Electrical calibration for measuring average power of a ns timescale HV pulsed discharge

R. T. Nguyen-Smith , A. Al Hamdan, I. Korolov, P. Awakowicz and T. Mussenbrock

Chair of Applied Electrodynamics and Plasma Technologoy, Faculty of Electrical Engineering and Information Sciences, Ruhr University Bochum, Bochum, Germany

Abstract: Frequency resolved complex calibration procedures of standard current and voltage probes are used on measured current and voltage traces to correct for the probe responses. An additional frequency resolved phase shifting method that is new to ns timescale HV pulses, or not typically applied to, is applied to correct for time delays between the measured traces and further complex effects induced by the discharge. Combination of both methods provides accurate average dissipated powers of a ns timescale HV pulsed discharge.

Keywords: ns HV pulse, calibration, time delay, DBD, current, voltage, instantaneous power

1. Background

Nanosecond timescale HV pulses are typically composed of a complex broadband spectrum, often reaching into the 100 MHz range. Many capacitive high voltage probes are by design limited in their maximum bandwidths, the most common of which is reported to be limited to 75 MHz. Furthermore, the bandwidth limitation is not a step transition from measuring accurately to measuring inaccurately, but rather has a functional form. This makes accurately measuring the voltage of ns timescale HV pulse a very challenging task.

Similarly, the current induced by the ns timescale HV pulses are challenging measurements. Standard current transformers and Rogowski coils are either not fast enough, easily oversaturated, or pick up interference produced by either the generator and/or the discharge. Therefore, current measurements are either not performed, or in house built current shunts are used to measure the current induced by the HV pulses. However, the quality and accuracy of the shunt is highly dependent on the resistors used and the skill of the researcher/technician who built the shunt, and thus vary in frequency response.

Furthermore, both the current and voltage are likely measured at separate physical locations of the HV feed line, must be measured on separate transmission lines, and the transmission lines may be of differing lengths. A wave traveling at $2/3$ the speed of light requires approximately 5 ns to travel 1 m. Therefore, ns timescale delays between the measured current and voltage traces easily occur, which has detrimental effects on determining the electrical power of ns timescale HV pulses.

Traditional methods of correcting for such time delays involve using a low voltage setting of the generator and finding a Δt necessary to produce an average power of 0 W. However, a unique Δt is not guaranteed, *i.e.* it may be either positive or negative, the proper choice of which is not necessarily always clear. Moreover, this method is not applicable for all setups, for example when the generator cannot reach low voltages. Furthermore, this method requires already accurate and corrected current and voltage traces. Lastly, assuming and correcting for only a Δt does not correct for potential phase shifts induced by the discharge igniting.

2. This Work

These methods were developed and tested on a twin surface dielectric barrier discharge previously reported on in [1] and references therein. However, these methods are presented in a generalized form; therefore, are expected be directly applicable to any atmospheric pressure discharge powered by a nanosecond timescale HV pulse.

In this work we present a methodology to:

1) Accurately determine the probe response of a shunt resistor,
2) Accurately determine the probe response of a capacitive voltage divider,
3) Correct measured current and voltages traces for said probe responses,
4) Measure a single unique frequency resolved phase shift associated with the discharge ignition, temporal delays in the current and voltage measurements, and other complex effects resulting from the measurement setup,
5) Adjust the phase of the corrected current to account for the measured unique frequency resolved phase shift,
6) Determine the average dissipated power of the ns HV pulse into the discharge.

3. Methodology

3.1. Current shunt frequency response

The shunt resistor investigated in this work made from multiple resistors in parallel, providing the characteristic resistance R_{shunt}. This the simple relation between the voltage across the oscilloscope $\left(U_{\mathrm{scope}}\right)$ to the measured current (I_{m}) via:

$$\frac{a_{\mathrm{ext}}}{R_{\mathrm{shunt}}} U_{\mathrm{scope}} = I_{\mathrm{m}}$$

Where a_{ext} is the external attenuation factor due to the selected input impedance of the chosen oscilloscope channel and other additional attenuators in the measurement line. We assume that R_{shunt} is frequency dependent; in order to correct for the dependency I_m is multiplied by a correction factor ($\dot{\xi}_{\text{shunt}}$), given by:

$$\dot{\xi}_{\text{shunt}}(f) = \frac{\dot{Z}_{\text{shunt}}(f)}{R_{\text{shunt}}}$$

Where $\dot{Z}_{\text{shunt}}$ is the frequency resolved complex transmission impedance of the shunt resistor, and is measured via a vector network analyser. This is carried out via a 2-port measurement where one port is connected to the input and ground connections of the shunt, and the second port is the coaxial output connection for the oscilloscope. $\dot{Z}_{\text{shunt}}$ is then measured as the complex impedance from port one to port two.

