SYSTEMS ANALYSIS, MODELING, SIMULATION, AND SIGNAL PROCESSING ASPECTS OF COORDINATED EXPERIMENTAL AND MODELING INVESTIGATIONS OF HIGH-SPEED GAS DISCHARGE SWITCH BREAKDOWN BEHAVIOR

Ron Pate, Doug Riley, Paull Patterson, Larry Rinehart, Malcolm Buttram, Scott MacGregor[+], Andrew Dick[+], Erich Kunhardt[*], and Tom Hussey[#]

Sandia National Laboratories, Albuquerque, NM, 87185-1153 USA Email: rcpate@sandia.gov
[+] *University of Strathclyde, Glasgow, Scotland, UK*
[*] *Stevens Institute of Technology, Hoboken, NJ, USA*
[#] *Air Force Research Laboratory, Kirtland AFB, NM, USA*

Abstract

The authors have been engaged in experimental and modeling investigations of the electrical turn-on behavior of high-pressure gas discharge switching. Emphasis has been on characterizing the first few nanoseconds of switch turn-on for a range of operational conditions (i.e., gas type, gas pressure, gap length, drive circuit impedance, etc.). This paper describes the modeling, signal processing, and systems analysis aspects of the investigations, which were driven by interest in pursuing the extent to which limited experimental data could be usefully augmented with available computer modeling tools and techniques. A high-fidelity 3-D model of the experimental apparatus was developed and simulations performed using a full 3-D time-domain Maxwell solver. This provided detailed electrical characterization of the experimental system that allowed for the development of transfer functions enabling the estimation of time-varying discharge gap voltage and current waveforms based on experimental D-dot probe measurements taken some distance away from the discharge gap. The steps of this process are outlined, example results shown, conclusions presented, and directions for future work suggested.

I. INTRODUCTION

The time required for plasma channel voltage collapse in a gas discharge switch can become an appreciable fraction of the overall pulse duration in fast, short-pulse applications. This results in high switch energy losses that can severely impact circuit operation and system performance. The problem is exacerbated in low-impedance, high-power circuits, where switch losses can cause operational problems even under much slower and longer pulse-duration conditions [1]. The design and operational performance of gas discharge switches, particularly for use in ultra-fast, short-pulse-duration applications, could benefit from improved predictive modeling of the macroscopic electrical behavior of the discharge turn-on process as a function of switch and discharge circuit parameters (e.g., gas type, gas pressure, gap length, circuit impedance, etc.). To address this, the authors have pursued experimental and modeling investigations that focus on quantitative electrical characterization of the first few nanoseconds of plasma closing switch turn-on behavior as a function of key operational parameters. The experimental work to-date has focused on self-break switching under relatively controlled low over-voltage conditions for a range of gas types and operational parameters [2-5]. The experimental apparatus consists of a family of pulse-charged pulse-forming-line (PFL) structures closely coupled to a gas switch. Upon breakdown, the charged PFL discharges through the switch. Experimental diagnostics consist of medium bandwidth (100-MHz) charge voltage measurements and high-bandwidth (multi-GHZ) D-dot probe measurements of the high-speed discharge event [2-5]. The diagnostics were limited by equipment availability, resources, and the desire to minimize impact on test system operation.

II. MODELING APPROACH

High-fidelity 3-D electromagnetic modeling and simulation has been combined with linear systems analysis in order to augment the experimental data. The modeling and simulation provides detailed electrical characterization of the discharge system and allows for the relatively accurate estimation of the time-varying discharge channel voltage and current based on the available experimental data. Addition of detailed discharge channel physical process modeling within this overall system modeling and simulation framework will allow for the estimation of time-varying discharge channel resistance and energy loss for a given set of experimental conditions. This approach is expected to provide for optimization of the discharge model and associated parameters for best agreement with experiment, which can lead to improved switch design and performance prediction. This is shown schematically in Fig-1.

III. DAC SYSTEM DECONVOLUTION

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14. ABSTRACT
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To restore maximum usable information content, the experimental D-dot probe measurement data must be compensated to correct for bandwidth limitation and other signal loss effects imposed by the data acquisition (DAC) system, shown in Fig-2. The D-dot probe, shown in Fig-3, has a response bandwidth in excess of 6-GHz [4], while the SCD5000 Transient Digitizer is limited to about 2.5-GHz due to an internal delay line. The cabling, connectors, and attenuators have high bandwidth, but introduce minor additional amplitude loss.

