REVERSE SWITCHING DYNISTOR PULSERS

S. Schneider
Consultant
Red Bank, NJ

T.F. Podlesak,
U.S. Army Research Laboratory
ATTN: AMSRL-SE-DP
2800 Powder Mill Road
Adelphi, MD 20783-1197

Abstract

A unique type of thyristor, the reverse switching dynistor (RSD), has been studied in specially designed pulsers to evaluate their performance for several high-power applications. The dynistor is an asymmetric thyristor with an alternating p+ and n+ structure in its anode. It is a two-terminal device. Application of a reverse voltage across the dynistor makes the n+ regions inject electrons, the device operates like a transistor during turn-on and generates a uniform plasma distribution, enabling fast turn-on. This reduces commutation dissipation and permits high *di/dt* operation to be achieved. An 80mm diameter device was evaluated in a pulser using a 0.5 ms (FWHM), 10 mΩ PFN with a matched load. Recent work with a 2.3 kA driver demonstrated operation at *di/dt* of 1.7 kA/μs (26.6 percent to 70.7 percent) and 177 kA. Differentiation of the current pulse gave a *di/dt* of 2.8 kA/μs. These tests were performed using a two RSD stack in series with a diode to protect against voltage reversal. The devices were triggered by a common driver. The driver unit must be capable of holding off the PFN voltage and generating a high voltage reverse pulse for turn-on. A saturable reactor is required to isolate the main discharge circuit for a period of 2 μs. This technique can be extended to many devices in series, thus enabling a high voltage switch to be built using a single driver.

Two dynistor-based pulsers, the MPG-1 and the MPG-2, were tested. The MPG-1 used a stack of 24 mm devices and operated in bursts of 50 pulses, each 1 μs (FWHM) wide, at a rate of 1 kHz. At 19.6 kV, peak current and *di/dt* were 6.9 kA and 24.5 kA/μs, respectively. The bursts were repeated at a rate of 2 Hz. The MPG-2 is a single pulse generator consisting of 80 mm devices. It was tested to 101.5 kA at 27 kV with a pulse width of 55 μs (FWHM) and a *di/dt* of 8.2 kA/μs. The dynistors in the initial version of the MPG-2 pulser failed because of the high *di/dt*. The redesigned dynistor stack and a trigger circuit providing a 3 kA pulse current enabled successful operation. The dynistor study demonstrated that highly interdigitated gate structures combined with high trigger currents are essential to switch high peak currents and high *di/dt's*.

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I. INTRODUCTION

A unique type of thyristor, the reverse switching dynistor (RSD) has been studied in specially designed pulsers to evaluate their claimed performance and potential application for electric gun, high-power microwave (HPM) and other high power military, laser and industrial applications. The dynistor is similar in design to a thyristor in that it has pnpn regions in the device, but the anode also has n+ regions. These regions make part of the dynistor behave like transistors, which are in parallel with the thyristor portions of the device. These n+ regions in the dynistor are the gate for this device. When a positive bias is applied to the cathode, the n+ regions inject charge into the device. This electron plasma layer spreads, breaking down the blocking junctions and allowing the device to turn on rapidly. Figure 1 is a cross section of the dynistor, showing how the electrons spread and pointing out the thyristor and transistor portions of the device. The main pulse must be delayed for approximately 2 μs to permit the turn-on process to proceed.

The trigger circuitry is much larger than that of a conventional trigger and introduces inductance, which may reduce the circuit risetime capability. The device is necessarily asymmetric and requires a series diode for reverse voltage blocking. These aspects may limit the device's application. One advantage for series operation is that one common trigger may be used for all devices and no individual floating decks are required.

The dynistors were evaluated in the High Action Pulser, which is designed for evaluation of power semiconductors for electric gun and counter munitions applications. In addition, two high voltage pulsers, the MPG-1 and the MPG-2, were built by Mega Pulse of St.