3.2. Voltage probe frequency response

Similar to the current shunt, the measured voltage (U_{m}) is related to the voltage across the oscilloscope $\left(U_{\text{scope}}\right)$ via:

$$\frac{a_{\text{ext}}}{H} U_{\text{scope}} = U_{\text{m}}$$

Where H is the expected transfer function of the voltage probe. The utilized probe is a capacitive voltage divider built from two capacitors in series, forming a HV portion and a LV portion. H is defined as the ratio of the voltage drop across the LV portion to the voltage drop across the HV portion, or alternatively as the ratio of the total capacitance to the HV capacitance. In terms of complex impedance, the frequency resolved complex transfer function $\left(\dot{H}\right)$ is given as:

$$\dot{H}(f) = \frac{\dot{Z}_{\text{T}}(f)}{\dot{Z}_{\text{HV}}(f)}$$

Both complex impedances $\left(\dot{Z}_{\text{T}}, \dot{Z}_{\text{HV}}\right)$ are measured via a vector network analyser, either as 1-port or 2-port measurements. However, a portion of the voltage probe must be disassembled to measure $\dot{Z}_{\text{HV}}$. The probe response $\left(\dot{\xi}_{\text{U}}\right)$ is then determined as the ratio of the expected transfer function to the measured transfer function:

$$\dot{\xi}_{\text{U}}(f) = \frac{H}{\dot{H}(f)}$$

3.3. Correction of probe response

Both $\dot{\xi}_{\text{shunt}}$ and $\dot{\xi}_{\text{U}}$ are measured prior to a standard measurement set and are treated as look up tables. Because $\dot{Z}_{\text{shunt}}$ and therefore $\dot{\xi}_{\text{shunt}}$ are complex values, *i.e.* have both magnitude and phase, the multiplication of I_{m} and $\dot{\xi}_{\text{shunt}}$ must take place in the frequency space. Therefore, I_{m} is first transformed to the frequency space $\left(\dot{\jmath}_{\text{m}}\right)$ via a *fast Fourier transform*:

$$I_{\text{m}}(t) \overset{F}{\Leftrightarrow} \dot{\jmath}_{\text{m}}(f)$$

The current spectra and correction factor are multiplied by one another providing the frequency space corrected current spectra $\left(\dot{\jmath}_{\text{c}}\right)$:

$$\dot{\jmath}_{\text{c}}(f) = \dot{\jmath}_{\text{m}}(f)\dot{\xi}_{\text{shunt}}(f)$$

Similar to the current shunt, the frequency resolved corrected voltage spectra $\left(\dot{\mathcal{U}}_{\text{c}}\right)$ is determined by multiplying in the frequency space the measured voltage spectra $\left(\dot{\mathcal{U}}_{\text{m}}\right)$ by the complex calibration factor:

$$U_{\text{m}}(t) \overset{F}{\Leftrightarrow} \dot{\mathcal{U}}_{\text{m}}(f)$$
$$\dot{\mathcal{U}}_{\text{c}}(f) = \dot{\mathcal{U}}_{\text{m}}(f)\dot{\xi}_{\text{U}}(f)$$

3.4. $\Delta\phi$ measurement

The measured current and voltage traces are prone to time delays on the nanosecond timescale and corresponding phase shifts, as well as phase shifts associated with various aspects of the measurement setup, including the ignition of the discharge. By measuring the current and voltage traces without the discharge ignited, a complex comparison to the theoretical system impedance allows for the determination of a unique phase shift associated with a 0 W power input.

