AN INNOVATIVE FAST-RESPONSE, CO-AXIAL, CAPACITIVE HIGH VOLTAGE PROBE

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Abstract

This paper describes the detailed design for a fast-response, co-axial, capacitive, high voltage probe. Capacitive voltage probes are generally preferred for high repetition rate systems because of the disadvantages inherent in using a resistive voltage divider. A resistive voltage probe requires a low resistance in order to provide adequate frequency response, but this low impedance can imply excessive heating due to the high repetition rate of the system. The basic design and its operation are discussed. The coaxial design of the probe minimizes stray impedances. This method of construction also enables the probe to provide good impedance matching characteristics to the output signal cable. The combination of these effects allows the probe to perform with good high frequency response. Another advantage of the probe design is that the probe capacitance can be readily predicted through simple analytical calculations. An analysis of the probe performance is included in the discussion. Actual experimental data reviewing the probe response will also be presented.

Introduction

This paper describes the design, construction and testing of a fast risetime, coaxial, high voltage capacitive probe for use in measuring the voltage generated by a compact, repetitive, high power pulser. Capacitive voltage probes are generally preferred over resistive voltage probes for high repetition rate systems because of the disadvantages inherent in using a resistive voltage divider. A resistive voltage divider requires a low probe resistance in order to provide adequate frequency response, but this low impedance can lead to excessive heating due to the high repetition rate of the system. A capacitive voltage probe can avoid this problem and still provide a fast, accurate representation of the output waveform.

The probe described in this paper is a differentiating probe. The output signal of this probe must be integrated in order to reproduce the input signal. A differentiating probe has several advantages over a capacitive voltage divider. Capacitive voltage dividers must be used with a specified, well defined length of output cable to eliminate inaccuracies in their lower frequency range due to the cable capacitance. Capacitive dividers usually have a resistance parallel to the capacitance in the high voltage leg to balance the cable impedance which appears in parallel with the low voltage leg. This is necessary to preserve the high frequency response of the probe. The cable impedance forces this resistance to be a certain value which may not be optimal from the standpoint of probe risetime or power dissipation in the probe. Differentiating probes do not suffer these difficulties. They have an inherent droop and may have a baseline shift associated with their output, but both of these are easily compensated for in a data acquisition system.

The basic design of the probe and its operation are discussed in the following section. The coaxial layout of the probe minimizes stray impedances between the probe and other surrounding components. This method of construction also enables the probe to provide good impedance matching characteristics between itself and the output signal cable. The combination of these effects allows the probe to perform with good high frequency response. Another advantage of the probe design is that the probe capacitance can be readily determined through simple analytical calculations. These calculations allow both the probe capacitance and the voltage rating to be easily modified during the design effort. Computer simulations of the probe demonstrated the analytically developed design values for the probe were indeed the correct values.

Probe Design

This probe is required to measure the voltage produced by a 400 kV, 100 pps pulser whose pulses have a 150 ns half width and a 30 ns risetime. In order to measure such a pulse accurately, the probe generally must be an integral part of the pulser or the load which the pulser is driving. This places unique constraints on the construction of a probe for any individual system. For this particular pulser, a coaxial, oil filled probe was desired. At this voltage it was determined that a center conductor diameter of 7.62 cm (3") and an outer diameter of 30.5 cm (12") would be satisfactory to hold off the voltage. The peak field stress in the oil is approximately 38 kV/cm, which is 40% of the breakdown stress for the oil to be used in the pulser.

In order to accurately calculate the probe capacitance analytically, the electric field in the capacitance should have a relatively simple dependence on the geometry of the probe. For a coaxial probe, the capacitance is easily calculated if the electric field is as close as possible to that in a long coaxial structure. One method of accomplishing this is to make the probe capacitance a small section in the center of a longer coaxial structure, as shown in Figure 1. Internally, the probe should be designed to maintain a 50 Ω geometry as much as possible to reduce the effects of impedance mismatches on the transmitted signal. The connection from the probe capacitance to the output cable should have a 50 Ω termination for this reason.