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14. ABSTRACT
A unique type of thyristor, the reverse switching dynistor (RSD), has been studied in specially designed pulsers to evaluate their performance for several highpower applications. The dynistor is an asymmetric thyristor with an alternating p+ and n+ structure in its anode. It is a two-terminal device. Application of a reverse voltage across the dynistor makes the n+ regions inject electrons, the device operates like a transistor during turn-on and generates a uniform plasma distribution, enabling fast turn-on. This reduces commutation dissipation and permits high di/dt operation to be achieved. An 801~ diameter device was evaluated in a pulser using a 0.5 ms (FWHM), 10 i(l PFN with a matched load. Recent work -with a 2.3 kA driver demonstrated operation at di/dt of 1.7 kA/ps (26.6 percent to 70.7 percent) and 177 kA. Differentiation of the current pulse gave a di/dt of 2.8 kA&. These tests were performed using a two RSD stack in series with a diode to protect against voltage reversal. The devices were triggered by a common driver. The driver unit must be capable of holding off the PFN voltage and generating a high voltage reverse pulse for turn-on. A saturable reactor is required to isolate the main discharge circuit for a period of 2 ps. This technique can be extended to many devices in series, thus enabling a high voltage switch to be built using a single driver.

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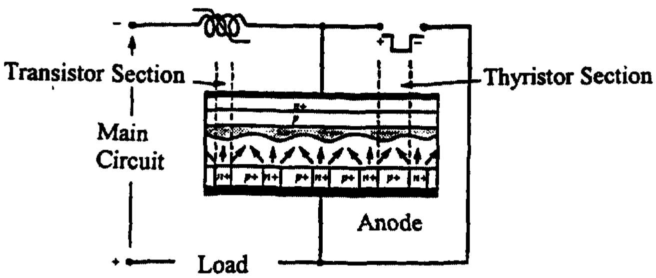

Figure 1. Internal structure of dynistor showing unique alternating p+ and n+ structure of the anode, the isolating saturable reactor, and inverse triggering.

Petersburg, Russia, for evaluating high voltage dynistor stacks under narrower pulse conditions and higher di/dt's.

II. 80MM DYNISTOR

The 80mm dynistor, type TDR173-1250, is rated for a peak forward off-state voltage of 3.1 to 3.5 kV and a peak repetitive 50 μs sine current pulse of 250 kA. For a 10 μs duration (50 Hz) pulse, the surge on-state current rating decreases to 25 kA. The silicon thickness of the die is 0.6 mm, the anode transistor sections are 50 μm wide, the anode thyristor sections are 300 μm wide and the perimeter termination is 4 mm wide. The Army Research Laboratory tests were performed at a pulse width of 450 μs using the High action Testbed [1]. The High Action Testbed, shown in Figure 2, consists of three parallel 30 mΩ pulse forming networks (PFNs) with a total capacitance of 21 mF and a variable load. Since

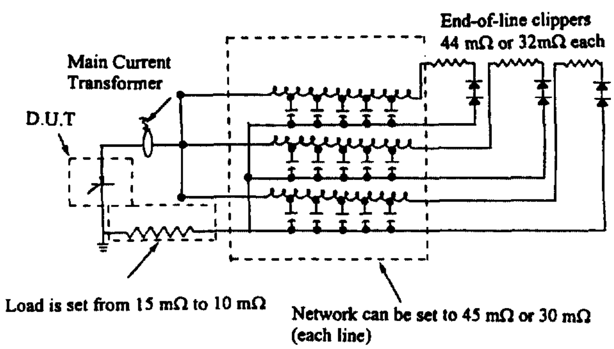

Figure 2. High Action Testbed schematic. Energy is stored in three 5-section PFNs, operated in parallel. Each PFN has additional taps that permit adjusting risetime and pulse shape, and provide for two different PFN impedances.

the dynistor is asymmetrical, a matched load and end-of-line clippers were used to avoid voltage reversals. Tests were conducted with two different trigger circuits. The first one had a maximum current drive of 750 A and the second had a current drive of 2300 A. To achieve high peak current two dynistors were operated in series at a voltage higher than that of a single device. Two dynistors failed these tests, one at 147 kA peak current and a *di/dt* of 1.14 kA/μs and the second at 167 kA and a *di/dt* of 2.0 kA/μs. The di/dt's were measured between 26.6 percent and 70.7 percent of the peak current. In these cases the trigger current was about 750 A. The results for the latter case are shown in Figure 3.

