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Multi-megavolt switching in water: considerations for the Z-R machine

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Abstract: Sandia's Z machine used water as both an insulator in power storage components as well as a switching media. The anomalously high energy density, coupled with its high dielectric strength, allow f[1]or a significant reduction in size over a gas insulated design. Moreover, the high currents required to produce ICF demand a low inductance design, which is aided by the high electrical breakdown strength of water. The inductance introduced by the spark channel is a significant source of inductance. The new design will also increase the charge voltage on the water switches and introduces serious concerns regarding the physics of electrical breakdown in water in general and the scaling of water switches in particular. A major concern is the losses associated with water switching in the multi-megavolt regime. In such large pulsed power machines, accurate estimations of switch losses are necessary for new high efficiency pulsed power the switch losses constitute a major portion of the total energy loss. Previous underestimating of energy losses have caused over predicting the accelerator outputs.

Introduction

The largest pulsed power machine at Sandia, Z, began in December 1985[1] as the Particle Beam Fusion Accelerator II (PBFA II). PBFA II was designed to produce high voltages (~15 MV) in a single-gap diode to accelerate and focus ions on small mm size fuel pellet and produce controlled fusion. In the mid-90's, breakthroughs were achieved in High Energy Density Physics (HEDP) on the 2-MV, 10-MA Saturn accelerator with z-pinch[2]. The z-pinch approach uses large electrical currents to produce plasma by vaporizing a cylindrical array of wires, each a few microns in diameter or by ionizing a supersonically injected gas puff into the anode-cathode gap of the device. The high currents produce powerful magnetic fields that surround the plasma, pinching it on the vertical "z" axis to densities and temperatures sufficient to generate intense x-rays. The total radiated x-ray power of 85 TW achieved on Saturn was four times Saturn's peak electrical power and more than three times the ion power on PBFA II. PBFA II was subsequently modified in 1996 to provide high current rather than a high voltage in order to run a six-month set of scaling experiments for z-pinches. Because of the success of the six-month z-pinch campaign, the machine was never converted back, and was renamed Z in July 1997. Z now provides a unique capability to a number of basic science communities, and routinely produces x-ray power more than five times (and energy 50 times) greater than any other non-pulsed power laboratory device. Z has now become a workhorse for HEDP physics and radiation effects research, Inertial Fusion Energy (IFE) studies, a range of basic scientific and university collaborations, and more recently, material properties research. The HEDP and ICF experimental community, however, clearly want Z to provide more shots, better precision and pulse shaping versatility, and more current. These factors are the impetus for refurbishing the accelerator.

The Z pulsed power design is based on the conventional Sandia pulsed power technology of Marx generators, water insulated pulseforming and transmission lines, vacuum Magnetically Insulated Transmission Lines, and post-hole convolutes.[3] The oil and water sections contain 36 modules with identical components. The prime power source of each module is a Marx generator with 60, 1.3 μF capacitors which are usually charged to 90 kV. When the Marx erects, it transfers its energy to a water-dielectric coaxial capacitor, which reaches a peak voltage of 5 MV in 300 ns. In turn the intermediate store capacitor discharges into a lower-inductance coaxial water capacitor through a laser-triggered gas switch in ~300 ns. From there and through self-breaking water switches the electrical energy is transferred first into a 4.32-Ω water transmission line and then through it into the water-vacuum-interface insulating stack and central vacuum section. The pulse at this point has a voltage of 2.5 MV and width of 105 ns FWHM. The total power generated by the accelerator is of the order of 60 TW. The pulses are then combined together in parallel into four equal number groups, 9 each, and feed four bi-

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[1] [1] *Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94-AL85000

conical vacuum MITLs. The four pulses are then combined again via a double post-hole convolute section into a single ~20 MA, 2.5 MV pulse which finally drives the z-pinch load on axis. The 4m diameter vacuum MITLs are of constant impedance (2Ω the upper two and 2.75Ω for the lower two and are operating in quite a remarkable regime of 10 times higher fields than the cathode explosive emission threshold. The power transfer from the insulating stack to the load is extremely successful. The z driver successfully operates at the 60-TW, 5-MJ electrical design point and delivers routinely up to 20-MA currents to a variety of z-pinch and Isentropic Compression (ICE) loads.

