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Fault detection system for ICRF transmission line in LHD

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HIGHLIGHTS

- We developed a fault detection system for the ICRF transmission line in the LHD.
- For the precise detection of faults, the iterative calibration method was developed.
- Insensitive regions in the transmission line disappeared by the double-probe method.
- Self-oscillation as well as breakdown will be detected.

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ABSTRACT

The transmission line is one of the most important components of ion cyclotron range of frequencies (ICRF) heating devices. In the case of unexpected trouble on the line, such as a breakdown, immediate power-off is necessary in order to avoid severe damage on the line. Breakdowns are difficult to detect with a reflection monitor, since the reflection may originate from a change in the antenna-plasma coupling. In the Large Helical Device (LHD), a Fault Detection System (FDS) for the transmission line was developed, which detects the breakdown utilizing the unbalance of three signals from the both ends of the line. For the precise balancing in the normal condition, the calibration is iteratively conducted. FDS is insensitive to the change of the antenna impedance, therefore, FDS can detect breakdown clearly. Frequency shift is also detectable with the FDS applied to a long transmission line. Therefore, the self-oscillation accompanying frequency shift could be detected in addition to breakdown.

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1. Introduction

Ion cyclotron range of frequencies (ICRF) heating is one of the plasma heating methods in the Large Helical Device (LHD) [1]. High-frequency power of approximately 1 MW can be fed from the final power amplifier (FPA) [2] to the ICRF antenna [3] via an impedance matching device [4] using a transmission line. Problems, such as melting caused by breakdown, have occurred on the line between the FPA and the impedance matching device in the LHD. In the case of trouble on the line, immediate power-off is necessary in order to avoid severe damage, such as melting, which can cause a fire, especially during long-pulse operation [5,6]. The impedance matching device is located near the LHD, because the shorter the distance between the ICRF antenna and the matching device, the better for reducing power loss. As a result, the distance between the FPA and the impedance matching device reaches more than 100 m. Moreover, the route of the line is complicated. Therefore, it is difficult to monitor the temperature all the way along the line in order to detect the breakdown. It is also difficult to recognize faults by reflected power, since the increase in reflection may be caused by the normal variation of the antenna-plasma coupling. For these reasons, we developed a Fault Detection System (FDS) for the ICRF transmission line in the LHD by applying the technique of the Scattering Matrix Arc Detection (SMAD) system in the JET ITER-like ICRF antenna [7], which is sensitive only to the change in the S-matrix of the antenna caused by arcing, and is insensitive to the antenna-plasma coupling.

The principles and setup of the FDS are described in Section 2. In Section 3, we introduce a newly developed calibration method. Simulation of FDS is presented in Section 4. Section 5 presents the results of a low-power test, and Section 6 is the conclusion.

2. Principle and setup of FDS

We assume that ports 1 and 2 are the input and output ports, respectively, of a transmission line. V_{f1} and V_{r1} are the forward and

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the reflected wave voltages at port 1, and V_{f2} and V_{r2} are the forward and the reflected wave voltages at port 2. The relation between these voltages can be written with the S-matrix as

$$\begin{pmatrix} V_{r1} \\ V_{f2} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} V_{f1} \\ V_{r2} \end{pmatrix} \quad . \tag{1}$$

V_2 is the combined voltage of V_{f2} and V_{r2} defined as

$$V_2 \equiv c_f V_{f2} + c_r V_{r2} \quad . \tag{2}$$

By eliminating V_{f2} and V_{r2} from Eqs. (1) and (2), the following relation is derived:

$$V_2 - \{c_f(S_{21} - \frac{S_{11}S_{22}}{S_{12}}) - c_r\frac{S_{11}}{S_{12}}\}V_{f1} - (c_f\frac{S_{22}}{S_{12}} + \frac{c_r}{S_{12}})V_{r1} = 0 \quad . \tag{3}$$

The left-hand side is independent of output impedance. Therefore, if the left-hand side deviates from zero, this means that the S-matrix has changed, and there is a fault in the line.

The FDS simulates Eq. (3) in the outer circuit, as shown in Fig. 1. Assuming that v is the voltage of the detected signal for V_2 with the coupling factor c_2 (=v/V_2), Eq. (3) is written with the definition of δ as

$$\delta \equiv v + v_f + v_r = 0 \tag{4}$$

where v_f and v_r are defined as follows:

$$\begin{cases} v_f = -c_2\{c_f(S_{21} - \frac{S_{11}S_{22}}{S_{12}}) - c_r\frac{S_{11}}{S_{12}}\}V_{f1} \\ v_r = -c_2(c_f\frac{S_{22}}{S_{12}} + \frac{c_r}{S_{12}})V_{r1} \quad . \end{cases} \tag{5}$$

