MASTER

UCRL--50025-85-1

DE85 015313

Electronics Engineering Department

EE Technical Review

Manuscript date: June 1985

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California · Livermore, California · 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$8.50 per copy • (Microfiche \$4.50)

i. b.
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Preface

The EE Technical Review has two purposes—to inform readers of various activities within the Electronics Engineering Department and to promote the exchange of ideas.

The articles, by design, are brief summaries of EE work. For further details on a subject covered, please contact one of the authors. The authors are primarily responsible for the content of their articles. Inasmuch as most projects are the result of the cooperative efforts of many individuals, the person you contact will either provide the requested information directly or refer you to the appropriate person to answer your question.

EE Department personnel are encouraged to submit articles for consideration to the Editorial Board. Board members include:

H. S. Ames—Nuclear Energy Systems Division
F. Dean Lee—Fusion Energy Systems Division
M. S. Genin—Technical Editor
K. S. Kunz—Engineering Research Division
H. D. Francis—Field Test Systems Division
J. W. Spencer—Engineering Services Division
W. F. Thompson—EE Department Staff
P. J. Van Arsdall—Laser Engineering Division

E. A. Lafranchi
Electronics Engineering
Department Head

Contents

Ultrafast Gating of Microchannel Plate X-Ray Spectrometers	1
Study of Power MOS Fast Switching Techniques	9
Lightning Vulnerability of Nuclear Explosive Test Systems at the Nevada Test Site	19
A Computer Model of the MFTF-B Neutral Beam Accel DC Power Supply	29
Index	34

Ultrafast Gating of Microchannel Plate X-Ray Spectrometers

J. D. Wiedwald

We have developed a laser-triggered microchannel-plate (MCP) gating system using a photoconductive switch. This system has obtained a dramatic improvement in performance for three MCP-intensified x-ray spectrometers during recent x-ray laser experiments at the LLNL Novette laser facility.

The x-ray laser experiment

Experiments conducted at the Novette laser facility have demonstrated an x-ray laser with a process known as resonant photo-excitation.^{1,2} In this process, the two Novette beams are line focused onto two selenium foils that are located on the outside of an x-ray laser target (Fig. 1). These foils produce x rays that pump the gas-filled cavity between the two foils. Then, through resonant photo-excitation, a population inversion is created that results in enhanced radiation at 50 to 60 eV (about 200 Å). This radiation exits both ends of the laser target. We diagnosed the radiation from the target with three low-energy x-ray spectrometers. Two spectrometers known as McPIGS (Microchannel Plate-Intensified Grazing Incidence Spectrometer) were used in conjunction with a single SIRGAS (Slitless Intensified Readout Gated Spectrometer) design. The McPIGS spectrometer contains a slit and a diffraction grating that disperses the x rays onto a microchannel plate (MCP) that serves as the detector (Fig. 2). The SIRGAS spectrometer also uses a diffraction grating that disperses the x rays onto a curved MCP detector located on the Rowland circle.

The x-ray signals of interest have a duration of approximately 300 ps while background in the same spectral region continues for several nanoseconds. The effects of the background are minimized by turning the MCP off immediately after the signal is detected. The MCPs are turned on by charging to approximately -1 kV with a slow rise-time (500-ns) pulse and are rapidly turned off by a photoconductive switch connected to the MCP through transmission lines. We stagger the turnoff times of three microstrip lines across the MCP by 250 ps in order to provide some time discrimination.

In this discussion of our x-ray laser experiment, we describe the details of the gating system,

including the pulse-charging system, trigger-beam delivery optics, and system diagnostics.

Functional description of the diagnostics

Microchannel plates are spatially-coherent electron multipliers that have been found to be useful in a wide range of scientific applications. They are used in these instruments to detect low-energy x-ray signals (40 to 150 eV) by photo-electric conversion. X-ray-generated photo-electrons are multiplied along each multiplier channel by a factor of up to 100,000, as determined by the MCP bias voltage. The resultant electron cloud is accelerated by several kilovolts and strikes a phosphor screen where the light it creates is recorded on film.

The gain of an MCP is a very sensitive function of the bias voltage. For example, dropping the bias voltage from 1000 to 700 V results in a factor-of-forty decrease in MCP gain. We use this characteristic to achieve gate turnoff that is somewhat faster than the electrical gating signal. We estimate that the effective gate closes in less than 100 ps.

The MCP must be biased to about -1 kV in order to achieve sufficient gain during signal detection. Then, in order to avoid detecting the background x rays, the bias must be removed quickly after the signal of interest arrives. The MCP bias structure is made up of 3-mm-wide gold strips plated on the front surface of the MCP and a ground plane provided by a gold-plated back surface. These strips form 25-Ω microstrip transmission lines and there may be up to four strips for each MCP. Therefore, we need to drive a gating signal into an equivalent 6.25-Ω load. Rapid gating speed and low jitter are important because background is minimized by turning the

Fig. 1. Resonant photo-excitation x-ray laser.

MCP off as soon as possible after recording the signal.

The need to gate a relatively high voltage with a very fast low-jitter transition greatly limited the range of possible solutions. We considered laser-triggered spark gaps, step-recovery diodes, and avalanche transistor strings as possible solutions, but these were all ultimately rejected as incapable of meeting all of our requirements. We found the requirements could be met by using laser-triggered photoconductive switches.

The photoconductive switch

A photoconductive switch,³⁻⁵ sometimes called an Auston switch after one of its early developers, is essentially a slab of near-intrinsic semiconductor with two ohmic contacts. Carriers freed by photo-electric conversion of light are available to conduct current across the gap between the two contacts. A great number of carriers can be generated very quickly by a short, intense laser pulse, causing the semiconductor to become

Fig. 2. A McPIGS spectrometer. A McPIGS spectrometer uses a diffraction grating to disperse x rays onto an MCP detector.

a quasi-metal and close the switch between the two contacts very quickly. After the illumination is removed, the conductivity decreases (at a rate determined by the carrier recombination time) until it reaches the dark level that results from thermal generation of the carriers and charge injection from the contacts. With the availability of sub-picosecond lasers, experimenters have generated low-level electrical pulses with edges as fast as 400 fs.

Silicon was chosen as the semiconductor for our switch. It has a recombination time of about 100 μ s, allowing sufficient time for the bias voltage to be removed before the carriers recombine. It is also quite sensitive to the 1.053- μ m light available from the Novette glass laser, which provides a portion of its energy to activate this switch. Gallium arsenide was also considered but its short recombination time of 300 ps would have made it impossible to remove the bias voltage before the switch reopened.

Silicon has other characteristics that cause a slight increase in system complexity. Because of its long carrier lifetime and low dark resistance, a silicon switch may experience thermal runaway

under high voltage DC bias. To prevent this, a bias pulse generator was developed that provides a negative 1-kV pulsed bias for only about 1 μ s. This is too short a time for thermal runaway to occur. The bias pulse generator is described later in this article.

Fast gating circuitry

As first conceived, a short gating pulse (a few hundred picoseconds in duration) would have been required to gate the MCP on during the period of interest. We soon recognized that the background occurs only after the signal, and only a fast turnoff is sufficient. This allowed us to take the approach shown in Fig. 3, which was somewhat less difficult than producing an ultra-narrow electrical pulse.⁶ This approach uses the photoconductive switch to short the bias voltage to ground very quickly, thus disabling the MCP detector. The transition time is determined largely by the width of the laser pulse. For our experiments this pulse width ranged from 100 to 400 ps, resulting in similar electrical fall times.