Many options and budgets were considered and a balanced approach is being followed for the Z refurbishment. In the conversion of the PBFA II into Z only the center vacuum section was changed; the ZR refurbishment effort now aims to replace, redesign, improve and optimize the rest of the accelerator for z-pinch and ICE loads.

Component Test Bed: Z-20

With the inherently probabilistic nature of the mechanisms of electrical breakdown, the design of large pulsed power machines require both detailed modeling and component testing and validation. A 20° section of an early concept of ZR has been built where two entire new modules will be tested and qualified including new Marxes, intermediate store capacitors, gas switches, water switches and triplate water transmission lines The test bed consists of a 36.7 nF Marx generator, consisting of sixty 2.2 μF capacitors, and an intermediate storage capacitance with a total storage capacitance of 21 nF switching into a 5.5 Ω copper sulfate resistor. A critical test is currently underway to test the performance of the water switch section. In addition to verifying the performance of the water switches under multi-megavolt operation, the new design for the transition to the transmission lines will be tested.

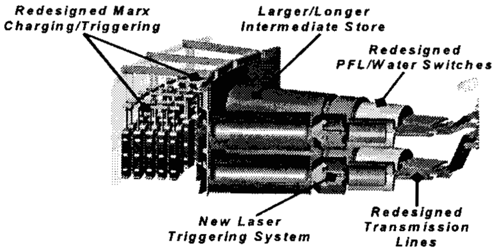

Figure 1: Schematic showing the Z-20 component test bed. Energy storage stages are the Marx generators, the Intermediate energy store and a pulse forming line. The Z-20 machine is presently being used to conduct experiments on water switch performance and losses.

Water switching

The generation of terrawatt power pulses in high current applications is limited mainly by the performance of switches in the vicinity of the intermediate store. Many accelerators have used water as the insulator in the intermediate store because of the combination of its high energy density and high dielectric strength. This combination of insulating properties allows for a significant reduction of the size of the intermediate store, which results in a reduction in the system cost. Given that the intermediate store is insulated with water, a natural extension is to incorporate high power water switches into the system design. High power water switches have many advantages over gas switches, as well as a few disadvantages. This tradeoff is the subject of considerable interest for the next generation of accelerators at Sandia National Laboratories Pulsed Power Group. The main interest for machine design is self-closing water switches and both multi-site and multiple single site switching. Limitations are jitter and switch losses. Jitter determines how closely the sites can be located and hence how many sites or channels can be supported. Jitter increased proportionally with charge time, and perhaps with spacing or voltage. Sharper, but shorter lived, electrodes may achieve lower jitter. Losses would increase since longer gap lengths would be necessary. On the other hand, losses are a critical aspect of the machine design since the losses determine how much energy must be stored initially in the Marx banks. Moreover, new loss mechanisms become important as voltages and gap lengths are increased. Thus, losses may result in waveform distortion and lower than expected peak values, which can be disastrous for the overall operation of a large pulsed power machine.

In addition to measuring the losses in the water switches, we intend to develop scalable predictive models of the switches and switch losses. The inclusion of these predictive models into detailed circuit simulations will provide the basis for the next generation of high current driver for Z pinches for fusion research. The ultimate goal of Sandia's Pulsed Power group is for a 60 MA drivers to drive two z pinches and a high fusion yield of over 200MJ.

In circuit simulations, losses are represented as resistances. In the case of spark gap losses, the equivalent resistance is a function of time, to reflect the change from the large initial value to the small plateau value. Models of gaseous switches typically lump all the losses into a single dynamic parameter. In the present effort, the contributions of the various loss mechanisms will be separated in order to determine their scaling with current. Three loss mechanisms for water switches have been identified: the loss due to ionization and expansion of the spark channel, prebreakdown current generated by the rate of change of the capacitance of the advancing arc and energy lost through the shock/acoustic wave associated with the electrical breakdown in water. A generic circuit model of the dynamic behavior of a water switch is shown in Figure 2.