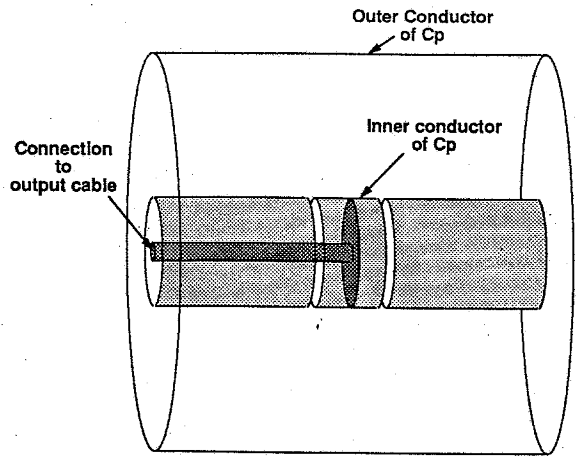

Figure 1. Simplified Probe Structure

A simplified schematic of the probe which includes the calculated component values of the probe and the integrator is shown in Figure 2. These values were calculated to cause the probe to deliver an output of < 50 V for a 500 kV input, making the divider ratio for the probe > 10,000:1. R_{lim} is intended to limit any possible fault current to prevent damage to the probe and associated equipment. C_p is the probe capacitance, R_p is the 50 Ω matching resistor(s), and R_i and C_i are the integrator resistor and capacitor, respectively. Figure 3 shows a drawing of the probe which was constructed. The components are labeled with the same names as in Figure 2. Note that the impedance of the coaxial structure formed by the outer and inner conductors of C_p is 50 Ω, as is that of the coaxial

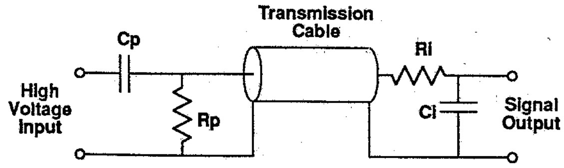

Figure 2. Simplified Probe Schematic

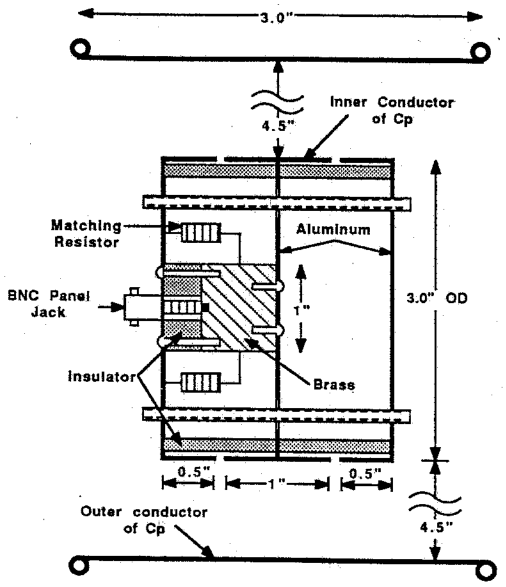

Figure 3. Capacitive Probe Assembly

structure formed by the inner conductor of C_p and the inner conductor of the probe structure, which is the section connected to the output BNC connection and terminated in 50 Ω. This design feature provides good matching to the output cable, which is essential to retain the fast risetime capabilities of the pulser.

Stray components can have a very significant effect on high voltage diagnostics, particularly if those components have large frequency response bandwidths. As a result, any realistic modeling of a fast high voltage probe must include estimates for the stray components associated with that probe. The stray inductances for the probe which is shown in Figure 3 were calculated and included in the probe model, which is shown in Figure 4. With these stray components, the expected risetime limit of the probe is 3 ns. The input pulse to this model and the differentiated signal are shown as the two upper traces in Figure 5. The input pulse is intended to be as close as possible to the expected output of the actual pulser. The output of the 900 ns integrator is shown in the lower trace in Figure 5. The output trace shows that a probe with these component and stray values can accurately reproduce the input pulse, which has a risetime of approximately 20 ns and a half width of 150 ns. The output pulse shows the expected droop, but this droop is not difficult to compensate when the probe component values are known. The divider ratio for the probe in this simulation is 14,700:1.

