Switch evaluation test system for the National Ignition Facility[§]
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Flashlamp pumped lasers use pulsed power switches to commute energy stored in capacitor banks to the flashlamps. The particular application in which we are interested is the National Ignition Facility (NIF), being designed by Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories. To lower the total cost of these switches, Sandia National Laboratories has a research program to evaluate large closing switches. The target value of the energy switched by a single device is 1.6 MJ, from a 6 mF, 24kV capacitor bank. The peak current is 500 kA. The lifetime of the NIF facility is 24 thousand shots.

There is no switch today proven at these parameters. Several short-lived switches (100's of shots) exist that can handle the voltage and current, but would require maintenance during the facility life. Other type devices, notably ignitrons, have published lifetimes in excess of 20 thousand shots, but at lower currents and shorter pulse widths.

The goal of the experiments at Sandia is to test switches with the full NIF wave shape, and at the correct voltage. The Sandia facility can provide over 500 kA at 24 kV charge voltage. The facility has 6.4 mF total capacitance, arranged in 25 sub-modules. The modular design makes the facility more flexible (for possible testing at lower current) and safer. For pulse shaping (the NIF wave shape is critically damped) there is an inductor and resistor for each of the 25 modules. Rather than one large inductor and resistor, this lowers the current in the pulse shaping components, and raises their value to those more easily attained with lumped inductors and resistors.

We will show the design of the facility, and show results from testing conducted thus far. We will also show details of the testing plan for high current switches.

Introduction

Sandia National Laboratories has a study underway to evaluate large pulsed power closing switches for the National Ignition Facility laser system. The National Ignition Facility (NIF) is a large (1.8 MJ optical output) glass laser based system. In the NIF design, many independent capacitor bank modules store the laser drive energy, and a single switch in each module transfers the capacitor bank energy to multiple flashlamps. These flashlamps in turn pump the laser medium.

Goals of reducing the cost of the primary energy storage and transfer system motivated the change to a single pulsed power switch for each large (24 kV, 1.6 MJ, 500 kA peak) capacitor bank module. This design reduces the total cost of the power conditioning system, but needs a closing switch larger than that used in laser systems before. Coupled with the long lifetime (24 thousand shots) and high reliability desired (less than 1 pre-fire or no-fire in 10 thousand charge cycles for each switch), the demands upon the main switches are severe.

One of Sandia National Laboratories' tasks in the NIF effort is to test and evaluate candidate switches. To do this, Sandia built a facility dedicated to testing switches at the full NIF parameters. To get the proper current wave shape, hold-off voltage, and charge transfer required building a full energy

[§] This work supported by the U.S. Department of Energy under contract number DE-AC04-94AL8500

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prototype capacitor bank. For ease of use, the facility uses resistor loads instead of flashlamps. To help in the testing process, the Sandia facility has features that allow switch testing in several configurations.

Figure 1a shows the schematic of the full capacitor bank. Twenty-five sub-modules make up the whole bank. Each of the twenty-five sub-modules has 5 series pairs of 100 μF , 22 kV capacitors. Thus, each sub-module is 250 μF at a rated voltage of 44 kV. Each sub-module has a 50 μH inductor and a 800 m Ω resistor in series with the capacitance. The switch under test connects electrically to the capacitor modules via two parallel 50 Ω coaxial cables; each is 45 ns long. If the 20 kA module current flowed in a single cable (RG-218) the losses would be 0.9 kJ per meter of cable. Two cables reduces the temperature rise of the cabling at high shot rate, as well as lower the effect of cable inductance and resistance. The inductance and resistance of a single run of cabling is very much smaller than each modules' pulse-forming values. Because of this, changing the number of modules connected changes the driver impedance, but does not change the pulse shape. This allows us to observe switches at any current from 20 kA to 500 kA with the correct pulse shape.

The current through the device under test is shown in Figure 1b. At 24 kV charge voltage, the peak current is 525 kA, and 150 Coulombs is transferred through the switch. This is slightly higher than the charge stored in an actual NIF module because the Sandia facility has more total capacitance than NIF. Using 22 modules would lower the stored charge to 132 C. The action integral,

$$\text{action} = \int_{\tau=0}^{\tau=\infty} I_{\text{switch}}^2 dt$$

has an ultimate value of 48 MJ/ Ω .

Figure 1a. Schematic showing two of the 25 sub-modules of the switch test system. The charge resistors and dump relays are not shown.

Figure 1b. The current pulse for the NIF switch. This was acquired with 24 kV charge on the capacitor bank.