Fig. 3. Fast-gating circuitry. Throughout the system, 25- Ω semi-rigid cable is used. Since up to four separate 25- Ω MCP strips are to be gated, the system impedance is about 6 Ω . In order to physically match photoconductive switches that were already available, two switches (each 3 mm wide), are mounted side-by-side onto a 6-mm-wide stripline. The resulting stripline is sandwiched between two 0.5-mm-thick epoxy-fiberglass printed circuit boards to obtain a 6- Ω characteristic impedance. The 6-mm stripline is fanned out into four 1.5-mm strips, each terminated in the 25- Ω semi-rigid coaxial cable. The pulse edge is then propagated in 25- Ω cable through the vacuum wall to the MCP. Three 3-mm-wide conductive strips plated onto the MCP provide 25- Ω micro-strip transmission lines with the MCP serving as the dielectric. In order to minimize electrical reflections, the pulse exits the MCP on another 25- Ω semi-rigid cable and is terminated in a capacitively coupled terminator assembly. The terminator assembly also allows us to monitor the electrical performance of the system. This assures us that the switch is being triggered at the correct time, that laser energy is sufficient to completely saturate the switch, and that the turnoff edge is being properly transmitted.

Bias pulse generator

At low frequencies, the combination of the MCP and the photoconductive switch is a capacitive load that must be charged to about -1 kV in order to achieve adequate MCP gain. The MCP, charge cables, and photoconductive switch have a combined capacitance of about 3 nF. To prevent thermal runaway, we determined that a rise time of 500 ns or less, a 300-ns flat top (to make timing easier), and a fall time of 500 ns or less were needed. We arrived at a design using two stacks of ten power field effect transistors (FETs). The circuit diagram is shown in Fig. 4. The series stack of FETs discharges a 0.1- μ F capacitor, charged to about -1 kV, into the load capacitance of 3 nF. The shunt stack then discharges the load capacitance to ground. A pair of oscilloscope pictures demonstrating the pulse-charger performance is shown in Fig. 5. Figure 5a shows the output of the bias pulse generator across the photoconductive switch with no switch activation. The same signal with the activation of the switch by a light pulse is shown in Fig. 5b. Here, the voltage falls abruptly to about -400 V when the switch is activated. In

fact, the MCP voltage drops nearly to zero within a few nanoseconds. The difference, however, is the result of measurement limitations.

Photoconductive switch activation

The short laser pulses that activate the photoconductive switches have three essential requirements. The pulses must have at least a millijoule of energy each, the beam profiles must be stable and free of large interference patterns, and the pulses must arrive at the switches precisely timed to the x-ray signals from the target.

The laser beam that activates the switches is obtained by reflection off a polarizer located in the main Novette laser chain (Fig. 6). An adjustable wave plate allows us to vary the energy in the trigger beam. The main Novette pulse and the trigger beam must arrive at the target chamber at approximately the same time. Since the Novette pulse travels 175 m, the trigger beam must travel about the same distance. The straight-line distance from the wave plate to the target chamber is only 36 m. Therefore, a considerable amount of

Fig. 4. Schematic of bias-pulse generator.

trigger-beam path folding must be incorporated. Additionally, in order to obtain uniform beam profiles at the photoconductive switches, the trigger beam must be image-relayed along its entire path length.

To meet these requirements, an image-relaying-and-folding system is used (Fig. 6 inset). This folding system allows the laser beam to travel across 120 m of beam-path length in only 25 m of space. The system uses four mirrors and two lenses with a focal-length of 6 m to relay the beam across the necessary 120 m. The first mirror is used to direct the incoming collimated beam down the common axis of the two lenses. The second and third mirrors, which are placed at opposite ends of the relay path, direct the beam off axis with each successive pass. After the beam has made five passes through the system, the fourth mirror extracts the beam and directs it toward the target chamber area.

Once near the target chamber area, the beam is split into five separate beams. Three of these beams are directed to the two McPIGS and SIRCAS switches. A fourth beam is directed to a photodiode which monitors the trigger-beam energy, while the final beam activates a reserve photoconductive switch. The reserve switch is monitored to assure that the laser is gating the switches properly. An optical trombone is also incorporated into each of the three spectrometer trigger-beam paths. This feature allows adjustment of each beam-path length to achieve the proper delay time required for each switch.

This optical system provides the excellent stability and beam uniformity required by the photoconductive switches.

(a)

(b)

Fig. 5. Pulsed bias voltage across photoconductive switch (a) without activating switch and (b) with activating switch. The vertical scale is 200 V/Div.

System performance

The electrical performance of the system is monitored by recording the terminator output signal on a Tektronix R7912 transient recorder. Although the 500-MHz bandwidth of this instrument is insufficient to accurately reproduce the actual transient, it provides a good timing indicator that is checked against light scattered from the x-ray laser. (See Fig. 7 for a typical record.) In addition to confirming system timing, the amplitude of the electrical reflections recorded here proves to be a useful indicator of the photoconductive switch "on" resistance.

Since the turnoff pulse is AC coupled at the terminator, a reflection from the terminator builds up as the coupling capacitor charges. This reflected signal "probes" the photoconductive switch, resulting in a second reflection which is a function of the switch resistance. Computer simulations using the SPICE circuit analysis program allow us to determine the resistance based on the

Fig. 6. The Novette laser system showing the photoconductive switch trigger-beam path with a schematic of the trigger-beam path-folding system (inset).

Fig. 7. The terminator output and scattered light signal from the target combined to monitor timing and switch performance. The region of electrical reflections from the switch is used to determine switch "on" resistance.

nature of the doubly reflected signal. In these experiments, we have determined that the switch resistance, regardless of laser intensity, was never less than $2\ \Omega$, which we attribute to contact resistance. Reflections consistent with a switch resistance of greater than $3\ \Omega$ caused us to check the alignment of the laser beam and to look for any beam attenuation. This was an effective way to evaluate the quality of the illuminating beam.

Another real-time diagnostic is an oscilloscope recording of the bias pulse (Fig. 5b). This diagnostic confirms that the amplitude and timing are correct. Along with these two records, timing (coarse and fine), laser illumination, and MCP bias level are provided on every system shot. These routinely provide a high level of confidence in the performance of this diagnostic.

Scientific results

Three independent gating systems were fielded on a series of Novette experiments. These involved one SIRCAS and two McPIGS x-ray spectrometers. Only three strips of each MCP were implemented; the fourth channel bypassed the MCP and was connected directly to the terminator assembly. Cable lengths were adjusted to stagger the gating of each strip by 250 ps.

Two film records of one of the McPIGS are shown in Fig. 8. Figure 8a shows the diagnostic properly timed. The top strip is gated off within 200 ps after the peak of target illumination. The middle strip turned off 500 ps after the top and has a background that is several times that of the top strip. Figure 8b shows another shot for which the gate-off circuit was intentionally disabled, allowing full integration of the background. The background and contaminant lines in this case are many times that of the top strip in Fig. 8a.

The large improvement in instrument dynamic range allowed experimenters to observe and measure lines that would have otherwise remained unnoticed. Particular attention was first drawn to the 206- and 209-Å lines because of their high relative brightness in the first time strip. These lines were then investigated for their brightness, directionality, and intensity as a function of cavity length. The results verified that amplification is indeed occurring; an x-ray laser had been demonstrated.