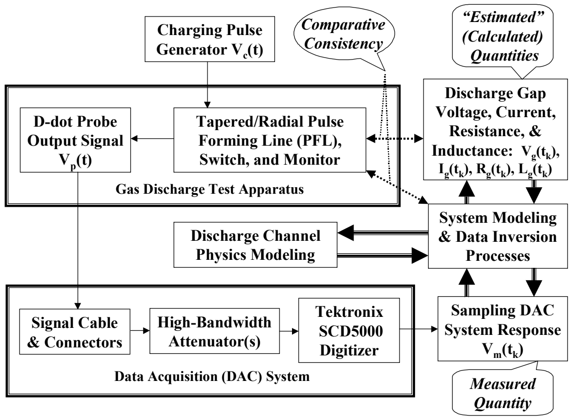

Figure 1. Block Diagram Showing Key Elements of the Experimental and Modeling Investigations

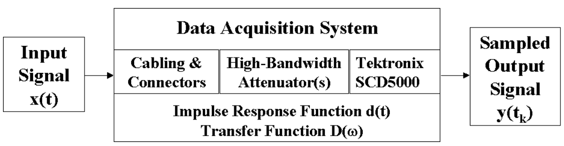

Figure 2. Block diagram of DAC System

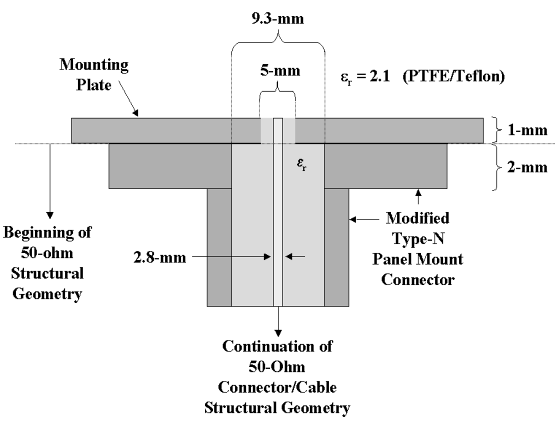

Figure 3. Cross Section of D-dot Probe

The DAC system response is removed from the measured D-dot data by first developing a deconvolution operator for the system. This is accomplished by providing a well-characterized high-bandwidth sampled reference pulse as input x(t) to the DAC system, and recording the response $y(t_k)$, as shown in Fig-2. The input reference and

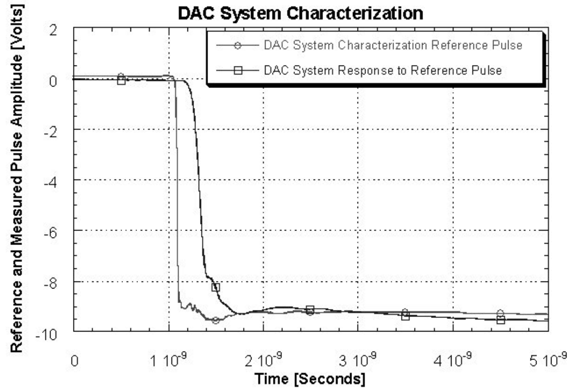

Figure 4. DAC System Input Reference Pulse x(t) and Output Response Pulse y(t)

output response signals are shown in Fig-4. The reference signal used in this study was a fast-rising (15-ps) step-like pulse provided by a tunnel diode generator (Picosecond Labs Model 4015B). The reference pulse was recorded using a high-bandwidth (20-GHz) sampling oscilloscope (Tektronix CSA-803 with an SD-26 Sampling Head). Uniform sampling of both input and output signals was done using 1024-points over a 5-ns time window. The resulting step-like pulses were then converted to duration-limited waveforms and transformed into the frequency-domain using the complete FFT technique [7-8,10]. A deconvolution operator was then developed which incorporates a form of Wiener filtering to preserve accuracy while minimizing noise errors [9]. The process is as follows: The DAC is assumed to be a linear time-invarient system which can be characterized by an impulse response function d(t). The system output is then related to the input by

$$y(t) = d(t) * x(t) , \qquad (1)$$

where * denotes time-domain convolution. Taking the Fourier transform of (1) yields

$$Y(\omega) = D(\omega) \bullet X(\omega) , \qquad (2)$$

where, Y(ω) is the Fourier transform of y(t), X(ω) is the Fourier transform of x(t), and • denotes multiplication. D(ω) is the DAC system transfer function, which is the Fourier transform of d(t). D(ω) can then be estimated by