The 50 coaxial cables from the modules converge in the switch mounting fixture, shown in Figure 1. This is a coaxial structure which can house switches up to 45 cm in diameter and 150 cm long. The size came somewhat arbitrarily from the dimensions of a series pair of "size-D" ignitrons, but is expected to be large enough to hold any switches envisioned for testing. The return current flows in 12 2.54 cm diameter stainless steel rods.

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Figure 2. The coaxial cable collection plates and test stand. The top collection plate is one meter square.

The current from each module flows through the pulse-shaping inductors and resistors. The inductors are copper wound, and have an inductance of $50\ \mu\text{H}$ and $25\ \text{m}\Omega$ resistance at $2\ \text{kHz}$. The resistors are high-voltage ceramic units of 8 each $0.1\ \Omega$ in a heat-sink fixture. The free-air power dissipation is $800\ \text{W}$ for each resistor stack, or $20\ \text{kW}$ for the whole facility. The average power at full charge is $600\ \text{W}$ per module, at one shot per two minutes.

There is three operating modes for the facility. We allowed for full current at lower voltage to test switches that would handle full current, but are not able to withstand $24\ \text{kV}$. An example would be ignitrons, which may be reliable at $12\ \text{kV}$, but unable to tolerate $24\ \text{kV}$. This would be handled on NIF by using a pair of series devices, but our facility lets us perform this test with only one device. We have this flexibility because we use $100\ \mu\text{F}$, $22\ \text{kV}$ capacitors in series pairs. By using half of the capacitors directly (not in series pairs) we can double the capacitance. We have another set of inductors that is half the value of the standard ones, and we short out sections of the $0.75\ \Omega$ resistors. In this way, we halve the impedance of the bank, and maintain the correct pulse shape. By using all the capacitors in parallel, and using some modules with the half-value pulse-shaping components, and some modules with short-circuited pulse-shaping inductors and resistors, we can supply $500\ \text{kA}$ at $6\ \text{kV}$. The pulse shape deviates some at low impedance due to the cable and mounting stand inductance, but is it close enough for switch testing. Any device qualified for NIF would have to ultimately be tested at full voltage. The low voltage test modes allow us to save time and money by testing single switch technologies before investing in two switches and mounting hardware.

With any bank configuration, we can control the current by selecting the number of active modules, with high-current pneumatic relays we developed for this application. These relays will tolerate at least $50\ \text{kA}$ with this pulse shape.

A UNIX computer running Labview and IDL controls the facility. The communication to and from the facility is via fiber-optic link. Wave forms are recorded with digital oscilloscopes and stored for each test. Before charging the capacitor bank, the computer conducts a test of the trigger system, and compares the wave forms to reference wave forms stored at the beginning of a test sequence. If the trigger voltage and current are different than the reference by more than a user-defined tolerance, the test is stopped and the operator notified. Before each charge cycle, electrically controlled valves and regulators purge the switch fill gas and set the switch gas pressure to the specified value (if the switch uses an external gas supply). Then, if the trigger test passes and the pressure is within tolerance, after a user-specified delay, the power supply begins to charge the capacitor bank. It takes 60 seconds to charge the full bank to $24\ \text{kV}$. There is also prefire detection and capacitor failure detection. If at any time in the charge sequence the bank voltage drops by more than 50 Volts since the last value (sampled at a $4\ \text{Hz}$ rate) the test is aborted. There is also extensive safety fencing and interlock systems for personnel protection.

Testing

Testing to date has been done on large ignitrons, high pressure spark gaps, vacuum switches, and low-pressure switches.

The first test series was done with large hollow-anode ignitrons¹. The advantages of ignitrons² are well known: a self-healing liquid mercury cathode should be tolerant to the intense cathode spot activity. The anode of the ignitron is kept heated and the cathode is cooled, so that evaporated mercury will return to the cathode. The vapor pressure of mercury is 0.1 to 1 milli Torr at typical operating temperatures. If the gas in the ignitron is only mercury, this pressure, with the cm-size gaps in ignitrons, allows high voltage holdoff (more than 50 kV). Typical of vacuum switches, ignitrons have a wide triggering range. A ceramic trigger electrode (the ignitor) dipping into the mercury pool allows triggering with millijoules to joules of energy at 100 to 3000 volts. Ignitrons are thus very attractive to pulsed-power switching applications.

We have tested several versions of the NL-9000 ignitron from Richardson Electronics. The NL-9000 is a "hollow anode" ignitron³. The hollow anode design reduces the gap between the anode and the mercury pool, and increases the gap between the anode and the tube wall. This is to stabilize the arc and reduce the tendency of the discharge to transfer to the ignitron wall. Wall transfer liberates wall material, and coats internal parts with metal.