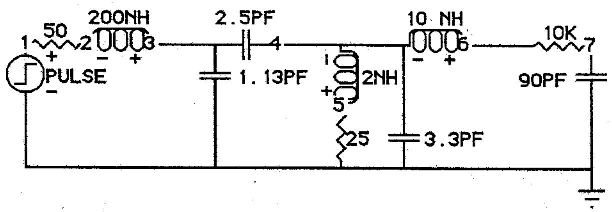

Figure 4. Capacitive Probe Simulation Model

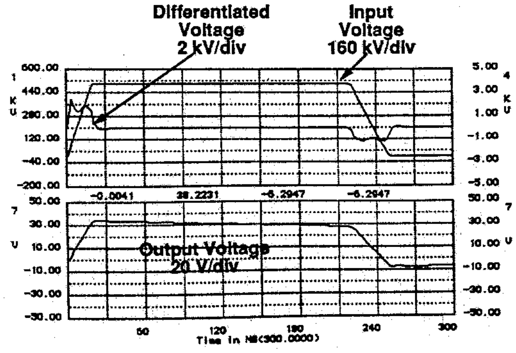

Figure 5. Probe Simulation Results

Experimental Probe Performance

The probe drawn in Figure 3 has been constructed. This probe is to be integrated into a coaxial water resistor which serves as a dummy load, as shown in Figure 6. The inner conductor for the water resistor serves as the outer conductor for the probe. To simulate this in testing the probe, the actual inner conductor for the water resistor was used. The pulse for the test was generated by a 4.0 meter, 50 Ω pulse forming line (PFL) which was charged to approximately 80 kV and switched through a spark gap to the load. Since the probe appears as an open circuit to the cable, this will produce a 80 kV pulse with a very fast risetime at the probe. The top of the pulse should be fairly flat for 30 ns, then the pulse should slowly die out. Based on the simulation results, the output voltage of the probe should be 5.5 V. This is a linear probe, so these results can be extrapolated to the final operational levels for the pulser for which the probe was designed.

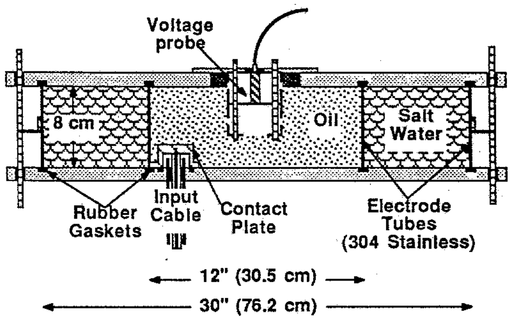

Figure 6. Dummy Load with Integrated Capacitive Probe

Figure 7 shows the oscilloscope trace of an output waveform of the probe with an 80 kV, 30 ns pulsewidth, fast risetime pulse applied to it. This waveform is typical of all the shots taken during testing. The risetime of this signal is approximately 2 ns. The

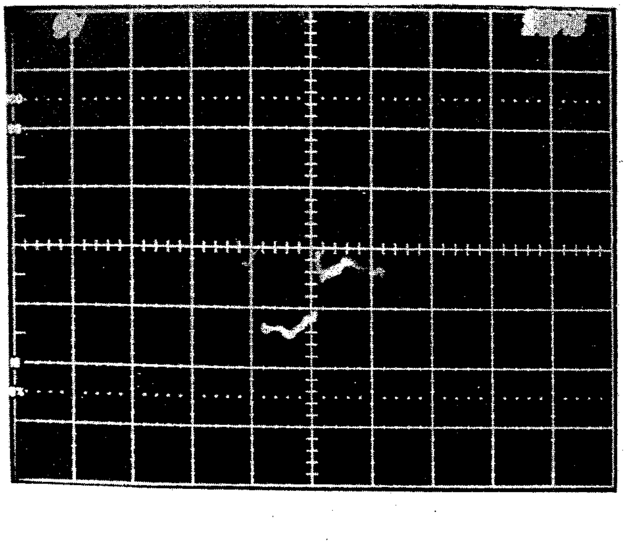

Figure 7. Oscilloscope Trace of Probe Output.

trailing edge of the pulse at 30 ns and the reflected pulse are characteristics which are expected from a PFL switched into an open circuit. The measured amplitude is about seven volts, which is slightly higher than the value in the probe simulation, but not significantly so. This output corresponds to a probe divider ratio of 11,500:1, which is near the desired value of 10,000:1. Some fine tuning of the component values will set this ratio to the desired value. The probe droop is difficult to determine from a pulse this short, due primarily to the limitations of available diagnostic equipment. Longer pulses will be tested in future tests, which will allow for accurate measurement of the actual droop.

Conclusions

The probe discussed in the sections above has been designed, constructed, and tested successfully. It has met its primary objectives in that its design allows for analytical design of the probe parameters, it has an bandwidth which is large enough for it to be used to measure the output voltage of the pulser for which it was designed, and it is well matched to both the pulser and the output cable. Probes of similar design can be used in a large number of pulsed power machines which are in use or in construction today. The advantages in using a differentiating probe over either resistive or capacitive dividers become even more pronounced as the voltage of the pulser increases. This type of probe is a very promising device for use as a high voltage diagnostic for high voltage, high power repetitive pulsers.