The three gating systems were operated on more than 150 Novette laser shots with no malfunctions. The ultrafast gating characteristics of these systems coupled with their excellent reliability have allowed the x-ray spectrometers to be an invaluable diagnostic on the Novette x-ray laser experiments.

Fig. 8. A comparison of gated (a) and ungated (b) McPIGS performance. These were exceptionally bright shots. The signal-to-noise ratio was even more impressive in shots having less intensity. The turn-off sequence for the gated image is: top, bottom, middle.

Related applications

Photoconductive switches have been used by various experimenters for:

- Low-jitter streak-camera sweep generators
- Fast electro-optic pulse gating
- Electro-optic pulse shaping.

The results of this work show that photoconductive switches are also usable as gate generators for one-dimensional (and potentially two-dimensional) imaging. Their attributes include economy, reliability, geometric flexibility, high voltage, bi-polar operation, and speed (limited essentially by the speed of the illumination). It is, of course, necessary to have an appropriate illumination source available. Typically, this is a sub-nanosecond laser of moderately long wavelength (500 to 1060 nm) having at least 100 μ J of energy.

Acknowledgments

There were many contributors to the success of this effort. Foremost are the co-authors of the original paper⁷ on this system: David J. Christie, David G. Nilson, and Russell B. Wilcox. Others deserving particular recognition are Lynn Seppala, Mark Eckart, and Michael Gerassimenko.

Special thanks go to Dennis Matthews, Lead Scientist for the x-ray laser experiments, for his continued encouragement and enthusiasm.

References

1. P. L. Hagelstein, *Plasma Phys.* **25**(12), 1345-1367 (1983).
2. D. L. Matthews et al., *Phys. Rev. Lett.* **54**(2) 110-113 (1985).
3. D. H. Auston, "High Speed Optical Techniques," *SPIE* **94** (Bellingham, WA, 1976), pp. 78-82.
4. P. LoFur and D. H. Auston, *Appl. Phys. Lett.* **28**(1) 21-23 (1976).
5. G. Mourou and W. Knox, *Appl. Phys. Lett.* **35**(7) (1979).
6. Lawrence Livermore National Laboratory Drawing Number LEA84-1307.
7. D. J. Christie, D. G. Nilson, J. D. Wiedwald, and R. B. Wilcox, *An Ultrafast Turnoff Laser Triggered Gating System for Microchannel Plate Intensified X-Ray Spectrometers*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-91227 (1984).

Study of Power MOS* Fast Switching Techniques

J. A. Oicles and G. J. Krauss[†]

Pulsed power is a method of storing energy over a long period of time and releasing that energy in a very short period of time at a very high power level. An increasing number of tasks rapidly emerging in the scientific community are demonstrating the need to generate bursts of power at speeds approaching the limits of current pulsed-power technology. When there is a need to generate, for example, 10 kW at several hundred volts in less than 3 ns, a circuit designer will typically turn to vacuum tubes. However, the planar triodes required for such performance can cost over \$400. With a growing list of applications such as low-power lasers, marine communications, particle accelerators, cancer treatment, military countermeasures equipment, nuclear testing, and university research, this need has attracted some attention. So, to solve the problems of speed, power-handling capability, low jitter requirements (under 50 ps), and cost, researchers at the University of California's two national laboratories at Livermore and Los Alamos have found an inexpensive solution in a new approach to transistor packaging.

Introduction

The emergence of power MOS field-effect transistors (FET) over the past few years has created a revolution in the design of mass-produced circuits such as switching power supplies. Circuit designers have been able to use them to achieve switching speeds of 20 to 50 ns in power-supply applications, which is a significant improvement over conventional bipolar transistors. We have examined the inherent switching-speed limitations of this technology and we have discovered that, using some reasonably simple techniques, power MOS can be improved to become an efficient medium for production of high-power pulse generators with switching times approaching 1 ns.

The generation of energetic pulses has depended strongly on non-solid-state switching technology when speed and voltage requirements are less than a few nanoseconds and greater than a few hundred volts, respectively. Switching requirements of greater than 10 kW in less than 3 ns, for example, limit the circuit designer to only a few technologies, none of them particularly simple or inexpensive. The addition of high repe-

tition-rate requirements compounds the problem, and will generally limit the designer to a vacuum-tube approach if the repetition rate and/or rise time are outside available thyatron capabilities.¹

We have experimentally obtained switching speeds of 1.3 ns under lightly loaded conditions (i.e., 400 V into 50 Ω) and single-device peak currents of 145 A in approximately 5 ns. Foreseeable improvements in this new development promise to make our approach even more versatile and useful in the future.

Background

In the past few years, power MOS has solved many power-circuit problems and created a new generation of high-frequency switching power supplies which are small and lightweight. This improvement in power-supply performance still does not satisfy the specialized needs of high-voltage pulse generators requiring output voltages of up to 10 kV and with rise-time requirements sometimes below 1 ns. Such pulsers find use in lasers and other optical systems, radio frequency modulators, other sensor drivers, and a variety of miscellaneous tasks continually emerging in the scientific community.

* Metal Oxide Semiconductor.

[†] Currently employed at Los Alamos National Laboratory.

The key element in a pulse-generator circuit is the switch which provides the fast rise-time output. Several technologies have been available for fast, high-voltage applications in the past. However, for work under 5 ns, the choices are somewhat limited. Gas switches (spark gaps) and krytrons, for example, have been popular for their high performance and low cost. Their use is often precluded, however, by high jitter and poor operational lifetime. More recently, the bulk-semiconductor photoconductive (Auston) switch has emerged as an effective high-voltage switch.² This device relies on the photon-induced generation of carriers within a bulk-semiconductor material. Typically, the Auston switch requires a complex pulsed laser system for turn-on. Some other approaches rely on rise-time improvement using various magnetic techniques, but waveform is difficult to control with these methods and an active pulse generator must be provided. Avalanche-mode transistors continue to be used and indeed present an attractive solution to many engineering problems. They are, however, power limited and often exhibit reliability problems. Such difficulties are compounded when multiple devices are used to attempt to circumvent the power issue. For completeness, the hydrogen thyratron is mentioned, but it is limited to a rise time of around 3 ns.³ Most thyratrons are no faster than 15 ns.

This often leaves the vacuum tube as the only viable switching element available for rise-time requirements under 3 ns and greater than 10 kW and for circuits with repetition-rate conditions requiring low jitter. Such specifications would describe a device which could function as a Pockels cell driver, for instance. Pockels cells are high speed electro-optic devices used as shutters in laser systems. For such a speed requirement, component selection is generally limited to microwave planar triodes such as the Varian/Eimac Y-690.⁴ High speed circuits used with these devices tend to be complex because the circuit-induced multiplication of the input capacitance of the triode (known as the Miller Effect) limits power gain. The vacuum-tube current for pulse applications also is limited to around 12 A/cm² of cathode area. Higher currents are possible but tube lifetime may be degraded.

Device development

All power MOS is implemented as an array of thousands of minute cells on each transistor chip. Because the cells are so small, the switching speed

inherent in any cell is very fast. Consequently, the cell array of a power MOS transistor can be made to switch very fast but special techniques are required. Figure 1 depicts a simple equivalent circuit of a conventional power MOS transistor, showing those equivalent elements which limit switching speed. It is possible to partially circumvent these charging limitations with conventional packages by applying a higher voltage to the transistor gate (see Fig. 1).