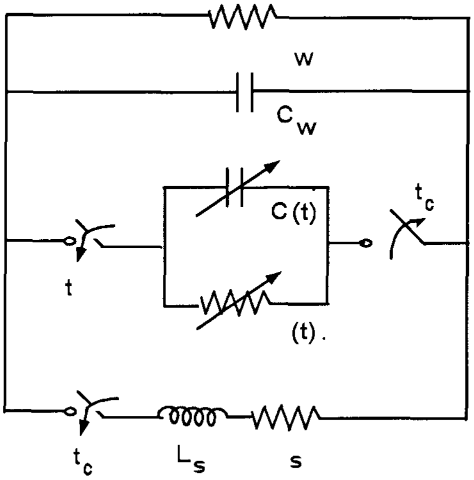

Figure 2: A ciruit model of a water switch. The model accounts for the intrinsic properites o fthe water, $C_w$and R_w, the evolution of the formation of the spark channel, C(t) and R(t), and the arc components, L_s ad R_s.

Water's high dielectric constant is represented by the capacitance C_w, and the conduction current by R_w. This capacitance is geometrical in nature and accounts for the displacement current, C_w dV/dt and the electrostatic energy storage. Similiarly, the resistance R_w is the resistance associated with the leakage current of the spark gap in the prebreakdown phase. These two quantities are related by the relation, $R_w C_w = \dfrac{\varepsilon}{\sigma}$, where σ is the water conductivity and ε is the permittivity. The evolution of the spark channel, prebreakdown phenomena, is represented by the time dependent capacitance,C(t), and resistance, R(t). The fully established arc is represented by the saturation resistance, R_s and spark channel inductance, L_s.

Dynamic Arc Resistance

Many researchers have studied the discharge behavior of spark gaps. For circuit modeling purposes, it is critical to allow the resistance to go from a large value, prior to breakdown and fall dramatically to its plateau value, R_s. This time dependent arc resistance is notorious for being very difficult to measure and can be obtained from the arc voltage and the arc current. One difficulty is the accurate measurement of the voltage as it changes from a very high value at prebreakdown to a value on the order of several hundred volts at the plateau resistance value. Moreover, it is difficult to distinguish the resistive and inductive components of the switch impedance. Thus, dynamic impedances are rarely measured, and designers rely heavily on representative numbers and models.

Time Dependent Capacitance Effects

The anomalously high permittivity of water make is very desirable for applications requiring high energy densities. Moreover, its high dielectric strength allows for even large systems to significantly reduce their size. Both these attributes, however, result in strong capacitive coupling across the water switch. Even when the capacitive coupling is reduced by specialized techniques there may still be a contribution from the time dependent capacitance associated with the conducting bush of the streamer through the water. In switch operations, the gap length can be on the order of 15 cm and a significant time to transverse the gap. Figure 3 illustrates the advancing streamer.

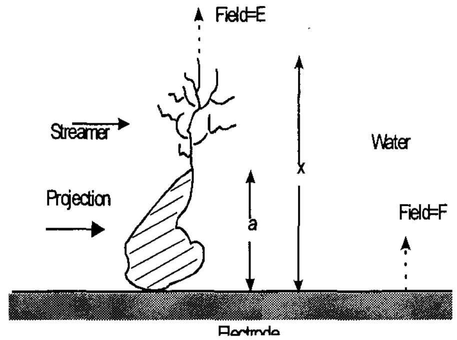

Figure 3: The advancing bush-like arc can introduce C-dot effects. This has been shown to be an important loss mechanism in multi-megavolt water spark gap switches.

The bushlike structure is known to be highly conducting. Thus, the advancing streamer has a time dependence capacitance associated with it.