Discharge inhibition should be achieved without drastically modifying the measurement setup. Using low voltage output settings of the generator is possible; however, is not feasible for the used generator. Furthermore, it is not guaranteed that the resulting phase shift is voltage amplitude independent. Therefore, minor modification of the electrode system via filling the discharge area with a vacuum epoxy is used instead.

The vacuum epoxy coated electrode system successfully inhibits the discharge ignition. Current and voltage traces at varying voltage amplitudes are measured and corrected in the frequency space with the above detailed correction factors $\left(\dot{\xi}_{\text{I}}, \dot{\xi}_{\text{U}}\right)$. The impedance of the non-discharged system $\left(\dot{Z}_{\text{c}}^{\text{nd}}\right)$ is then determined via:

$$\dot{Z}_{\text{c}}^{\text{nd}}(f) = \frac{\dot{\mathcal{U}}_{\text{c}}^{\text{nd}}(f)}{\dot{\jmath}_{\text{c}}^{\text{nd}}(f)}$$

$\dot{Z}_{\text{c}}^{\text{nd}}$ is then compared to the theoretical impedance of the system $\left(\dot{\text{Z}}_{\text{E}}\right)$ (without discharge ignition) to form a phase shift $\Delta\phi$:

$$\Delta\phi(f) = \phi_{\dot{Z}_{\text{c}}^{\text{nd}}}(f) - \phi_{\dot{Z}_{\text{E}}}(f)$$

$\dot{\text{Z}}_{\text{E}}$ is measured and calculated with the help of a vector network analyser while considering the impedance of the electrode system used, the measurement setup, and the generator used to produce the HV pulses. $\Delta\phi$ is then formulated into a current phase shifting factor $\left(\dot{\xi}_{\Phi}\right)$ via:

$$\dot{\xi}_{\Phi}(f) = \text{e}^{i\Delta\phi(f)}$$

3.5. $\Delta\phi$ correction

$\dot{\xi}_{\Phi}$ is independent of current and voltage traces with a discharge ignited and is therefore measured prior to a standard measurement set and is treated as a look up table. As formulated, $\dot{\xi}_{\Phi}$ is applied only to the corrected current

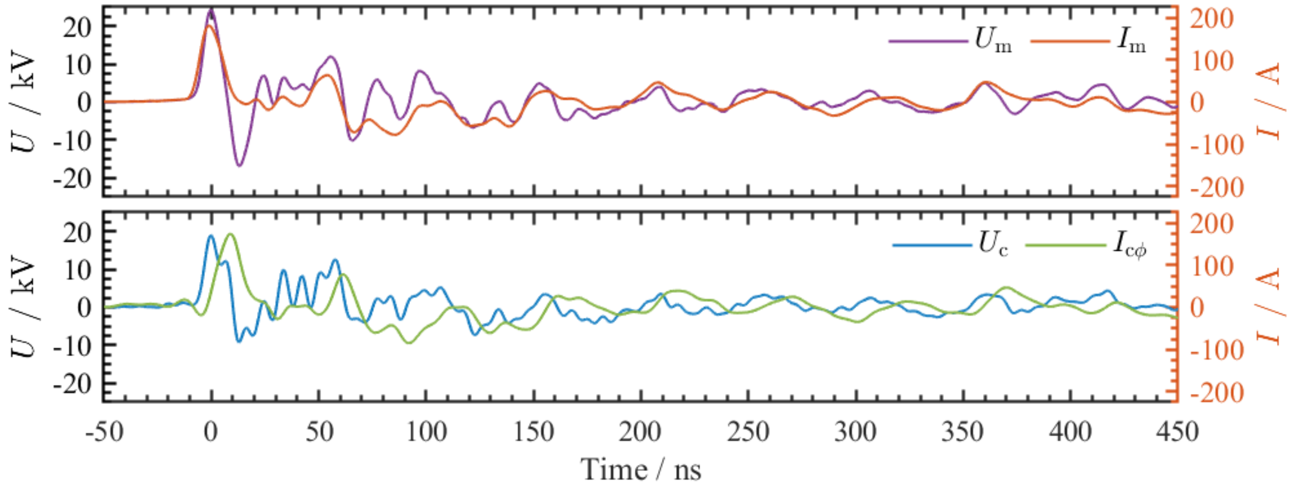

Fig. 1. (a) Measured voltage and current traces (U_m, I_m) and (b) corrected voltage and both corrected and shifted current $(U_c, I_{c\phi})$ traces as a function of time.