A more reliable and versatile method of attacking the problem is to repack the transistor chips in a manner which meets our special requirements. This approach, which has been previously investigated by others,⁵ is depicted schematically in Fig. 2. Our approach is based on a new package design in which lead inductances are minimized in the same way as they are in microwave strip-line transistors. We also employ multiple bond wires from the chip to the package lead connections to help minimize the inductances found in Fig. 2. An important further change is the addition of a second source lead with inductance L_{cs} , reserved for an ungrounded gate drive. This is implemented by an extra set of bond wires to the transistor chip and an extra package lead. Except for the common inductance on the chip itself, this prevents reduction of gate-source voltage caused by current passing through the source inductance.

Circuit development

We discovered that two of these chips would fit nicely in the Kyocera package, forming a hybrid circuit with twice the current-handling capability. The inherent current-sharing feature of MOS makes this paralleling possible without elaborate precautions. Chip mounting and bonding were carried out by Los Alamos National Laboratory with twelve 2-mil wires going from each bonding pad to the appropriate package terminal. Chip pad areas are ample for even the 20 individual bonding wires for the dual-source connection, as shown in Fig. 3. Finally, after some effort, we have developed the gate-drive circuit shown in Fig. 4. This design provides a drive signal swing from zero to +25 V, with the critical +4 to +10 V transition taking place in 0.8 ns, when driving the 3500 pF gate-source load. The driving transistors are high-frequency devices in strip-line packages normally used in communications equipment. The circuit provides a zero volt level for FET turn-off, a highly desirable feature shared only with the vacuum tube in this speed/power regime.

Fig. 1a. Equivalent circuit of a conventional power MOS transistor.

Fig. 1b. Conventional transistor package TO-220.

An MOS transistor has three elements: the gate, the drain and the source. The output current of a transistor flows from the drain to the source. This current is controlled by the voltage impressed from the gate to the source. Given an ideal step generator (with zero rise time), e_p , there remain several circuit elements impeding rapid turn-on. In order to turn on the transistor, one must apply a charge to gate-source capacitance, C_{iss} , and to the smaller drain-gate reverse capacitance, C_{rss} , such that the required gate-source voltage is obtained. The latter's significance is multiplied by the Miller Effect. The source impedance, R_G , of the generator must be sufficiently low to charge these capacitances in the required time. Included in R_G is also the resistivity of the gate interconnection on the chip itself.

Lead inductances also limit switching speed. Using devices in conventional transistor packages such as the TO-220, the circuit designer is limited by the inductances, L_G and L_S , of such commercial packages. The value of these inductances is approximately 10 nH using the TO-220 package in a compact circuit configuration. Inductance L_G , in particular, adversely affects rise time. As the device turns on, the voltage from the gate to the source is reduced and results in a delaying step in the drain fall time. It is possible to partially circumvent these charging limitations with conventional packages by applying a higher voltage to the gate.

It is possible to partially circumvent the limitations in switching speed illustrated in Fig. 1a. For example, the Intersil IVN6000CNU (as in Fig. 1b) transistor is specified to withstand a maximum gate-source voltage of 30 V. We found, however, that it will generally withstand a gate-source stress of 100 V and we were able to switch 300 V into 30 Ω in approximately 3 ns using this approach. However, we would limit such overstressing techniques to information-gathering circuit experiments where reliability and reproducibility are not issues.

Fig. 2. Equivalent circuit of special packaging. In the new design, lead inductances are minimized with the help of multiple bond wires from the chip to the package lead connections and the addition of a second source lead.

Experimental performance

In order to determine the effectiveness of the new package, tests were conducted with two IRF840 transistors in parallel substituted in the circuit. Each of these devices consisted of an IRFC440 chip in a TO-220 plastic package. (See Figs. 5-7.) We found that the custom package yielded more than a factor-of-two improvement in switching speed over conventional packages (1.9 vs 4.9 ns).

Cost

This new package design carries with it an attractive cost improvement in the technology of switching power supplies. By bonding together two \$15 power MOS transistors in the special package costing \$60, we have created a significant improvement over the use of \$400 planar triodes.

Proposed improvements

During the course of testing, several areas capable of improvement were noted. Most of these were concerned with a reduction of circuit inductance. Design of a transistor package with an even lower inductance is in progress at Los Alamos National Laboratory. More careful circuit layout also appears to be in order. Gate-drive requirements of less than 1 Ω and less than 1 ns present some interesting challenges to both the circuit designer and packaging engineer.

Emerging higher voltage chips also promise higher single device power levels and higher output voltages. We are presently preparing to test developmental Motorola 850-V devices in our package and we have 1000-V components on order.

We are also investigating techniques for summing pulse outputs from multiple generators, either by a stacking arrangement (which presents gate-drive problems) or by the use of transformers. It is reasonable to expect that the several kilovolts required to drive Pockels cells, for instance, could be achieved using this approach and at a cost comparable to, or less than, existing vacuum-tube, thyatron, or spark-gap drivers.

Based on our relatively brief experience in this medium, we predict single device maximum currents of 200 A, rise times less than 1 ns and voltage holdoff ability of at least 1 kV when technology matures. Allowable repetition rates are circuit dependent, but could be in the several megahertz range. Such performance is assumed to be within the realm of available (or soon to be available) limitations on device voltage and chip dissipation, and should be suitable for reliable circuit performance in mass-produced equipment.

Conclusions

It has become apparent that the power MOS approach is competitive with planar triodes in terms of speed, power handling capability, jitter, and cost for many applications. The advantages of operational lifetime, ruggedness, size, and reliability normally attributed to solid-state circuitry make this new approach particularly attractive. We expect usage to spread to many fast-pulse areas as experience accumulates.

Fig. 3a. Photo of transistor package KMC-19629.

Fig. 3b. Schematic of transistor package KMC-19629.

We polled vendors of microwave-style transistor packages seeking a large chip-mounting cavity, wide strip-line style leads and the willingness to add a custom lead for the second source connection. We selected the Kyocera International, Inc. KMC-19629 package and ordered a number of units. We also spoke with a number of power MOS vendors, particularly with Intersil Inc. and International Rectifier, Inc., and selected the latter's IRFC440 chip as most suitable for our needs. (Rated voltage is 500 V.) An assembled device is depicted in Fig. 3. In talking to the manufacturers regarding damage thresholds, it became clear that heating the chip to temperatures approaching 1 J during the pulse was the only significant limitation to its current handling capability.^{6,7} Transistor data sheets typically limit pulse current to four times the steady-state current specifications. This, however, is a somewhat artificial limit tailored for the "slow" power supply designer and unnecessarily pessimistic for fast pulses less than 50 ns in duration. A more significant limit is the increase in on-resistance with increasing drain current. Either data sheets may be extrapolated to estimate this or special device testing may be independently carried out.

The two IRFC440 chips mounted together in our single package have a combined input capacitance, C_{iss} (from Fig. 2), of approximately 3000 pF. If we wish to impress a gate-source voltage, V , on the devices in a time period, T , of 1 ns, the average charging current, $C_{iss}V/T$, equals 10 A. Alternately, the required source impedance, R_G , is approximately T/C_{iss} , or 0.3 Ω . The gate drive circuit, therefore, represents a major challenge to the circuit designer. The power output circuit might take on a number of forms, depending on application. We have accomplished our testing using simple resistive loads of 50 Ω and less in order to characterize performance. Tight circuit layout is critical, with a low inductance ground plane necessary along with wide, short, interconnections to minimize circuit inductance.

