtained. The probe voltages picked up from the transmission line is processed to find phase of the reflection coefficient. Magnitude of the reflection coefficient is determined using directional coupler. Magnitude and phase of reflection coefficient are used to find plasma impedance.

Voltage probe data so obtained is transmitted over a distance of about 100 meters from tokamak hall to data acquisition and control (DAC) room. In this process error is introduced into the probe data because of pickups and other noise signals. The errors in the probe data needs to be minimized, in order to get better estimate of VSWR curve. To minimize this error least square method has been used on the voltage probe data. Here in this paper we have used LabVIEW program to optimize the number of probes and their separation.

II. VSWR CURVE FORMATION

The single frequency time-harmonic voltage distribution on a uniform two-wire transmission line is given by

$$V(z) = V_1 e^{-\gamma z} + V_2 e^{+\gamma z} \qquad (1)$$

where V_1 and V_2 are the arbitrary phasor voltages and $\gamma = \alpha + j\beta$ is the propagation constant [3]. The transmission circuit is shown below

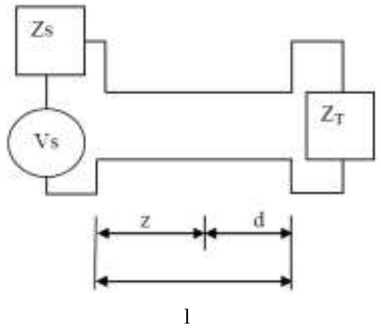

Figure 1. RF Power Flow

Here ‘Z_S’ is the RF source impedance while ‘Z_T’ is the load impedance. ‘V_S’ is source voltage, ‘z’ is the distance measured from source, ‘d’ is the distance from load while ‘l’ is the length of the transmission line.
The reflection coefficient at the terminal load end is given by

$$\rho_T = \frac{V_2 e^{+\gamma l}}{V_1 e^{-\gamma l}} = \frac{\frac{Z_T}{Z_0} - 1}{\frac{Z_T}{Z_0} + 1} \qquad (2)$$

For all practical purposes, it is assumed that line has minimal losses and hence line attenuation $\alpha=0$ and $\Upsilon = j\beta$. Equation (1) can be rewritten using $z = l - d$ and (2) as

$$V(d) = V_1 e^{-j\beta l}\left(e^{j\beta d} + \rho_T e^{-j\beta d}\right) \quad (3)$$

To obtain the graphical expression for general case of reflection; ρ_T must be expressed in an exponential term. Let

$$\rho_T = |\rho_T| e^{j\phi_T} = e^{-2(p+jq)}$$

Putting this value of ρ_T into (3) and simplifying, we get

$$V(d) = 2V_1 e^{-j\beta .l}\sqrt{\rho_T}\begin{bmatrix}\cosh p \cosh\left(j(\beta d + q)\right) \\ + \sinh p \sinh\left(j(\beta d + q)\right)\end{bmatrix}$$

From above equation, the magnitude of the standing wave can be written as:
$|V(d)| = \left|2V_1 e^{-j\beta .l}\sqrt{\rho_T}\right| \left\{(\cos^2(\beta d + q) + \sinh^2 p\right\}^{1/2}$ The scaling factor $\left|2V_1 e^{-j\beta l}\sqrt{\rho_T}\right|$ in the magnitude term has no significance since it will just shift the curve up or down and will not affect the position of minima. So making $\left|2V_1 e^{-j\beta l}\sqrt{\rho_T}\right|$ as unity, we get

$$|V(d)| = \left\{\sinh^2 p + \cos^2(\beta d + q)\right\}^{1/2} \quad (4)$$

No assumption has been made so far at arriving this equation (except the scaling factor) so this equation gives the value of the VSWR curve for different values of distance (d) from the terminal load.
The voltage minima will occur when $\cos^2(\beta d + q)$=0, which on simplification gives

$$\phi_T = 4\pi\left(\frac{d_{\min}}{\lambda} \pm \frac{n}{2}\right) - \pi$$

So from the VSWR curve; position of nth minima (d_{min}) will be found out. From this information, phase of reflection coefficient at load end (ϕ_T) will be determined.

III. LEAST SQUARE TECHNIQUE

In our case a series of voltage probes have been installed on the transmission line. These probes pick up the voltage signal. There could be some errors in the signal levels picked up by these probes. Best curve fitting technique is used to minimize these errors [4]. The magnitude of the voltage signal is given by the (4) as

$$|V(d)| = \{\sinh^2 p + \cos^2(\beta d + q)\}^{1/2}$$

Squaring it on both sides and simplifying gives

$$2V^2(d) - 1 = 2\sinh^2 p + \cos 2\beta d \cos 2q - \sin 2\beta d \sin 2q$$

Or

$$y = a_1 + a_2 \cos 2\beta d - a_3 \sin 2\beta d \qquad (5)$$

where $y = 2V^2(d) - 1$,

$a_1 = 2\sinh^2 p$, $a_2 = \cos 2q$ and $a_3 = \sin 2q$

Using least squares approximation technique, the sum of squares of errors S is found out as

$$S = \sum_i (y_i - y)^2 \quad (6)$$

where y_i gives the observed value and y gives the calculated value or function value at a particular distance. Putting the value of y from Eq. (5) in Eq. (6), we get

$$S = \sum_i (y_i - a_1 - a_2 \cos 2\beta d_i + a_3 \sin 2\beta d_i)^2 \quad (7)$$

Differentiating (7) with respect to a_1, a_2, a_3 and equating with zero for minimum error; we get three linear equations in a_1, a_2 and a_3. Solving these equations give values of a_1, a_2, a_3. From a_2, a_3, phase of reflection coefficient can be found out as

$$\phi_T = -\tan^{-1}\left(\frac{a_3}{a_2}\right).$$

So from the voltage probe data, VSWR curve may be drawn. The error into the voltage probe data and hence VSWR curve is minimized using least curve fitting technique. A program in LabVIEW has been developed to verify this technique. This program takes the voltage probe values at desired probe positions as input and then calculates the phase of the reflection coefficient at the terminal load using the least square technique explained above.

IV. SIMULATION RESULTS

The error of 20% is deliberately added in input voltage and that curve is fitted using linear curve fitting technique. The output error is measured for different frequencies. The experiment is done by decreasing the number of probes so that we can find the optimized number upto which the output error is within limits. The experimental results are shown in following table:

No. of probes	Output Error at different frequencies (%)				
	60Mhz	65Mhz	70Mhz	75Mhz	80Mhz
15	2.37	0.73	5.71	4.48	4.56
14	1.89	3.32	4.39	3.73	5.12
13	2.07	5.43	6.47	2.24	3.09
12	4.51	3.72	6.12	6.13	4.49
11	5.28	2.96	8.36	6.51	7.59
10	3.30	5.29	9.43	4.57	4.76
9	4.05	6.88	5.25	6.17	8.97
8	4.46	8.23	10.26	6.51	6.20
7	9.37	6.57	3.64	10.23	15.25
6	8.94	11.62	22.48	15.42	12.50
5	9.70	5.48	7.90	8.50	5.69
4	10.15	10.78	17.46	16.52	15.42
3	18.20	23.28	27.50	42.46	37.80

V. CONCLUSION

From the above results it is concluded that the minimum number of probes required is five and minimum separation should be more than quarter wavelength.

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