The first ignitron tested was a NL-9000 with a stainless steel anode. Two prototypes had shields over the ignitors and attached to the cathode. This was an attempt to protect the ignitors from mercury sloshing. In use however, the discharge preferentially connected to this ignitor shield, liberating shield material inside the ignitron. The tube with a boron-nitride shield would suffer large internal pressure rise after conducting current. The tube with a molybdenum shield suffered because of molybdenum coating on the ignitors which prevented triggering. A third version had no ignitor shield. Extensive testing at 14 kV charge and 350 kA peak current show that the arc does not appear to reach the wall at these levels. After 800 shots at this level, the ignitor resistance was still high, showing a lack of metal deposition inside the tube. Tube failure was caused by lack of voltage hold-off and sudden shorting of the auxiliary ignitor. This failure may indicate a broken ignitor feed-through insulator which let air into the device.

Testing of a second NL-9000, this one with a graphite anode, was done after the first tube failed. The graphite anode tube would not hold voltage after a single test at 250 kA peak and 75 coulombs. The tube could be re-conditioned with a high-voltage power supply (up to 30 kV), but subsequent 250 kA tests would again destroy voltage hold-off. We concluded that at these levels, the gas liberation rate inside the ignitron far exceeded the self-pumping ability, and the pressure was raised to over 100 mTorr. We conditioned the tube and tested a single shot at 24 kV, 525 kA before returning the tube to the manufacturer. The graphite anode suffered no catastrophic damage during these tests, but the pressure rise is a fatal flaw.

The most successful ignitron tests to date have been with the NL-8900, a smaller version of the NL-9000. We tested this device at 12 kV and 250 kA for hundreds of shots. After 20 shots at this level, the trigger electrode broke. This forced us to use a 10 kV trigger generator which flashed the trigger feedthrough insulator inside, effectively triggering the device. This ignitron lasted 1300 total shots, 200 of which were at 250 kA and 12 kV. The tube began to prefire at 11 kV, so we stopped the testing.

We tried other testing levels on the NL-8900 and found that higher voltage and lower current is not possible for this device. We attempted to test at 24 kV and 125 kA, but the prefire rate of the tube was about one in four. There is a non-linear relationship between conducted current and voltage hold-off due to internal pressure. Commercial ignitrons have no vacuum-pumping mechanism other than the discharge itself. If the discharge liberates more gas than it pumps, the pressure will rise, and holdoff voltage will fall¹. The pumping rate is probably linear with charge conducted (and is a function of pressure), but the gas liberation is probably at least the integral of current squared. This would set a limit on the peak current for a given voltage capability. The large number of modules in the National Ignition Facility places strict limits on the prefire probability of switches.

EEV High Current Switch

English Electric Valve in cooperation with the Atomic Weapons Research Establishment, Aldermaston, England developed a vacuum spark gap for high current, high charge transfer applications. We tested one of these switches. The HCS3 is a vacuum triggered spark gap. Like ignitrons, a vacuum spark gap has a wide operating voltage range. The HCS3 requires 15 kV for triggering, with a trigger energy of about one joule. On arrival, our switch withstood 45 kV voltage. After sitting idle however, the switch would not hold over 2400 volts. The pressure had risen in the device. Using attached getters, we were able to recover the switch to withstand over 35 kV. We then began testing with only a portion of the Switch Test Facility bank. We acquired 670 total shots on the switch. The majority of the testing was at 180 kA, but with a high prefire rate. The prefire rate was attributed to a mechanical problem within the switch. We will test another version of this switch in mid-1997.

Physics International ST-300 Spark Gap Switch

The Physics International ST-300 switch⁴ is a two-electrode spark gap with graphite electrodes. The graphite electrodes are robust, and allow material liberated from the electrodes to oxidize in the dry-air environment inside the switch, and exit as CO and CO₂. This seems to be effective, but the nitrogen in dry air forms nitrous oxides (among other things), which can corrode the aluminum switch housing and other gas system components. The ST-300 also has substantially higher on-state resistance than other switches we have tested. This may be due to the graphite resistivity, which is especially important near the small arc. Near the small arc, the current density is extremely high. The erosion rate of the graphite electrodes is a concern for the ST-300 application, as periodic electrode replacement will be required. Gas fill pressure changes can compensate for electrode wear, as can a high voltage trigger.