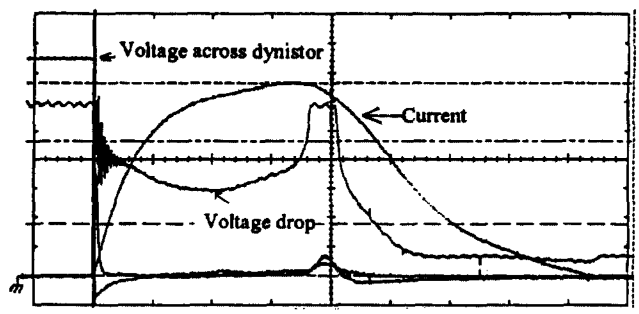

Figure 3. Operation of two dynistors in series at a peak current of 167 kA. The bottom dynistor failed. This can be observed in the voltage drop (bottom waveform - 10 V/division) behavior: the sudden rise at 360 μs (100 μs/division) into the pulse. The voltage scale (top waveform) across the dynistor and current scale (center waveform) are 500 V/division and 25 kA/division, respectively.

The observed failures can be described as follows. In the dynistor, many discharges are initiated throughout the volume of the silicon wafer. However, switching losses during the turn-on are dependent on plasma spreading, both vertically and horizontally. The degree of horizontal spreading is dependent on the magnitude of the trigger current in such a discharge and the delay time introduced by the saturable reactor before the main PFN current flows. At higher *di/dt's*, the rate of horizontal plasma spread limits the effective conduction area and localized heating of the p and n bases and their junctions can occur. If the silicon temperature in the lightly doped bases exceeds about 100° C, the silicon acquires a negative temperature coefficient of resistance. Consequently, current funneling occurs and the area goes into thermal runaway. Since all of the current is dumped into a limited area, a higher voltage drop is observed. Areas of failure show silicon cracking and melting. The damage also occurs in the current carrying-contacts.

A new trigger was designed by Mega Pulse that provided, at the same operating voltage, a trigger current that was higher than that of the previous device by a factor of three (2.3 kA). In the same testbed a two-dynistor series stack demonstrated operation at peak current of 177 kA with *di/dt* of 1.7 kA/μs (26.6 percent to 70.7 percent). Differentiating the current pulse gave a maximum *di/dt* of 2.8 kA/μs. Figure 4 shows the results obtained at the same peak current of 168 kA, as was the case in Figure 3.

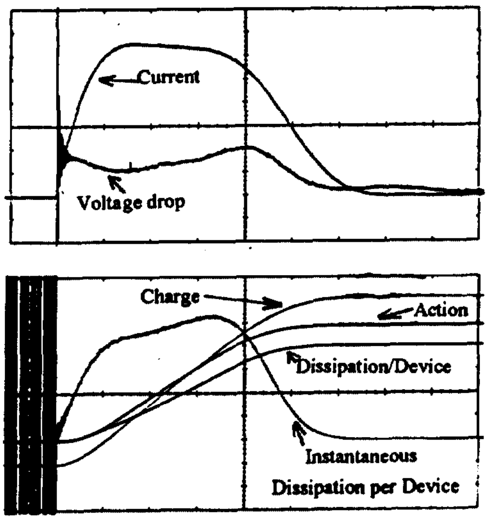

Figure 4. Operation of the thyristors at 168 kA with a new 2.3 kA driver circuit and reduced lead inductance in the PFN. Dark areas on the left side are digitizer resolving error. Top graph shows current (top - 20 kA/division) and voltage drop (bottom - 5 V/division). The bottom graph shows, from top to bottom on the right side charge (10 C/division), action (2 MA^2s/division), dissipation per device (500 W/division) and instantaneous dissipation per device (1 MW/division). Horizontal scale is 100 μs/division.

