PULSED HIGH VOLTAGE MEASUREMENTS WITH COMPACT COAXIAL CAPACITIVE SENSORS

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**Abstract**: This note describes the development of two extremely simple and compact coaxial capacitive sensors that have been developed for the non-intrusive measurement of pulsed high voltage in dual resonant waterline driven pulsed electron beam accelerator AMBICA-600. These sensors are located on the either side of pulse forming line (PFL) to monitor the charging of PFL and its discharge across the peaking gap. The electrical characterization experiments of primary (CVD-1) and secondary (CVD-2) divider confirms rise time/division ratio of about $1\mu s/25000\times$ and $10ns/2000\times$, respectively. Design details of these sensors are provided here together with simple and straightforward methodology of their fabrication. Developed sensors are capable of measuring high voltage pulse up to 600kV.
Abstract

This note describes the development of two extremely simple and compact coaxial capacitive sensors that have been developed for the non-intrusive measurement of pulsed high voltage in dual resonant waterline driven pulsed electron beam accelerator AMBICA-600. These sensors are located on the either side of pulse forming line (PFL) to monitor the charging of PFL and its discharge across the peaking gap. The electrical characterization experiments of primary (CVD-1) and secondary (CVD-2) divider confirms rise time/division ratio of about 1µs/25000× and 10ns/2000×, respectively. Design details of these sensors are provided here together with simple and straightforward methodology of their fabrication. Developed sensors are capable of measuring high voltage pulse up to 600kV.

Keywords: Capacitive voltage divider, high voltage pulse, pulsed accelerators.
I. Introduction

Experimental research on intense pulsed electron beam accelerators for modern pulsed power application [1,2] are constantly in progress and in the same context real time measurement of PFL charging voltage and the voltage appearing across the electron beam diode has important significance. The two well established techniques for gauging temporal characteristics of high voltage transients are resistive [3] and capacitive voltage dividers (CVD) [4,5]. Traditionally, in waterline driven pulsed electron beam accelerators utilization of resistive dividers is more common [3,6]. The inherent shortcoming in use of resistive voltage divider is that they are physically connected at the voltage measurement point and become part of the electrical circuit of accelerator. In such condition, the overall resistance of the divider appears in parallel with impedance of the measuring point. If the resistance of the divider is not significantly larger than the impedance of measuring point, the energy efficiency of the accelerator is adversely affected [5]. Resistive voltage dividers are bulky and also sensitive to ambient temperature and their regular usage requires frequent calibration [6,7]. The above-mentioned problems are avoidable with the use of CVD’s. The system customized CVD’s offer non-intrusive measurement of fast high voltage pulses along with advantage of compactness, ease of use, stability and reliability. This work introduces the construction and performance evaluation of indigenously developed coaxial CVD’s for the measurement of fast high voltage pulse up to 600kV.

The operating principle of capacitive voltage divider relies on the fact that two series capacitances connected between a high voltage point and a reference potential (e.g. ground), divide the voltage according to relation [8]:

\[
\frac{V_2}{V_1} = \frac{C_1}{C_1 + C_2}
\]  

(1)

In order to avoid cable reflections oscilloscope input impedance must match the cable impedance (i.e. typically 50Ω). This results in rather short time constant (often only few 100ns) making it possible to accurately measure only the high frequency component of the signal. This problem is solved by the inclusion of high impedance voltage follower between the capacitive divider and oscilloscope. It serves both, as an additional voltage divider and as a part of RC network with time constant chosen to
be much longer than the pulse length to be measured. The operation of CVD is practically explained by the equivalent circuit shown in Fig. 1.

![Diagram of Capacitive Voltage Divider](image)