Fig. 4b. Test circuit of the IRFC440 transistor chip.

Fig. 5. The drain waveform achieved with a $50\text{-}\Omega$ load using two IRFC440 chips in parallel in a single Kyocera package. When corrected for the 1.5-ns rise time of the instrumentation used, a 90-10 percent fall time of 1.3 ns or less has been obtained.

Fig. 6. The current waveform, with 10-90 percent rise time to 108 A in approximately 5 ns. Peak current handling capability was explored by reducing the load resistor to $0.6\text{ }\Omega$. Performance was evaluated with drain currents to 145 A (obtained by raising the drain voltage from 400 to 500 V). Fall times were only slightly slower at the higher current level.

Fig. 7. On-resistance of the two different transistor types. In order to determine the effectiveness of the new package, tests were conducted with two IRF840 transistors in parallel substituted in the circuit. Each of these devices consisted of an IRFC440 chip in a TO-220 plastic package. A load resistance of 10Ω was selected for this test as an intermediate between the loadings used in initial testing. A similar set of data was taken on the original circuit. The corresponding drain currents were also measured. The reduced data are shown in Fig. 7 where they are plotted as on-resistance as a function of time for the two different transistor types. While the special packaging results in greatly improved performance, robust gate drive on the standard, inexpensive, TO-220 devices can produce impressive results also.

Acknowledgments

We would like to thank Steve Davis, formerly with Power Spectra, Inc., San Leandro, CA, and Steve Clemente of International Rectifier for comments which encouraged this development.

References

1. M. Weiner and L. Silber, "Pulse Sharpening Effects in Ferrites," *IEEE Transactions on Magnetics*, Mag-17(4) (July 1981).
2. D. H. Auston, *Appl. Phys. Lett.* **26**, 101 (1975).
3. J. A. Oicles and H. D. Kitchin, "A Low Jitter, Hydrogen Thyatron Pockels Cell Driver," *IEEE 4th International Pulsed Power Conference* (Albuquerque, NM, June 1983).
4. J. A. Oicles, D. C. Downs, and D. J. Kuizenga, "Fast Versatile Pockels Cell Driver," *IEEE 4th International Pulsed Power Conference* (Albuquerque, NM, June 1981).
5. Steve Davis, Power Spectra, Inc., San Leandro, CA., private communication (June 1982).
6. S. Clemente, B. R. Pelly, and A. Isidori, "Understanding HEXFET Switching Performance," *International Rectifier Application Note 947* (September 1982).
7. S. Clements, B. R. Pelly, and R. Ruttonsha, "Current Ratings, Safe Operating Area, and High Frequency Switching Performance of Power HEXFETs," *International Rectifier Application Note 1949* (September 1982).

Lightning Vulnerability of Nuclear Explosive Test Systems at the Nevada Test Site

R. T. Hasbrouck

A task force chartered to evaluate the effects of lightning on nuclear explosives at the Nevada Test Site has made several recommendations intended to provide lightning-invulnerable test device systems. When these recommendations have been implemented, the systems will be tested using full-threat-level simulated lightning.

Introduction

Lawrence Livermore National Laboratory conducts operations involving the underground detonation of nuclear explosive test devices at the U.S. Department of Energy's Nevada Test Site (NTS). To ensure nuclear explosive safety during these operations, the Laboratory analyzes all components, systems, and procedures, after which they are subjected to an interagency nuclear explosive safety study (NESS). This study considers all sources and paths of energy that could conceivably initiate an unwanted detonation. One of these sources, lightning, has been the subject of several studies.

In 1973 an extensive analytical study¹ considered the effects of lightning on nuclear explosive systems located at the bottom of an emplacement hole. Time-domain calculations were made to determine the downhole voltage and current waveforms resulting from lightning strikes directly to or near the interconnecting device cables. In 1974 an electromagnetic analysis program² was used to study how several distributed models of the system would respond to a direct lightning strike. Both studies^{1,2} concluded that the magnitude of energy produced by a direct or nearby lightning strike to the device cables (and reaching the high explosive and its detonators) was small compared to the energy required to produce a detonation. These studies also served as the principal references for a 1975 NESS committee,³ which concluded that the proposed nuclear explosive operations (the subject of that NESS) "provided adequate nuclear explosive safety" where lightning was a threat.

In response to the recommendation of a 1982 NESS,⁴ the Laboratory established a three-person task force to reevaluate the lightning vulnerability of nuclear explosive test devices. This task force was chartered to:

- Immediately identify any serious deficiencies.
 - Determine if the 1973¹ and 1974² studies were still valid in light of present-day knowledge.
 - Identify the most vulnerable phase of the nuclear test operation.
 - Recommend improvements to enhance the safety of nuclear explosive systems.
 - Recommend a method for verifying the effectiveness of these improvements.
- The recommendations, conclusions, and details considered by the task force are contained in Ref. 5.

Background

Natural environment

The 3000-km² (approximate) area of remote high desert country that forms the Nevada Test Site is located 180 km north of Las Vegas. This area contains wide flat valleys (flats), flat-top mesas, and mountains. Although the area experiences most lightning activity from May through September, occasional lightning can be observed throughout the year. During summer, the mountainous terrain and hot desert combine to produce strong updrafts of heated air that contribute to the formation of cumulonimbus (thunder) clouds. Summer's frontal storms generally move up the Colorado River Valley, bringing moisture from the Gulf of California, while the cyclonic storms of winter typically approach from the mountains to the northwest. The isokeraunic chart, which depicts the annual number of thunderstorm days (any day on which thunder is heard at least once at a designated observation point) for this region, shows that the NTS should, on the average, experience 20 thunderstorm days per year. During the summers of 1971 and 1972, a study to characterize lightning activity at the NTS⁶ concluded that the order of magnitude of thunderstorm days

was the same as that presented by the isokeraunic chart. However, investigators found that the number of lightning strikes to ground was, per square kilometer, 50 to 100 times greater for the mesas than it was for the flats. Actual observations at the McCarran International Airport in Las Vegas reported 23 thunderstorm days in both 1978 and 1980.

Test environment

Each test operation (*event*) at the NTS takes place on the flats (elev. ~ 1.2 km) or on a mesa (elev. ~ 2.2 km), at a site containing an area known as ground zero (GZ). This GZ is centered approximately around the point of detonation. During the months required to prepare for an event, the GZ undergoes many changes (Fig. 1). The task force considered only the residence time of the nuclear explosive test device when determining the most vulnerable phase of the GZ operation.

At device delivery time, about two weeks before shot day, one or two all-metal installation buildings and cranes are in place (Fig. 2). Then the nuclear explosive test device, which has been assembled at a special NTS facility, is delivered to the GZ and moved into the device installation building. There it is mounted inside a cylindrical structure (device system pedestal) that also contains the arming and firing (A&F) and ancillary components. During an event, the A&F components receive remotely controlled electrical power and produce the signals required to fire the detonators that initiate the detonation. Device cables (typically nine) enter the device system pedestal through its steel lid and are terminated with terminal strips and connectors. Smaller conductors and cables carry the power and signals to their final destination. An insulated grounding cable of solid copper enters with the other cables and is bolted to the pedestal. Later in the installation process, the pedestal is covered with aluminum skins and inserted into a steel canister. A separate canister containing diagnostics systems is housed in the diagnostics building and is subsequently bolted to the device canister to form the test assembly.