In the upper set of waveforms in Figure 4, the current and voltage drop of the bottom dynistor are shown at an operating voltage of 3.7 kV. The lower set shows the quantities calculated from the waveforms. Of major importance is the plot of the instantaneous dissipation. There is no commutation dissipation indicating that the increased drive current provided enough drive to eliminate the initial high-voltage drop shown in Figure 3. The voltage drop shown in Figure 4 shows a rising characteristic indicating that at this current level the maximum pulse width for reliable operation has been approached. The charge switched was 72 C, the action was 10 MA^2s, the total dissipation in the device was 2.04 kW, and the peak instantaneous dissipation was 5.5 MW at 360 μs into the pulse. Several discharges at 177 kA were conducted with no deleterious effects.

The discussion of *di/dt* relates to some extent to the data shown in Figure 5. We conducted experimental tests on symmetric thyristors with diameters of 50 to 100 mm, and various gate structures to determine their failure levels at submillisecond pulse width and *di/dt's* in excess of 500 A/μs. In general, the failure current appears to be directly related to the square of the diameter of the device. The main exception is the dynistor, which exhibited a current-carrying capability in the High Action Pulser equal to or better than that of a symmetric 100 mm phase-control thyristor. The dynistor, however, has an area of only 64 percent of that of this thyristor. The dynistor with a high drive current, which is an order of magnitude greater than a conventional thyristor, initially turns on a

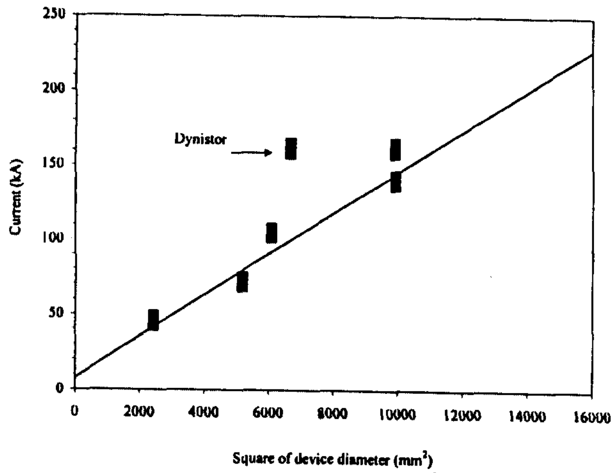

Figure 5. Results of experimental tests on symmetric thyristors with diameters of 50 to 100 mm to determine their failure levels. The dynistor is asymmetric and has a highly interdigitated drive structure and a high current drive.

far larger conducting area, reducing the commutation (turn-on) dissipation, which can represent 30 percent of the dissipation and considerably reduce the temperature rise during commutation. For the same operating voltage, the asymmetric dynistor is 40% thinner than a symmetric thyristor, which reduces the forward drop and therefore increases the current-carrying capacity. The gain is offset by the need to add protective circuitry and/or diodes in applications generating reverse voltages.

III. HIGH VOLTAGE PULSERS

The next series of tests evaluated dynistors under pulse conditions where *di/dt* was higher, for such potential applications as radars, electronic counter measures (ECM) and mine clearing. Two experimental pulse generators, designated the MPG-1 and the MPG-2, were purchased for this task. The MPG-1 is a self-contained pulser designed to demonstrate repetitive pulse operation in the 5 to 10 kA range at a pulse width of 1 μs. The MPG-2 was designed to evaluate operation at 100 μs pulse width at up to 100 kA, using pulse capacitors, a load and a power supply provided by ARL.

MPG-1

The MPG-1 was designed for burst operation: a set of 50 pulses of 1 μs duration each at a repetition rate of 1000 Hz with the burst repeated at a rate of 2 Hz. The pulser consists of a high-voltage output unit, a remagnetizing/triggering system unit, a pulse-charging unit, and a control system unit. The high-voltage unit consists of a coaxial stack of twenty 1300 V_B (breakdown voltage) 24 mm RSDs with a resistor divider, a permalloy saturable core reactor in a coaxial configuration, and a PFN constructed of 20 kV capacitors. The MPG-1 pulser operates as follows. The pulse-charging power supply charges the two parallel four-section PFNs in 20 μs to 20 kV. A reverse trigger pulse of 27 kV is then generated across the dynistor stack, providing the reverse current of 480 to 680 kA required to turn on the dynistor transistor sections. After the pulse is, over the saturable reactor must be counterpulsed with a reverse current pulse to reset the core.