**Fig. 1.** The electrical equivalent circuit of capacitive voltage divider.

In the frequency range of interest, the voltage division occurs in two stages. Firstly, as capacitive \((C_1/C_2)\) and secondly as resistive \((R_1/R_2)\) divider. Here, since the signal is recorded across scope termination of \(~50\Omega\), hence \(R_2\) remains constant in the circuit. The parameters \(C_1, C_2\) and \(R_1\) are variable and their value determines total attenuation of divider. For an input step function the output signal \(V_2(t)\) is related to the input voltage waveform \(V_1(t)\) by the differential equation [9]:

\[
\frac{dV_2}{dt} + \frac{V_2}{RC} = \frac{R_2 C_1}{RC} \times \frac{dV_1}{dt} 
\]

where \(R = R_1 + R_2\) and \(C = C_1 + C_2\). If \(RC\) is much greater than the largest time of interest than the first term on the left side of Eq. (2) dominates and the output signal \(V_2\) is very closely approximated by Eq. (3) given below:

\[
\frac{V_2}{V_1} = \frac{R_2 C_1}{RC} = \left[ \frac{C_1}{C_1 + C_2} \right] \times \left[ \frac{R_2}{R_1 + R_2} \right] 
\]

It may be noted that the time constant of the probe \(\tau\) must be sufficiently large to minimize the droop in the output signal [10]. This implies larger values of \(R_1, R_2\) and \(C_1, C_2\). However, since \(C_1\) and \(C_2\) are usually fixed due to geometrical considerations and \(R_2\) is typically \(50\Omega\), the optimum value of \(R_1\) mainly decides the amount of droop that can be tolerated during the voltage measurement. The low frequency response of the divider is determined by the voltage decay across the capacitor \(C_2\) i.e. time
constant $\tau \approx (R_1 + R_2)C_2$. This corresponds to frequency bandwidth limitation of $0.35/\tau$ that can be adjusted by varying $R_1$ and $C_2$ according to the requirement [11,12]. The high frequency response is limited by following factors [11,12]: (i) the electrical length of capacitance $C_2$ (ii) internal inductance of the capacitor $C_2$ (iii) shunt capacitance and series inductance associated with series resistor $R_1$.

II. Construction and Results

In consideration to minimum bandwidth response requirement of high voltage sensors in our application, two extremely simple and compact capacitive voltage dividers have been designed and fabricated. Fig.2 shows the construction and electrical schematic of high voltage divider CVD-1 that is being used for the measurement of PFL charging voltage.

![Fig. 2. Construction and electrical schematic of CVD-1.](image)

The high voltage output from Tesla transformer is threaded to concentrically pass through Delrin cylinder of 50mm diameter and 80mm length. The cross-sectional diameter of HV conductor is ~2mm. Later on two concentric layers of 100µm thick copper foil (having four layers of 250µm Mylar insulation in between) are tightly wrapped over the Delrin cylinder. Width of the copper foils used in the Mylar interleaved inner and outer layer are 80mm and 50mm, respectively. The high voltage arm coupling capacitance $C_1$ is formed between the high voltage conductor of the Tesla transformer output (that charges PFL) and the inner layer of the copper foil. The low voltage arm capacitance $C_{2a}$ is formed between the two consecutive layers of Mylar separated copper foils of the inner and outer crust. The capacitance resulting from aforementioned coaxial geometry can be estimated from the formula for concentric cylinders of length $l$ [12].
Here $\varepsilon_r$ is the dielectric constant of insulating materials used in the divider construction. The insulations Mylar and Delrin interposed between inner and outer layers have dielectric constant $\varepsilon_r$ of 3.7 and 3. From the dimensions given earlier, the coupling capacitance $C_1$ and $C_{2a}$ are $\sim 5\text{pF}$ and $\sim 212\text{pF}$, respectively. After getting this primary attenuation, the output pulse was transmitted through a 2m long RG58 cable (that has characteristic impedance $Z_0$ of 50$\Omega$ and capacitance of $\sim 100\text{pF/m}$; i.e. $C_{2b}$ $\sim 200\text{pF}$) to a shielded box where in an additional internal capacitance $C_{2c}$ of 1nF (i.e. a low inductance ceramic disc capacitor) was connected in parallel. The utilization of $C_{2c}$ has been done to obtain large division ratio and increase the RC time of the voltage divider enabling the measurement of several $\mu$s long high voltage impulses. The estimated cumulative capacitance of low voltage arm $C_2$ ($\approx C_{2a}+C_{2b}+C_{2c}$) was $\sim 1.4\text{nF}$. A 5k$\Omega$ metal film resistor ($R_1$) that connects CVD (formed by capacitances $C_1$ and $C_2$) and the coaxial cable ($Z_0 \sim 50\Omega$) serves to further enhance the attenuation ratio and the probe RC time constant many times longer than the duration of pulse to be measured. The division ratio of resistive divider was determined as $\sim 100\times$. The overall voltage division ratio calculated from these component values of resistances and estimated values coupling capacitances, yields attenuation factor of $\sim 28,280\times$.

