Tests of an RF-Based Technique to Locate Arcs in a Coaxial Transmission Line*

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Abstract. A swept frequency reflectometry technique is being investigated as a means of determining the location of arcs in RF transmission lines. The method is applicable to both vacuum and pressurized transmission lines. Arcs are produced in a 6.3 m long resonant coaxial test line with an outer conductor diameter of 15 cm and Z0 = 26 Ω by injecting RF at a power level of 25-80 kW and f ~ 47 MHz. A septate coaxial coupler with a cutoff frequency of ~ 450 MHz injects a diagnostic wave swept over a portion of the range 475-550 MHz at a sweep frequency up to 200 kHz. During the sweep period, the arc impedance can be nearly constant. The rate of phase change of the reflection coefficient of the diagnostic wave as a function of frequency is measured and used to determine the distance to the arc.

INTRODUCTION

This paper describes a method which uses a swept frequency diagnostic wave injected into a high power coaxial RF transmission line to determine the location of high voltage breakdowns within the line. The basic approach, which has been described in a previous paper (1), is to introduce low power RF into the transmission line in a frequency range well above the frequency of the high power RF traveling through the line, but below the frequency of the first higher order coaxial mode. The diagnostic wave is swept in frequency over a time short compared to the arc duration. The distance to the arc is then determined from the measured frequency dependence of the phase of the diagnostic wave reflection coefficient. For the frequency range of interest, there is little phase shift introduced by the arc itself, which we assume can be represented by a a small inductance (≤ 30 nH) in series with a small resistance (≈ 1Ω). This impedance appears in parallel across the transmission line at the location of the arc. For arcs with inductances greater than several nH, additional phase shifts can be introduced by the impedance of the portion of the transmission line which is in parallel with the arc impedance. A baseline subtraction technique has been developed to improve the sensitivity of the technique to these high impedance arcs.

TEST CONFIGURATION AND ANALYSIS

Figure 1 is a sketch of the resonant coaxial test line used in the present investi-

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gation. Arcs can be produced by injecting high power (≤ 80 kW) into the line at a frequency at which the line is full-wave resonant (≈ 47 MHz). The line has an outer conductor diameter of 15 cm and a characteristic impedance of 26 Ω. A high frequency coupler attached to the opposite end of the line is used to introduce the diagnostic signal. This coupler has a cutoff frequency well above that of the main injected power and looks like a short circuit at 47 MHz. As a result, very little of the high power RF appears in the feed line through which the diagnostic signal is introduced. In an actual application, the coupler would be mounted at the end of a quarter-wave stub connected to the main transmission line via a tee junction.

Figure 2 shows two views of the high frequency coupler. It is constructed from a section of coaxial transmission line with a characteristic impedance of 50 Ω, with a septum located at a single azimuthal angle. The septum creates a type of compact waveguide in which the cutoff frequency corresponds approximately to the frequency at which one half the free-space wavelength equals the circumference halfway between the inner and outer conductors (2). The electric field and transverse magnetic field profile of the lowest order (TE 10) mode propagating through the coupler is a close match to the TEM mode propagating in the main transmission line. The diagnostic signal is introduced through a simple magnetic coupling loop. The transmission coefficient as a function of frequency between the coupler input and a 6 inch coax to type N 50 Ω adapter fitted to the end of the coupler has been measured and is shown in figure 3.

As seen in Fig. 1, there is a pair of directional couplers located in the main resonant line. These couplers have a frequency range of 400 –750 MHz, and 400 MHz high pass filters are attached to the coupler outputs to further attenuate the low frequency high power RF. The couplers are used to measure the reflection coefficient of the high frequency diagnostic wave, looking in the direction towards the high power feed. Arcs are produced by the high power RF, and modify the reflection coefficient measured by the directional couplers.

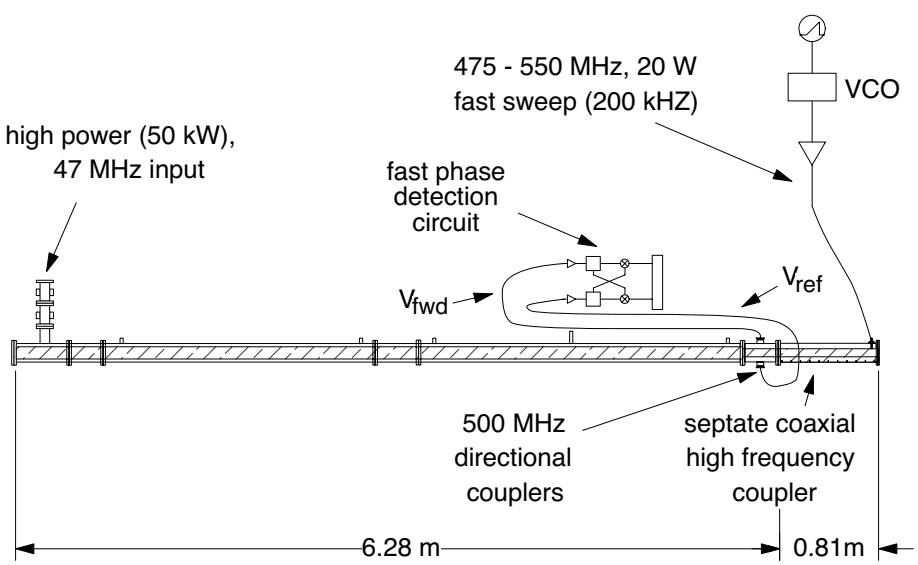

FIGURE 1. Resonant coaxial test line

Given a reflection coefficient ρ measured at the couplers, assuming that the arc is an ideal short circuit, and ignoring the change in characteristic impedance between the resonant line and directional coupler section, the phase of ρ will be observed to vary linearly with frequency according to $\phi = \phi_0 - 2j\beta d$, where ϕ is the phase of ρ, d is the distance between the arc and the measurement point, $\beta = 2\pi f/c$, f is the frequency, and c is the speed of light in vacuum. Thus the slope of the graph of ϕ vs. f directly yields the distance d.