The two values v_f and v_r can be generated by adjusting the forward and the reflection signals from the existing directional couplers at the outlet of the FPA, which is used for the impedance matching and the power monitoring. The adjustment is conducted with variable attenuators and phase shifters inserted in the lines of the forward and reflection signals. In order to avoid the nonlinearity caused by the variable attenuators and phase shifters, input signals must be sufficiently attenuated. Although v is generated with a combination of forward and reflected wave voltages at port 2, v can be easily generated with a combination of voltages at separate positions, as shown in Fig. 1. We used the combined voltage signal from two voltage probes for v, since there are voltage probe ports near the inlet of the impedance matching device. The summation of v, v_f, and v_r was realized with power combiners to generate the combined signal δ. This signal was then amplified, and bandpass filters were inserted to cut RF noise from the plasma. The signal was converted to a DC signal and connected to a comparator and an analog-digital converter through a low-pass filter. Due to the long distance between the directional couplers and the voltage probes, there is a time lag between signals. The low-pass filter was thus needed to ignore the finite δ at the timing of instantaneous turning on or off induced by the time lag. If the three signals lose balance in spite of the proper adjustment of phase shifters and attenuators, the finite combined signal δ is generated. This indicates that there is a fault somewhere in the transmission line, because the S-matrix has been changed, and the FDS will turn off the power before amplification. For a large $|\delta|$, the comparator outputs an off-signal instantaneously. However, the combined signal δ depends on the power. Therefore, the normalized combined signal defined as follows is used for the sensitive judgment of faults:

$$\delta_n = \frac{\delta}{\sqrt{|v|^2 + |v_f|^2 + |v_r|^2}} \, . \tag{6}$$

Self-oscillations sometimes occur in the FPA without input power, which may cause damage on ICRF devices. This accompanies the frequency shift that changes the S-matrix of the transmission line. Therefore, the FDS can also detect self-oscillation. If the power was turned off by the FDS before amplification however, the FDS still detected faults, then in such a case bias voltages on the anode and screen grid in the FPA will be dropped because the FDS identified it as a self-oscillation.

3. Iterative calibration

Normally, output impedance of the transmission line is adjusted to the characteristic impedance of the line of 50 Ω with the impedance matching device. However, the output impedance sometimes differs from the characteristic impedance due to the fast variation of antenna impedance. Therefore, the balance of the three signals must be maintained with arbitrary output impedance. Adjustment of phase shifters and attenuators based on Eq. (5) is possible in principle. However, all parameters in Eq. (5) and coupling factors of forward and reflected waves at the directional couplers must be measured or simulated as the SMAD in JET. Moreover, the dependences of attenuation and phase shift on control voltages must be determined. There will be a limitation in terms of accuracy with this method. For sensitive fault detection, therefore, we developed an iterative calibration method. In this method, adjustments of phase shifters and attenuators were conducted with the following procedure. First, v_f, v_r, and δ are measured using an oscilloscope, and v is deduced from Eq. (4):

$$v_{1,2} = \delta_{1,2} - v_{f1,2} - v_{r1,2} \tag{7}$$

where the output impedance is changed twice with the impedance matching device, as indicated by the suffixes 1 and 2. Assuming that forward and reflection signals are adjusted in order to reduce the combined voltage δ in arbitrary output impedance with phase shifters and attenuators as

$$v_f{}' = \alpha v_f \text{and} v_r{}' = \beta v_r, \tag{8}$$

the expected voltages of combined signals are written as follows:

$$\begin{cases} \delta_1' = v_1 + v_{f1}' + v_{r1}' = v_1 + \alpha v_{f1} + \beta v_{r1} \\ \delta_2' = v_2 + v_{f2}' + v_{r2}' = v_2 + \alpha v_{f2} + \beta v_{r2} \, . \end{cases} \tag{9}$$

These combined signals $\delta_{1,2}{}'$ should be zero. Therefore, the following equation is derived using Eq. (7),

$$\begin{cases} \alpha v_{f1} + \beta v_{r1} = -\delta_1 + v_{f1} + v_{r1} \\ \alpha v_{f2} + \beta v_{r2} = -\delta_2 + v_{f2} + v_{r2} \, . \end{cases} \tag{10}$$

Therefore, adjustment factors α and β are determined:

$$\begin{cases} \alpha = (-v_{r2}\delta_1 + v_{r1}\delta_2)/(v_{f1}v_{r2} - v_{r1}v_{f2}) + 1 \\ \beta = (v_{f2}\delta_1 - v_{f1}\delta_2)/(v_{f1}v_{r2} - v_{r1}v_{f2}) + 1 \, . \end{cases} \tag{11}$$

Phase shifters and attenuators are adjusted according to the determined α and β. Adjustment factors α and β are determined so that the combined signals $\delta_{1,2}$ are zero. Therefore, $\delta_{1,2}$ will be smaller than $\delta_{1,2}$ before the adjustment. As a result, $\delta_{1,2}$ will converge to zero in arbitrary output impedance by repeating this procedure several times.

4. FDS simulation

In order to investigate the behavior of the FDS, a simulation was conducted at the frequency of 38.47 MHz used in ICRF heating experiments in the LHD assuming the ideal transmission line ($S_{11} = S_{22} = 0$ and $S_{12} = S_{21} = e^{-jkL}$, where k is the wave number in the transmission line and L is the line length).

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