$$D_e(\omega) = Y(\omega) \bullet [\, X^*(\omega) / \{ \lambda + |X(\omega)|^2 \}] , \qquad (3)$$

where * denotes complex conjugate and λ is a filter parameter chosen in accordance with selected optimization criteria [9-10]. We now consider the case where the DAC system input is the D-dot probe output voltage signal $v_p(t)$ and the measured result is $v_m(t)$. Transforming to the frequency domain gives

$$V_m(\omega) \cong D_e(\omega) \bullet V_p(\omega) \quad , \qquad (4)$$

where $V_m(\omega)$ and $V_p(\omega)$ are the frequency-domain representations for the measured data and D-dot probe output voltage, respectively. Based on the known functions $V_m(\omega)$ and $D_e(\omega)$, $V_p(\omega)$ can be estimated from

$$V_p(\omega) \cong V_m(\omega) \bullet [\, D_e^*(\omega) \,/\, \{\, \beta + |D_e(\omega)|^2 \}] \;, \qquad (5)$$

where β is again a filter parameter chosen on the basis of selected optimization criteria [9]. Equation (5) represents the frequency-domain deconvolution of the DAC system response from the measured experimental data resulting in the "estimated" D-dot probe output signal. Proper selection of the filter parameters provides good estimate accuracy and minimum noise error within the limits of the available signal information content. Fig-5 shows an example of measured D-dot probe data before and after compensation.

IV. MODEL DEVELOPMENT

The next stage of the analysis involved development of a high-fidelity model of the experimental apparatus for use with a powerful time-domain modeling and simulation tool

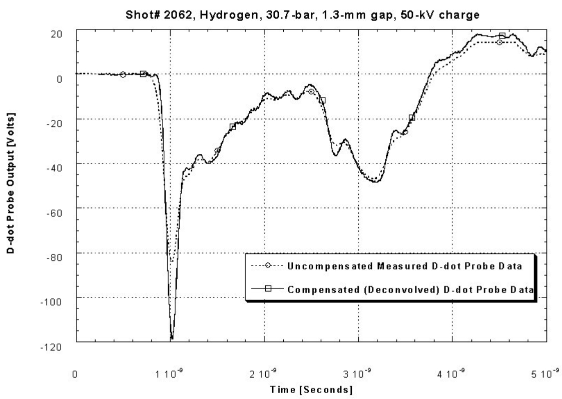

Figure 5. Overlay of D-dot Probe Data Before and After Compensation Through Deconvolution of the DAC System Response

developed at Sandia National Laboratories known as the *Vol*umtric *Max*well (VOLMAX) Solver System [11]. VOLMAX is a general-purpose 3-D transient electromagnetic (EM) field simulator that operates on hybrid grid structures generated with a commercial CAD system that provides advanced 3-D solid modeling, meshing, and post-processing capabilities [12]. Fig-6 shows the cross-section of a solid 3-D model of one of the high-pressure switch fixtures built and tested at Strathclyde University. The specific modeled apparatus has an 11.6-ohm tapered PFL driving a discharge gap of 1.3-mm. The model consists of a full 3-D mesh of 3-million tetrahedral elements. Computational economy is achieved by making use of 2-planes of symmetry to reduce the effective number of elements by a factor of four to 750,000 tetrahedra. The model includes the D-dot probe of Fig-3, located 57-mm from the discharge axis. Also included in the model is an absorbing boundary located 2-cm beyond the outer edges of the physical structure. This serves as the outer boundary for the model volume, and also absorbs the fields that radiate from the edges of the test apparatus. EM modeling and simulation with VOLMAX is discussed in greater detail elsewhere [6,11].

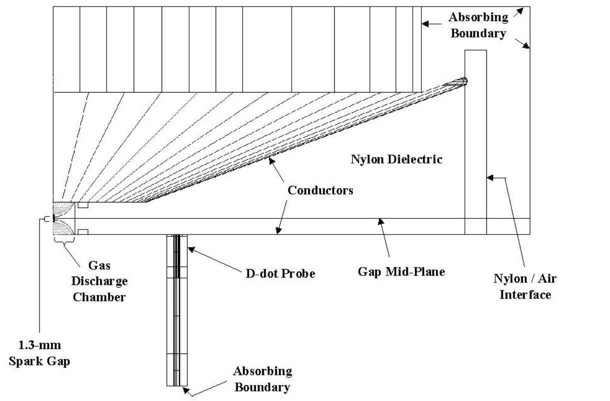

Figure 6. Cross sectional view of half of the 3-D model of the high-pressure test apparatus [5]