Initial testing was performed with loads ranging from 0.75 to 2.00 Ω load over an operating voltage range of −13.76 kV to −20 kV. The anode of the dynistor stack was grounded with the cathode floating. For convenience the cathode voltage waveform in Figure 6 is shown as measured and the current waveform is inverted. The maximum value of *di/dt* during the pulse was 24.5 kA/μs, which was obtained by differentiating the current waveform.

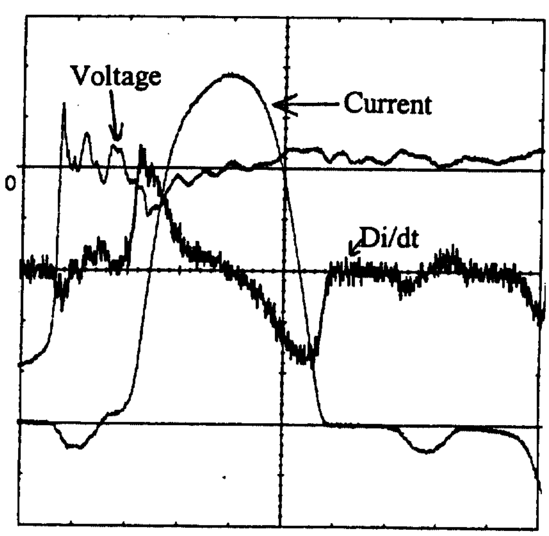

Figure 6. MPG-1 waveforms with a PFN impedance of 2 Ω and a mismatched load of 750 mΩ. At −19.6 kV (middle waveform - 5 kV/division), the current increased to −6.88 kA (top waveform - 1 kA/division) with a current risetime of 402 ns (10 to 90 percent) and current falltime of 410 ns. The pulse width (FWHM) is 1.104 μs. The third (bottom) waveform is the rate of change of the current (*di/dt* - 10 kA/μs/division). The maximum *di/dt* is 24.5 kA/μs. Horizontal scale is 400 ns/division.

MPG-2

To conclude this series of studies of dynistors, we examined two versions of an intermediate pulse length device capable of producing pulses of 110 μs at high currents. The dynistor stack for the MPG-2 consists of 80mm RSDs with a voltage rating of 3.1 to 3.5 kV each. A schematic of the circuit is shown in Figure 7.

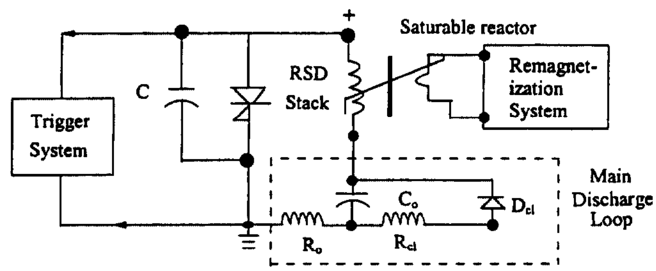

Figure 7. Discharge circuit for evaluation of MPG-2. C_o is 200 μF, R_o (load) is 143 mΩ. The reverse clipper circuit consists of a resistance R_{cl} of 34 mΩ and a diode D_{cl}.

In the first version of this pulser, the dynistor stack failed at 22.5 kV. Analysis of the failure indicated that the probable cause was inadequate trigger drive current during low-voltage operation. The capacitors of the trigger generator were parasitically charged by the system power supply and were therefore proportional to the system DC operating voltage, which restricted the discharge area at the cathode. This is the equivalent of a *di/dt* failure. The restricted discharge caused the 20 μm thick aluminum layer on the surface of each die to melt, forming an aluminum-silicon eutectic. This migrated into the n+ area and then the p area of the die. The leakage current increased until the device finally self-triggered and catastrophic failure occurred. Most of the failures normally observed occur near the edge termination because the current density is higher in this region, unless filamentation occurs elsewhere. This is because the voltage gradient on the edges of the planar devices are non-uniform and compressed. This is a common cause of problems in all high-voltage devices.