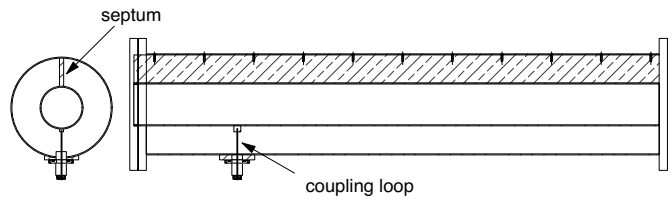

FIGURE 2. High frequency coupler

One problem with this technique is that if the arc inductance is relatively high, the frequency dependence of the reflection coefficient phase will include a contribution due to the impedance of the transmission line beyond the arc location. This effect can be compensated for by making a measurement of the reflection coefficient versus frequency before and during an arc. Denoting the value of the reflection coefficient measured before the arc occurs as ρ_b, and noting explicitly the dependence of ρ and ρ_b on f, we can translate them both along the line from the measurement point toward the arc location by a trial distance d:

$$\rho(f)' = \rho(f)\ \exp(2j\beta d) \tag{1}$$

$$\rho_b(f)' = \rho_b(f)\ \exp(2j\beta d) \tag{2}$$

where the primes denote values existing at the trial distance d from the measurement point. Since the arc and transmission line impedances occur in parallel, we convert the reflection coefficients to normalized admittances:

$$y(f) = (1-\rho(f)') / (1+\rho(f)') \tag{3}$$

$$y_b(f) = (1-\rho_b(f)') / (1+\rho_b(f)') \tag{4}$$

If we have guessed the correct value of d, then $y(f)$ will be the sum of the arc and transmission line admittances at the arc location, and $y_b(f)$, since it is determined from a measurement made before the arc, will be the transmission line admittance alone. Then the arc admittance is simply given by the expression

$$y_{arc}(f) = y(f) - y_b(f) \tag{5}$$

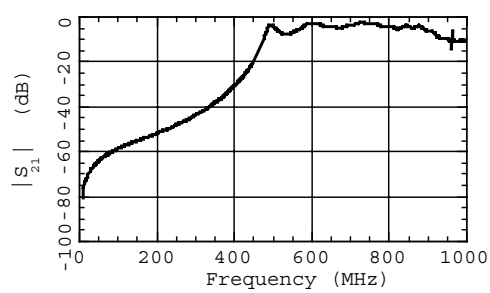

FIGURE 3. Attenuation coefficient vs. frequency of high frequency coupler

This can be converted back to a reflection coefficient, which is now equal to the reflection coefficient for the arc alone:

$$\rho_{arc}(f) = (1 - y_{arc}(f)) / (1 + y_{arc}(f)) \tag{6}$$

Since the phase of ρ_{arc} determined at the arc location should vary little with frequency, the distance to the arc is determined by finding the value of d which minimizes this variation. There are complications arising from the fact that spurious minima in the phase variation occur at integer multiples of the distance equal to a half-wavelength at the sweep center frequency. Techniques for eliminating these minima will be discussed in a future paper.

INITIAL MEASUREMENTS

The configuration shown in Fig. 1 differs from the planned implementation in a high power ICRF system for plasma heating and current drive in that the reflection coefficient is measured looking towards the generator. The feed line, which is ~ 30 m in length, together with the tetrode output coupling circuit, introduce a large number of very narrow resonances (Figure 4). As a result, although the phased detection system has been designed to have a bandwidth of > 50 MHz, this bandwidth can be exceeded even for sweep rates well below 100 kHz. By choosing a narrow frequency range which avoids most resonances, we have been able to obtain reflection coefficient data at sweep rates to 200 kHz. Figure 5 shows an initial result of a reflection coefficient phase vs. frequency measurement made at this fast sweep rate with no arcs. The slope corresponds to a distance of 5.5 m, which compares favorably to the distance of 6 m between the directional couplers and the shorted end of the resonant line, considering errors introduced by changes in characteristic impedance and the presence of the feed line. Fast measurements with arcs are now underway.

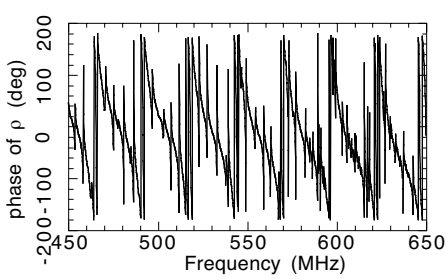

FIGURE 4. Slow reflection coefficient measurement made with network analyzer

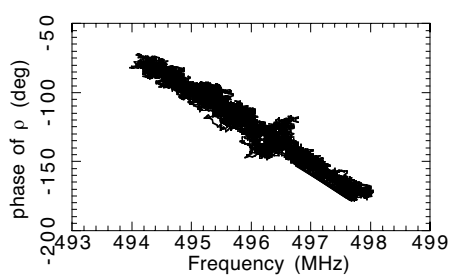

FIGURE 5. Fast reflection coefficient measurement summed over many sweeps with 200 kHz sweep rate

1. Goulding, R. H. , et al., "Investigation of High Voltage Breakdown and Arc Localization in RF Structures,", *AIP Conf. Proc*. 485, (Annapolis, 1999), pp. 425-428.

2. Barrow, W. L., and Schaevitz, H., "Hollow pipes of relatively small dimensions," AIEE Trans., **60**, pp. 119-122, March 1941.