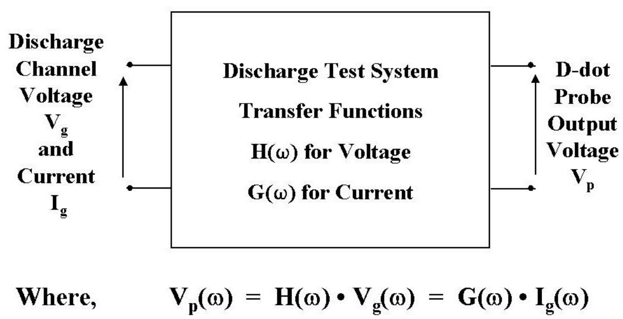

Figure 7. Block Diagram of Linear System model Transfer Function Characterization

V. SYSTEM CHARACTERIZATION

The detailed geometrical configuration and dimensions of the solid model of Fig-6 closely replicate the actual experimental apparatus with relatively high fidelity. The present model assumes perfect conductors and linear dielectrics. The relative permittivity of the nylon dielectric is about 3.0 for the dominant frequency content of the fast signals in this analysis. The O-ring seal material present in the actual test apparatus is not included in the present model, which assumes that the ring grooves are nylon-filled. From a linear systems analysis viewpoint, the system is represented by Fig-7, where the discharge gap voltage or current can be taken as the system input and the D-dot probe output voltage is taken to be the system response. Model system characterization is achieved through simulation with a known fast impulse (or step) input function. The simulated probe output then provides the impulse (or step) response of the system. Gap voltage is assumed to have uniform axial distribution. Current consistent with the applied voltage distribution and Maxwell's equations is calculated on the surface of a perfectly conducting cylinder 0.5-mm in diameter bridging the gap and centered on the symmetry axis. Fig-8 shows an impulse voltage input and resulting probe response. From the simulated impulse response data, the system transfer functions H(ω) and G(ω) shown in Fig-7 can be calculated. In a manner analogous to the earlier treatment of the DAC system, the model system transfer functions can be used to deconvolve the system response from the experimental D-dot

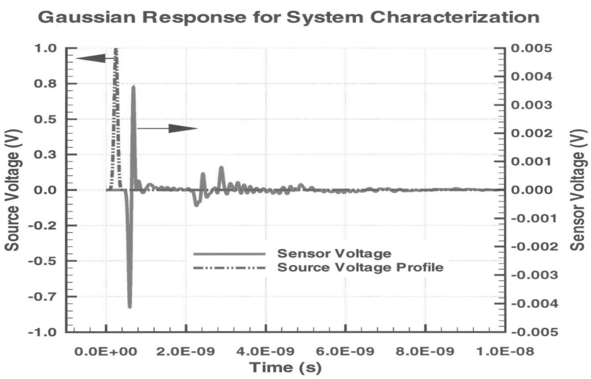

Figure-8. Simulated probe output response to an input impulse voltage across the discharge gap

probe data in order to obtain estimates for the voltage and current across the discharge gap. The model probe was calibrated by using measured charge voltage waveform data as input and comparison to the integral of the simulated probe response. A resulting model probe calibration factor of 1.40×10^{12} was obtained, which agrees within 5% of the experimentally-determined probe calibration factor of 1.45×10^{12}. This is shown in Fig-9.

VI. GAP VOLTAGE AND CURRENT

The model system transfer functions allow for the deconvolution of the system response from the experimental data. An example result of this process is shown in Fig-10, which gives estimates of discharge voltage and current for the case of hydrogen at 30.7-bar with 1.3-mm gap length at 50-kV breakdown voltage. The time derivative of current, dI/dt, is also plotted in Fig-10. The plot of dI/dt most clearly shows the initial wavefront launched into the

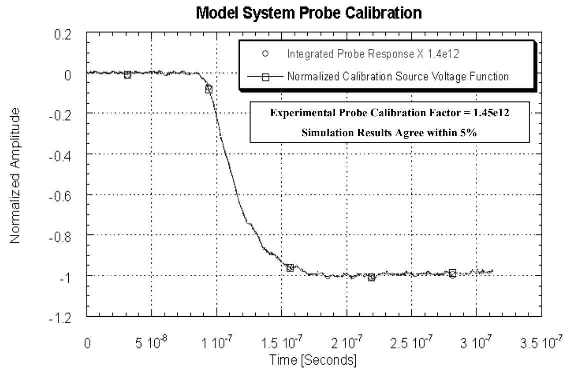

Figure 9. Normalized Charging Waveform and Integral of Simulated D-dot Probe Output Scaled by Calibration Factor of 1.40×10^{12}