After application of the driving voltage, the current associated with the water filled spark gap switch, in the prebreakdown phase, is

$$I \equiv \frac{dQ}{dt} = C\frac{dV}{dt} + V\frac{dC}{dt}$$

$$IV = CV\frac{dV}{dt} + V^2\frac{dC}{dt} = \frac{d}{dt}\left(\frac{1}{2}CV^2\right) + \frac{1}{2}V^2\frac{dC}{dt}$$

Referencing the second equation: the first term on the right is the electrostatic energy stored in the spark gap internal capacitance. The second term is the work done on the moving plates that make up the capacitance. In relation to high power switching, for very high voltage switching, such as for voltages exceeding 5 MV, large interelectrode gaps are used. The propagating bush like structure, which is known to be highly conducting, acts as one plate of a capacitance. The energy dissipated by the induced dC/dt effects is given by

$$E_{loss} = \frac{1}{2}\int\frac{dC}{dt}V^2\,dt$$

Estimates indicate that this loss mechanism may be as high as 20 % of the initial energy. Thus, it is clear that elimination of this effect would result in a significant increase in the output power.

Losses in the Acoustic Wave

Of the energy deposited in the water gap, a fraction of it is expanded as acoustic energy in a shock wave. The strength of the shock wave is an important part of designing the accelerator both for initial survival as well as for reliability. During operation of the large machines, the noise from the spark gaps is tremendous. Thus, it is not surprising to find that the acoustic wave does significant damage to the accelerator structure. Figure 4 shows the intermediate store after an unexpected water spark and shows a significant deflection in the steel. Depending on the energy dissipated and the distance from the arc, pressures can exceed several kilobars for tens of microseconds at typical structures of concern. The energy contained in the pressure pulse can be calculated from

$$W_a = \int d\Omega r^2 \int\frac{P^2}{\rho U_s}\,dt$$

Where P(t) is the pressure in pascals at a distance r in meters from the center of the switch channel, ρ, is the initial density of water, and U_s is the shock velocity.

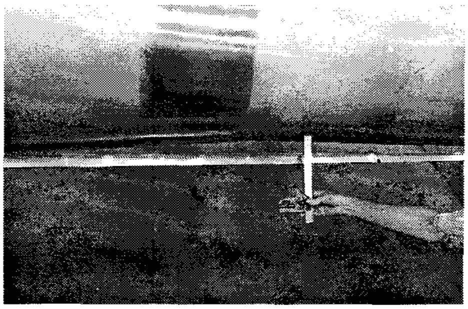

Figure 4: Damage on the stainless steel inner conductor of the intermediate store shows damage from an arc through water.

Water switches also have an associated acoustic wave, it is important to both insure that the machine can withstand it own operation, as well as do a complete failure analysis. This is particularly critical to Z-R with its reliability criteria and ambitious shot schedule.

The acoustic wave obviously carries a significant energy. Acoustic energy loss from water switches has been estimated between 30 kJ and 80 kJ for each of 36 modules of the Z machine. In the past, acoustic losses have been folded into the dynamic resistance models. Now, because future circuit modeling efforts will require models which scale with current, a detailed model of the acoustic loss mechanism is desirable. It is expected that the acoustic losses will scale differently than the resistive losses.

References:

1. B. N. Turman, et al., *Proc. Of theFifth IEEE Pulsed Power Conf.,* Arlington, VA 1985, pp. 155.
2. R. B. Spielman, et al., *Proc. Of the Seventh IEEE Pulsed Power Conf.,* Monterey, CA.
3. R. B. Spielman, et al., *Proc. Of the Tenth IEEE Pulsed Power Conf.,* Albuquerque, NM 1995, pp. 396.
4. D.L Johnson, JP VanDevender, and TH Martin, "Low Prepulse, High Power Density Switching," *Proc. 2nd IEEE Pulsed Power Conference*, Lubbock TX , pg 191, 1979.

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