The uphole (ground-level) portions of the A&F, instrumentation, control, and diagnostics systems are housed in large, metal-bodied trailers in the recording trailer park (RTP), approximately 300 m from GZ. These trailers are connected to the test assembly by means of 25 to 100 coaxial

and multiconductor cables (up to 1.4 km in overall length) that are laid out on the ground. One of the trailers—the Red Shack through which all downhole device system cables must pass—is initially located near the emplacement hole and later moved, before shot day, to the RTP.

The completed test assembly, which may reach a length of 30 m, is suspended by a string of interconnected sections of drill pipe and lowered, by crane, to the bottom of the emplacement hole. Emplacement holes range from 1.5 to 3.0 m in diameter and from 180 to 1100 m in depth. They incorporate a steel casing that extends from the surface to a depth of 37 m and is grouted in place. Figure 3 depicts GZ at the start of a downhole operation, and Fig. 4 shows a test assembly suspended from the crane. The device system is contained within the white canister at the bottom of the test assembly.

When the lowering operation is complete, the emplacement hole is filled (stemmed) with a combination of gravel, grout, and epoxy plugs. This stemming procedure prevents the radioactive debris produced by the detonation from dispersing by containing it underground. The area near the emplacement hole is gradually cleared until only a short length of drill pipe protrudes from the stemmed emplacement hole on shot day. The unburied surface run of cables terminates at the RTP.

Intended firing path

Figure 5 is a simplified but accurate representation of the more complex A&F system, showing the intended device firing path. All cables that enter the device canister originate or pass through the Red Shack. Until the last few hours before shot time, the A&F cables are disconnected and their connectors are locked in a lock box. The connectors are not terminated during disconnect so, in the event of a lightning strike, the resulting voltage peak will occur in the Red Shack rather than in the device canister.

A&F signals generated at the remote control point (and transmitted to the event site by the Command Microwave system) actuate relays in the Red Shack at specific times during the automatic countdown sequence. These relays control a dc voltage that is used to charge and subsequently trigger the capacitive discharge unit, which then fires the detonators. A major portion of each nuclear explosive safety study is devoted to ensuring that the A&F system can only be powered intentionally.

Fig. 1. Aerial view of typical event site.

Fig. 2. Ground-level view of ground zero, showing installation building, emplacement crane, and cable runs.

Fig. 3. Simplified elevation sketch of GZ facilities at start of downhole operation.

Fig. 4. Test assembly ready for emplacement.

Fig. 5. Simplified diagram of the intended device firing path.

Grounding system

A well-designed and carefully implemented low-resistance grounding system is installed at every GZ to provide personnel safety, lightning protection, and low electrical noise. The emplacement hole casing is used to "earth" the GZ single-point grounding system. Buildings and equipment are also grounded at the casing.

Results

The task force found, despite new data regarding lightning channel mechanisms and structure and faster current rates of rise, that the basic conclusions of the earlier reports^{1,2} were essentially correct. The only exception was the slower lightning current rise time used in the calculations. As mentioned previously, those conclusions were based on models that considered the effects of lightning on a device system located at the bottom of the emplacement hole.

The greatest potential hazard was found to exist when the test assembly is suspended by crane

and just entering the emplacement hole. If lightning were to strike the crane or test assembly directly, one or more of the device system cables could be punctured near the point where they enter the device canister. The system would not benefit from the high surge impedance provided by the cables when the system is emplaced downhole. Current division remote from the device canister, resulting from multipath arcing through the cable insulation to ground, could not take place. Thus, when a threat of lightning exists, emplacement operations are avoided. While the probability of a lightning strike during such operations is small, the consequences of an accidental detonation are totally unacceptable.

Inter-/intracloud lightning often induces large transient voltages in power lines and long cables. These voltages can damage unprotected electrical and electronic components or shock a person working on the unterminated end of a long cable. A conservative analysis of the effects of a 1-km long, 10-kA discharge that is 1 km high concluded that the magnitude of induced voltage to reach the device system would be small compared to that required to cause a detonation.

Recommendations

The task force made several recommendations relating to both nuclear explosive safety and the protection of uphole electronic systems. Because the topic of their investigation was limited to nuclear explosive safety, only recommendations relating to that topic will be considered for implementation at this time. Those recommendations are:

- *Reduce transient voltages to a controllable range, using a radial counterpoise grounding system to effect a major reduction in ground resistance and surge impedance.* When a so-called "grounded system" is struck, the lightning current initially encounters a surge impedance that is at least 10 times greater than the steady-state value, thereby causing the potential of the system to be significantly higher than that of the surrounding earth. For example, a 20-kA strike (50-percentile amplitude) passing through an 80- Ω surge impedance produces a 1.6-MV transient. This can cause electrical insulation to break down and become virtually nonexistent, large transient currents to flow unpredictably, and significant damage to occur.

To reduce surge impedance, the task force proposed a radial counterpoise grounding system consisting of eight bare-copper conductors (AWG No. 2/0), 60 m in length, which would be bonded to the well casing. These conductors would be equally spaced at 45 degrees and would extend radially at a buried depth of 0.3 m. The calculated net impedance of this ground, and that of the casing alone, was 11 and 80 Ω , respectively. While the method used to obtain these values was not considered "exact science," it demonstrates the benefits of using such a grounding system. The radials would also allow the surge impedance to decay rapidly to its steady-state value. Thus, the peak amplitude of the transient voltage would be greatly attenuated and exist for a much shorter period of time.

The obvious benefits of such a grounding system were weighed against the cost and construction problems it would introduce. A closer look at the existing GZ system revealed that it approximated the recommended counterpoise system. The Red Shack, installation buildings, crane, and several other GZ facilities are grounded to the casing by means of individual buried conductors of bare copper. Although the length, quantity, distribution, and depth of burial of the radials are not the same as those of the proposed system, the present grounding design provides a surge imped-

ance lower than that of the casing alone. This is supported by actual GZ resistance measurements (casing to surrounding earth), which indicate a typical steady-state value of 5 Ω or less.

Modifying the existing grounding system is also impractical because it could not be relied on to ensure nuclear explosive safety in a lightning environment, nor be easily verified experimentally. For these reasons, it was decided that the device canister should be modified to provide all necessary lightning protection.

- *Use a fortress design to protect all device system components.* Although a topologically closed metallic surface provides perfect protection for interior circuits, practical systems require that electrical signal and power conductors penetrate that surface, which represents the worst compromise of an otherwise impervious barrier.^{7,8} With the fortress approach, sensitive components are contained within a volume enclosed by a metallic skin. Cables containing penetrating conductors have overall shields that are bonded to the outer surface of the fortress by means of 360-degree backshell connectors. Within the fortress, and close to the feedthrough connectors, each conductor passes through a hybrid transient limiting network before it is routed to its final destination.

- *Use a hybrid limiter network to limit transient voltage.* The input portion of a hybrid limiter network consists of either a metal oxide varistor (MOV) or a gas-filled spark-gap tube that is shunt-connected from the conductor to a low-impedance ground (Fig. 6). When balanced pairs are involved, a line-to-line transient limiting component is also employed. This is followed by a series component (inductor or resistor) and by shunt-connected, bipolar avalanche diodes (Tranzorb). Under normal operating conditions, the shunt components present an extremely high impedance to ground, and the series component offers a very low impedance.