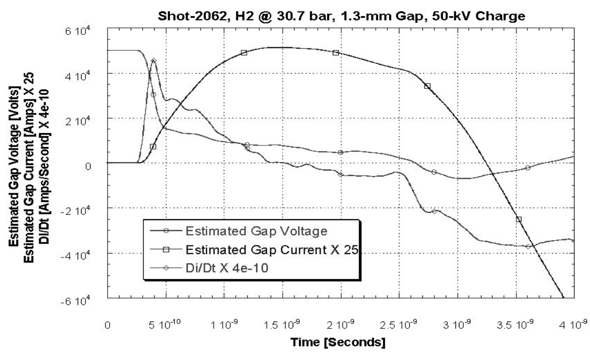

Figure 10. Example of estimated discharge Voltage, Current, and dI/dt as functions of time

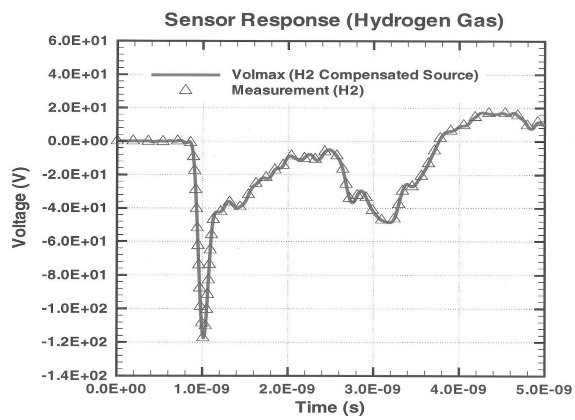

Figure 11. Comparison of Simulated and Experimentally-Measured Probe Response

system upon breakdown initiation, followed some 2.3-ns later by the return reflection from the outer edge of the test apparatus. Fig-11 shows the good agreement of the original compensated experimental D-dot data used to derive the discharge voltage estimate shown in Fig-10, and the simulated probe response obtained when this estimated voltage waveform is used as model input voltage for VOLMAX simulation. Fig-12 is a plot of discharge channel resistance assuming the two cases of zero inductance and a fixed inductance of 2.88-nH based on the voltage and dI/dt estimated at the first zero crossing of the discharge current, as shown in Fig-10. More realistic treatment of the time-varying channel inductance and resistance requires knowledge of the time-varying distribution of current flow in the expanding channel. This demands more detailed modeling and/or experimental measurement data [e.g., 13] of channel dynamics during the rapid expansion phase. Work in this direction is underway.

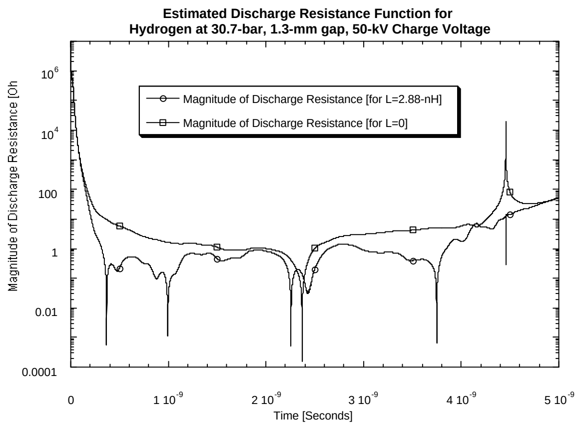

Figure 12. Example channel impedance magnitude plots assuming fixed zero and non-zero channel inductance. The fixed non-zero inductance of 2.88-nH is estimated from the first current zero-crossing shown in Fig-10.

VII. SUMMARY AND CONCLUSIONS

High-fidelity 3-D EM modeling, combined with linear systems analysis and signal processing techniques, shows considerable promise for complementing and extending high-speed gas discharge channel physics investigations and switch design and development. To fully realize the potential of this approach, further work is needed to incorporate detailed channel physics model(s) into the system. Proper integration of channel physics modeling with high-resolution 3-D transient EM modeling and experimental measurements may also provide an effective means of optimizing the channel model(s) and parameter(s) for useful engineering applications. Progress in this direction can be expected to help provide useful analytical tools and techniques capable of contributing to gas discharge switch design engineering and performance prediction.

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