A careful calibration is required for accurately establishing the voltage division ratio $V_2/V_1$. The in-situ calibration was performed by utilizing standard voltage divider (Model/Make – VD-100/NorthStar) in parallel with newly developed CVD-1 sensor. The observed waveforms from respective dividers have been shown in Fig. 3. The attenuation ratio ($V_2/V_1$) was experimentally confirmed to be $\approx 25000\times$.

Fig. 4 shows the construction and schematic of CVD-2 that was used for the measurement of high voltage appearing across the electron beam diode. The pulse duration and rise time of the compressed high voltage output from water PFL is typically $\sim 100\text{ns}$ and $\sim 10\text{ns}$, respectively. The discharge-end of the high voltage holding switch (or input of electron beam diode i.e. cathode) concentrically passes through a Delrin cylinder of $\sim 200\text{mm}$ outer diameter and $\sim 50\text{mm}$ length. The cross-sectional diameter of HV conductor is $\sim 100\text{mm}$. The coupling capacitance $C_1$ is
formed by tightly wrapped 100µm thick, 20mm wide copper foil over the outer diameter of Delrin cylinder in coaxial configuration. From Eq. (5), $C_1$ was estimated to be $\sim$6pF. The low voltage arm of this CVD, $C_2$ is formed by 2m-length RG58 cable. It is remarkable to note that high frequency response is limited by the transit time for signal to travel along the length of $C_2$ [13]. For a step pulse of rise time $t_r$, the probe will be able to respond accurately if $t_r \geq l_2/v$. Here $v$ is the velocity of propagation of electrical signal along the coaxial cable (i.e. $\sim 2 \times 10^8$ m/s). For the fixed length of 2m, $C_2 \approx 200pF$ and this imposes ultimate limit on sensor response time to be $t_r \geq 10$ns.

![Fig. 3. Measured impulse response of CVD-1 sensor.](image)

![Fig. 4. Construction and electrical schematic of CVD-2.](image)
A series resistance $R_1$ of $2\,\text{k}\Omega$ was used along with scope termination $R_2$ of $50\,\Omega$ for enhancing the attenuation ratio and matching the time constant $RC$, sufficiently greater than the duration of high voltage pulse to be measured. The overall division ratio calculated from resistance values and estimated values of coupling capacitances, yields attenuation factor of $\sim 2100\times$. The in-situ calibration of CVD-2 was performed by utilizing URM67, $50\,\Omega$ coaxial cable as pulse forming line. The 10m length of URM67 cable was discharged to matched load at $\sim 6\,\text{kV}$ through a indigenously developed low inductance spark gap. The obtained output pulses from standard high bandwidth probe (PVM-5, 80MHz) and the CVD-2 have been shown in Fig. 5. Experimentally the attenuation ratio of CVD-2 remained $\approx 2000\times$. It may be seen that CVD-2 sensor is able to respond the fast rising high voltage pulse reasonably well.

![Fig. 5. Measured impulse response of CVD-2 sensor.](image)

**III. Conclusion**

We have constructed and characterized the two indigenously developed coaxial capacitive voltage sensors. As demonstrated, obtained calibration factor and bandwidth response of respective dividers is well within the tolerance range of predicted limits and measurement accuracy is comparable to that of commercial probes. Minor discrepancy between the estimated and experimentally measured voltage division ratio in CVD-1 and CVD-2 sensors may be attributed to deviation in
estimated values of coupling capacitances $C_1$ and $C_2$ (i.e. contributed by physical geometry of interleaved layers of copper foils separated by Mylar dielectric). It may be noted that theoretical estimations neglect the reduction in capacitances resulting from small air-gaps trapped between interposed layers of copper foils and Mylar dielectric [10]. This inherent intricacy implicates calibration of CVD’s with compatible response time pulses for accurately establishing the voltage division ratio $V_2/V_1$. The major advantage of these dividers in pulsed high voltage measurement is that they are total isolated from ground and hence injection of electrical noise is negligible into measuring instruments.

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References