In the second version, the trigger generator capacitors were increased from 0.066 to 0.75 μF and were charged by an independent power supply, which provided a constant peak current of 3 kA. The trigger circuit was isolated from the main discharge circuit by a saturable reactor, which provided a delay of 3 μs at 25 kV. The main discharge circuit consisted of a 200 uF capacitance with a 143 mΩ load. A clipper was added to protect against inverse current. The MPG-2 was operated reliably up to 27.2 kV with a peak current of 101.5 kA and a *di/dt* of 8.2 kA/μs. The total charge transferred was 6.0 C and the action was 0.45 MA^2s. The results are shown on Figure 8.

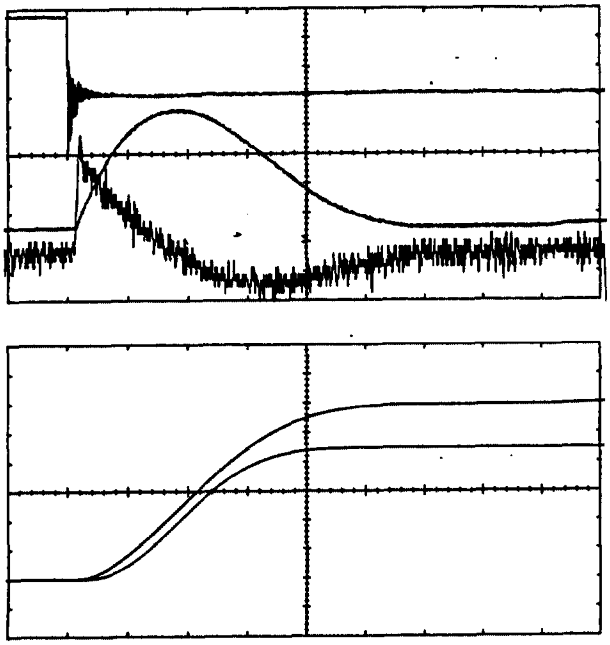

Figure 8. Voltage, current and *di/dt* temporal relationships of the MPG-2 pulser. Top graph shows, from top to bottom, voltage waveform (10 kV/division), current (25 kA/division) and *di/dt* (2 kA/μs/division). The bottom graph shows charge (top - 1 C/division) and action (bottom - 100 kA^2s/division). Horizontal scale is 20 μs/division.

IV. CONCLUSIONS

The dynistor has the potential of providing high peak currents with kiloampere per microsecond rates of current rise, for power semiconductor device applications which require no reverse voltage capabilities. The studies of the 80mm dynistors at 0.5 to 0.85 ms pulse widths and *di/dt's* greater than 1 kA/μs were conducted with a view towards electromagnetic launcher applications, i.e., electric guns, and for industrial processing, e.g., rock fracturing, metal forming.

The MPG-1 pulser demonstrated a very high *di/dt* of 24.5 kA/μs at 6.88 kA. This demonstration is significant at this current level. There are some restrictions on the pulser with a mismatched load. The devices are asymmetrical and require reverse voltage protection. As such, the pulser should be considered for application requiring high di/dt performance and where the restrictions will not adversely affect performance.

The MPG-2 pulser has operated with a *di/dt* of 8.2 kA/μs at 101.5 kA for a 50 μs (FWHM) monopulse. The initial failure was a *di/dt* problem caused by inadequate trigger current at lower voltage. We resolved the problem with a redesigned trigger circuit providing a constant 3 kA pulse current.

The dynistor study is significant because it demonstrates that highly interdigitated gate structures combined with high trigger currents are essential to switch high currents with high *di/dt*. The work of Ramezani [2] has demonstrated the effectiveness of this approach in the design of the AZ thyristors, where di/dt's in tens of kiloamperes per microsecond have been reported. The relative merits of each approach need to be evaluated. Device life, complexity of drive circuits, volume, weight, cost, graceful degradation and reverse voltage hold-off should be considered for each application.

V. ACKNOWLEDGMENT

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