When a lightning stroke attaches itself to one or more of the cables, the current divides. The path from the outer shield to the outer skin of the fortress represents a significantly lower surge impedance than that provided by the conductors and their transient limiter networks. Most of the current will flow from the shield to the outer skin and from there find its way to earth. Even if the skin were to rise momentarily to a very high potential with respect to earth, the interior would remain at an essentially equipotential state. The remaining current (about 10%) on the inner conductors will see the impedance of the limiter series element, as well as the surge impedance of

Fig. 6. Block diagram of hybrid transient limiter.

the conductors beyond the limiter. Once the voltage appearing across the Transorb exceeds the breakdown value, the series impedance element is essentially grounded. The Transorb responds in nanoseconds and is capable of carrying a sizable amount of transient current. As the current continues to rise, the voltage across the series impedance quickly reaches the spark-gap or MOV breakdown value. Essentially all of the remaining current is then conducted to ground. While the MOV and spark gap are slower to act, both are capable of accommodating very large amounts of transient energy.

- *Modify the device canister to incorporate the fortress concept for improved lightning protection.* A modified device canister—lightning-invulnerable device system (LIDS)—has been designed and fabricated to incorporate the fortress concept. Figure 7 shows a simplified comparison of the LIDS and the present canister design. The outer shields of the coaxial and multiconductor cables are bonded to the lid of the canister by means of 360-degree backshell connectors, and the safety ground cable is bolted to the outside of the lid. So that the ground conductor will not penetrate the fortress, a thru-bolt is not permitted. To ensure this, the ground cable inside the canister is bolted to a different portion of the lid's inner surface. Special transient limiter modules (for the multiconductor cables) and coaxial limiters (for the coaxial cables) are being developed by several manufacturers. Spark-gap and MOV input limiters and resistor and inductor series impedances will be evaluated.

Simulated lightning tests

The LIDS will be subjected to a series of simulated lightning tests conducted by the Lightning Transient Research Institute. These tests are designed to evaluate several hybrid transient limiter designs, determine the most vulnerable lightning attachment point, and obtain data that will substantiate the lightning-invulnerable claim. Subsequent tests to observe LIDS performance using a double-exponential current pulse that combines high current with a fast current rise time may be performed at Sandia National Laboratories' lightning simulator facility.

The limiter designs will first be tested to verify their performance at the specified limiting levels. Then several will be tested at levels increasing up to 50 kA to determine their failure levels and modes. The final tests will be made on the complete LIDS, with the limiters terminated by typical load impedances. Low-level coupling tests (20 kA and 20 kA/ μ s) will be used to determine mutual inductance and resistance parameters for the system. Increasing peak currents and rates of rise, up to maxima of 200 kA and 200 kA/ μ s, will be applied separately. A damped oscillatory current pulse will be used to avoid the damaging effects of the lightning-like double-exponential current pulse. Lightning attachments to various cable shield and conductor configurations will be made approximately 1 m from the lid.

Fig. 7. Simplified sketch showing comparison of the lightning-invulnerable device system (LIDS) and the present device canister.

Conclusions

The lightning vulnerability of a large and complex operation has been evaluated, and recommendations for improvements have been made. Because of the unacceptable consequences of a lightning-induced detonation of a nuclear test device, several commonly used protection techniques were determined to be of little use. Thus, the decision was made to emphasize the design of a lightning-invulnerable environment for the test device system. The effectiveness of this system

will be tested later this year, using full-threat-level simulated lightning. As time and funds permit, those portions of the event system that are not nuclear-safety critical will also receive improved protection.

References

1. F. A. Fisher, *Lightning Hazard Study*, General Electric Company, Environmental Electromagnetics Unit, Corporate Research and

- Development, Pittsfield, MA, 1973. Prepared for U.S. Atomic Energy Commission, Nevada Operations Office, Las Vegas, NV, under contract No. AT(26-1)-594.
2. J. P. Luetze, *Lightning Hazards Study of Nevada Test Site Arming and Firing System*, Sandia National Laboratories, Albuquerque, NM, SLA-74-0070 (1974).
 3. *Nuclear Explosive Safety Study of the Effect of Lightning on LLL Nuclear Explosive Operations at the NTS*, U.S. Energy Research and Development Administration, Las Vegas, NV (1975).
 4. *Nuclear Explosive Safety Study of the LLNL Arming & Firing and Timing & Control Systems and Operations at the NTS*, U.S. Department of Energy, Nuclear Operations Branch, Las Vegas, NV (1982).
 5. R. T. Hasbrouck, J. P. Johnson, R. J. Burton, S. R. Crawford, and J. D. Robb, *Final Report of the Nuclear Explosive Lightning Vulnerability Task Force*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-15618 (1984).
 6. K. Buset and K. W. Price, *Lightning Flash Densities and Calculation of Strike Probabilities to Certain Vulnerable Installations at the Nevada Test Site (NTS)*, Los Alamos Scientific Laboratory, Los Alamos, NM, LA-UR-74 (1953).
 7. W. Graf, J. Hamm, and E. F. Vance, "Relative Importance of Electromagnetic Shield Violations," *8th Int. Aerospace and Ground Conf. Lightning Technology Roundup*, 1983 (U.S. Department of Transportation, Fort Worth, TX, 1983).
 8. W. Graf and J. E. Nanecivz, "Topological Grounding Anomalies," *8th Int. Aerospace and Ground Conf. Lightning and Static Elect., Lightning Technology Roundup*, 1983 (U.S. Department of Transportation, Fort Worth, TX, 1983), p. 9-1.

A Computer Model of the MFTF-B Neutral Beam Accel DC Power Supply

J. H. Wilson

We have developed a successful computer model for the MFTF-B Neutral Beam Power Supply System (NBPSS) Accel DC Power Supply (ADCPS). The computer model is necessary to adequately understand the power supply's behavior over a wide range of load conditions and faults.

Introduction

Because of the complex behavior of the MFTF-B Neutral Beam Power Supply System Accel DC Power Supply, we developed a computer model to adequately understand the power supply's behavior over a wide range of load conditions and faults. We used the SCEPTRE circuit modeling code to model all the circuit components and parameters as well as some of the stray values.

When using a circuit-modeling code for a system with a wide range of time constants, it can become impossible to obtain solutions for all time ranges simultaneously. The model has been well validated for transients with times on the order of milliseconds or longer. The computer modeling effort concentrates on the ms-range transients, because the compensating capacitor bank tends to isolate the power supply from the load for faster transients. Attempts to include stray circuit elements with time constants in the microsecond and shorter range have had little success because of the huge increases in computer time.

Power supply

Figure 1 is the single-line diagram of the ADCPS. The power supply is rated to furnish 95 kV dc at 88 A dc for pulses up to 30 s duration, with a pulse repetition rate of 1 pulse in 5 min. Primary power control is performed by a metalclad switchgear assembly, including a line switch with current-limiting fuses, a high-speed vacuum circuit breaker, and a step-start contactor. When the power supply is energized, the step-start contactor switches in a resistance of 37.8Ω per phase for the first 100 ms. After this time delay, the vacuum circuit breaker closes. The step regulator is a three-phase autotransformer with tap changing under load, providing output at 6.9 kV to 13.8 kV for 13.8 kV input. The rectifier

transformer has an extended delta primary and two secondaries, one wye- and one delta-connected. The rectifier bridges associated with each secondary are connected in series to provide 95 kV dc output. The transformer impedance is 20% on a 8872 kV·A base. The rectifier assembly includes the rectifier diodes and associated snubber components, a voltage divider, a current shunt, and a dc overcurrent relay.