The ST-300 trigger requirements are another concern. The series-injection trigger we use requires a high voltage (over 100 kV) trigger generator, inductively coupled into the switch. We use 4 each, PE-11B ferrite cores. The cores each have a cross section of 19 cm². With a flux swing of 0.6 Tesla, this is ample magnetic material for the 120 kV trigger pulse with a 10 ns rise time (if the core are reset between pulses). In practice, the main pulse acts to reset the cores, but trigger tests or misfires could leave the cores saturated the wrong direction. To assure that the cores are always in a known state, we apply a low-voltage reset pulse to the cores 500 μ s before the trigger pulse. The reset pulse width and current are adequate for the PE-11B material and this geometry. The reset circuit uses a 12 μ F capacitor charged to 1 kV, switched by a large thyristor in a critically damped circuit.

A fast rise time trigger generator is desirable to minimize core material required. We use a generator with an impedance lower than 50 Ω , so we can use standard coaxial cable to connect the trigger generator to the switch. If the stray capacitance of the fixture is relatively low, and the core magnetizing current is also low, then the voltage will double at the end of the cable. The cores could also be used to step-up the trigger voltage, enabling the use of lower-impedance, lower voltage trigger pulsed.

Maxwell Rotating Arc Gap Switch

The rotating arc gap switch uses magnetic force on the discharge to move the arc around cylindrical electrodes. This would prevent the discharge from anchoring at one spot, and melting a large amount of material. The electrodes are a copper-tungsten alloy. A mid-plane trigger electrode initiates the discharge. This switch also requires a high voltage trigger (we use the same 100 kV generator as for the ST-300), but since the trigger mechanism is field-distortion, the generator could be much higher impedance.

The metal electrodes in the rotating arc gap switch have a lower erosion rate than the ST-300. The switch completed 957 tests with no prefires or misfires. After those tests, the self-break voltage of the switch rose about 10 percent. We operated the switch at 50 percent of self-break voltage, to demonstrate the low prefire rate needed for NIF. The total charge passed through the switch was 160 kCoulombs. This corresponds to 1200 NIF shots at 132 coulombs. Unless the wear rate accelerates, this switch could survive ten thousand shots before refurbishment. We will test the switch again.

Tetra Radial Pseudospark Switch

The radial pseudospark switch from Tetra is a low-pressure switching device. Using hydrogen at 100-200 milliTorr, the intent is to maintain a diffuse discharge. A diffuse-discharge switch would be ideal for this application, if the electrode current density is low enough to prevent damage. The long duration of our pulse makes it difficult to keep the discharge from constricting under magnetic force. The Tetra switch is designed to maintain a diffuse discharge.

Our switch was an actively pumped device, with hydrogen flow to keep the desired pressure. The switch we tested has a self-break voltage of 16-20 kV, and so operation at 24 kV was impossible. We converted the facility to lower impedance, where it could deliver 500 kA at 12 kV. We tested at 10 kV and 450 kA for a total of 209 shots. After the testing, the tungsten electrodes were in relatively good condition. The concern with this switch is the high prefire rate observed at 10 kV (more than one in 10). Further testing would require raising the self-break voltage and reducing prefires. Also, such a switch would have to be developed as a sealed vacuum tube to be viable for NIF.

Solid-state switches

Essentially a diffuse discharge, solid-state switches are attractive for an application requiring high reliability and low maintenance. The demonstrated current-handling ability of commercial requires several parallel devices for 500 kA. The voltage stand-off of commercial silicon devices is in the range of 5-9 kV, necessitating several series devices as well. These two limitations make solid-state devices more expensive than other technologies, at least in initial price. The higher cost is offset somewhat by lower maintenance. There are two solid-state devices in the schedule for testing at Sandia. One is the reverse-switched dynistor⁵. This device is a two-terminal switch that conducts when briefly reverse-biased. To reverse bias a switch requires a saturable inductor and a trigger generator with voltage greater than the applied bank voltage. The thyristor is a three terminal device that requires a small trigger pulse. This is attractive for our application. The largest thyristors available now are 125 mm diameter, and will block 6 kV forward and reverse voltage. The issue with any solid-state switch is current rate-of-rise, as trigger plasma spreading velocity limits how much of the device is active in the early part of the pulse. We will test both types of solid-state switches in the coming months.

Conclusion

We built a facility specifically for testing the candidate NIF switches. The facility is conservative, flexible, and safe. We have not found a switch that simultaneously meets all the performance and cost requirements. Our testing program will continue to evaluate switches, and the most desirable will be chosen.

Acknowledgements

The authors would like to thank Gary Mowrer for skilled assembly of many crucial parts of this facility. Also, we have had many fruitful collaborations, including A. P. Shulski of Richardson Electronics, Pierre Maciejewski and Patrice Patelli of the French CEA, and Kieth Hewitt of AWE, Aldermaston. Also, Doug Larson and Mark Newton of Lawrence Livermore National Laboratory have given helpful advice on the testing strategy.

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