spectra in order to obtain a phase shifted and corrected current spectra $(\dot{\jmath}_{c\phi})$ via:

$$\dot{\jmath}_{c\phi}(f) = \dot{\jmath}_c(f)\xi_\phi(f) = \dot{\jmath}_m(f)\dot{\xi}_{shunt}(f)\dot{\xi}_\phi(f)$$

With appropriate phase negation, the phase shifting correction factor could alternatively be applied to the corrected voltage spectra instead.

3.6. Average discharge power

After correcting both the current and voltage spectra and phase shifting the current spectra, the time space corrected current and voltage waveforms are obtained via an *inverse fast Fourier transform*:

$$U_c(t) \overset{F}{\Leftrightarrow} \dot{U}_c(f)$$
$$I_{c\phi}(t) \overset{F}{\Leftrightarrow} \dot{\jmath}_{c\phi}(f)$$

The average electrical power dissipated into the discharge $(\bar{P})$ is then determined from the standard formulation:

$$\bar{P} = \frac{1}{\tau}\int_0^\tau \mathrm{U_c}(t) I_{c\phi}(t)\,\mathrm{d}t$$

4. Results

Applying the three correction factors to measured current and voltage traces with discharge ignition of a positive polarity ns timescale HV pulse leads to the differences in measured and corrected traces observed in Fig. 1, where (a) shows the measured current (I_m) and the measured voltage (U_m) traces, and (b) shows the both corrected and shifted current $(I_{c\phi})$ and corrected (U_c) voltage traces.

Calculating the dissipated power $(\bar{P})$ of ns timescale HV pulses at varying peak voltages and at pulse repetition frequencies of 1, 2, and 4 kHz reveals a linear trend in dissipated discharge power as shown in Fig. 2. Voltage pulses of identical settings were applied to the coated electrodes, thus no discharge is ignited. 0 W dissipated power is obtained from applying the presented methods to current and voltage traces of the non-discharged system.

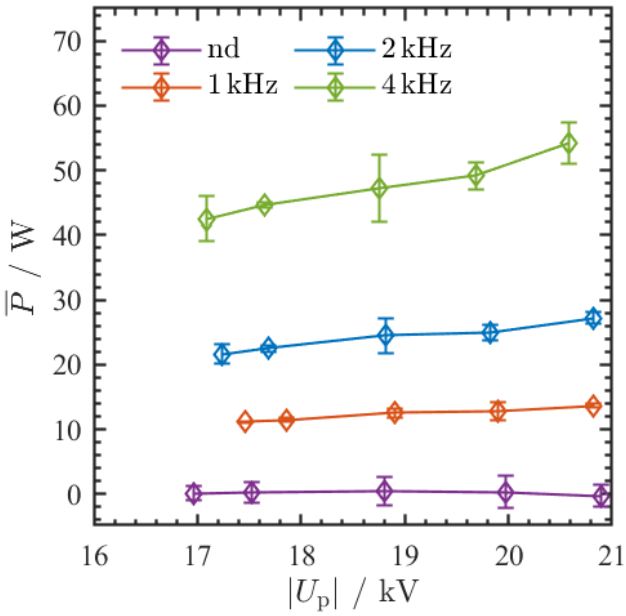

Fig. 2. Average dissipated power versus peak voltage at a pulse repeition frequencies of 1, 2, and 4 kHz. Dissipated power of a coated electrode without discharge ignition is also shown (nd).

5. Benefits

Correct and successful implementation of these methods allows for the determination of the average discharge power from only electrical measurements. These methods require a few simple preparative measurements of various aspects of the experimental setup; after which, live extraction and monitoring the discharge power is possible with proper implementation in control software such as LabView. Furthermore, additional live or post analysis of the current and voltage traces via an appropriate equivalent circuit model, such as the simplest equivalent circuit model [2-4] (in the case of dielectric barrier discharges) provides the possibility of determining the instantaneous discharge power as well.

6. Acknowledgements

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7. References

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