Modeling objectives

The ADCPS model meets the following objectives: (1) to provide a source of data on the steady-state performance of the ADCPS, including output voltage-current characteristics and ac system load characteristics; (2) to understand the transient behavior of the ADCPS for conditions ranging from dc steady-state to transients with time on the order of 100 μ s; (3) to study fault conditions of the ADCPS, including dc and ac short circuits, voltage surges, and shorted and open components.

Model description

Of the circuit-analysis codes available to us, SCEPTRE offers the most powerful capability to design and specify nonlinear models for devices with arbitrary transfer functions. SCEPTRE allows an integrated model of the entire accel-voltage system to be constructed. Extensive use is made of the SCEPTRE program's model capability to simplify and clarify the circuit structure.¹ Figure 2 shows the overall circuit diagram and the interconnection of the various models.

The computer model includes these subsystems: switchgear, step regulator, rectifier transformer, power factor correction, and rectifier assembly. The functions of the metalclad switchgear are modeled: a line switch with current-limiting

Fig. 1. Single-line diagram of the ADCPS with (52) circuit breaker, (73) starting contactor, and (89) line switch.

fuses, a high-speed vacuum circuit breaker, and a step-start contactor. The impedance of the step regulator is extremely low, so it is modeled by changing the primary voltage sources driving the model.

The model of the rectifier transformer includes the leakage and magnetizing impedances of the transformer, the winding dc resistances, and the bushing capacitances. Two 4000- Ω resistors are added to the model to lengthen time constants associated with the 296-pF bushing capacitances CD and CY, because numerical instabilities result without some damping at this point in the circuit.

The 1.2- μ s time constant that results from this resistance is well below the time regime of interest, but this constant is very effective in reducing computation time. Values for the self and mutual inductances are chosen from test data taken from the first rectifier transformer during short-circuit testing. No attempt is made to model the distributed inductances and capacitances of the transformer because of the time considerations described above. To avoid complexity, the transformer is modeled as if the primary were a simple delta connection instead of the extended delta actually used.

The power factor correction capacitors are modeled as a straightforward lumped model of the nominal component values, including the internal bleeder resistor. The rectifier stacks are modeled as a single diode with a very small exponent and a relatively large leakage current. The model approximates the exponential characteristic of the large number of diodes in series that makes up the rectifier stack. The location of the rectifier assembly made it impossible to include bushing capacitances in the rectifier model; they are represented by CY1, CY2, CY3, CD1, CD2, CD3, and the associated resistors in Fig. 2.

Switching

In this model, all switching is represented by variable resistors whose value is a piecewise-linear function of time, specified as a table. In most cases the open condition is represented by a resistance of 100 M Ω , and the closed condition is represented by a resistance of 0.1 Ω ; therefore, switches can be opened and closed at arbitrary times in the run. Representing a circuit breaker in the process of opening requires three runs. In the first run, the exact time of current zero can be

Fig. 2. ADCPS SCEPTRE circuit representation.

found for the first phase to clear. The table controlling the resistor that models that pole is changed to "open" the switch at current zero, then another run is made. From the second run, the time of current zero for the remaining two poles is determined, and the tables controlling the resistors that model those poles are changed to "open" the switches at current zero. A final run is then made to give the results. These results are shown in the Electron Cyclotron Resonance Heating (ECRH) crowbar study in Fig. 3. (ECRH is one of the twenty-four ADCPS feeds.)

The ADCPS load is switched and controlled by a series modulator-regulator tube which regulates the load voltage. To the ADCPS this looks like a current sink. SCEPTRE allows arbitrarily complex functions to be defined to control the value of any component, including a current sink, so load current waveforms can be simulated and their effect on ADCPS performance studied. Figure 4(a) shows the modulator which includes a shunt compensation capacitor and a crowbar (a crowbar refers to an electronic switch which intentionally short-circuits ADCPS to protect equipment fed by ADCPS). Figure 4(b) shows how testing the ADCPS with a resistive dummy load is simulated, using a resistor which switches from an open circuit to the load resistance value of 1000 Ω .

Problems encountered

A number of components were added to the model to lengthen time constants that otherwise

Fig. 3(a). Simulated NBPS crowbar current. Note this represents a system with a 54- μ F filter capacitor.

Fig. 3(b). Measured NBPS crowbar current. At the time of this measurement a $5\text{-}\mu\text{F}$ filter capacitor was used. Note the relatively short discharge time of the initial spike compared with Fig. 3(a).

Fig. 4. Two typical load models used to simulate specific situations.

Fig. 5(a). Simulated power supply voltage sag for a 20-ms load pulse with CSHN (shunt compensation capacitor) at 5 μ F.

Fig. 5(b). Measured sag for case studied in Fig. 5(a).

would have been too short for SCEPTRE to obtain good solutions. For example, the 4000- Ω resistors in series with all of the bushing capacitances result in a time constant of 1.2 μ s, as discussed above. If too-short time constants are present, SCEPTRE either fails to find any solution or prints a "SMALLER MINIMUM TIME STEP REQUIRED" error message. When we encountered this message, we had

more success changing the circuit topology by adding some damping in an appropriate place rather than reducing the minimum time step required in the "RUN CONTROLS" section of SCEPTRE input. In every case it was possible to do this without introducing longer time constants that could jeopardize the accuracy of the simulation over the time range of interest.

Two tests provide verification of the model. One of these tests involves operating a real ADCPS feeding the accel modulator under normal load conditions; the other is a crowbar operation in which the ADCPS output is deliberately short-circuited. Figures 3 and 5 show comparisons of the simulated and actual waveforms obtained. The close agreement inspires considerable confidence in the model.

Conclusion

A serviceable computer model with reasonable limitations of a complex dc power supply was produced. The model was verified by comparing the behavior of actual power supplies. Several design decisions have already been made with the aid of the model's results. For example, an important decision was made not to proceed with power factor correction in the ADCPS, because the model result indicated that a 27- μ F shunt compensation capacitance value was adequate to control the ADCPS output voltage transient when

current is switched on without power factor correction. With power factor correction, the model showed a value over 80 μ F is needed. Also, the model confirmed field measurements that indicated the power factor was within limitations specified by the contract with the electric utility.

The model has been used as a basis for much simpler models, of very limited scope, to approximate the ADCPS behavior over a small time frame. Designs can be worked out using the simplified model, then confirmed on the detailed model. The model has also proved useful during maintenance and repair. When a fault or an unexpected transient occurs, the model can be run with voltages, currents, and other parameters measured.

Reference

1. J. C. Bowers and S. R. Sedore, *SCEPTRE: A Computer Program for Circuit and Systems Analysis* (Prentice-Hall, Englewood Cliffs, N. J., 1971).

Index

This index lists the subjects and authors to be found in published EE Quarterlies and EE Technical Reviews (including this issue). The number after an item indicates the year and issue in which the item was published. For example: *Cross-borehole*, 79-1, 81-3 means the subject is in the first issue of 1979 (report No. UCRL-50025-79-1) and in the third issue of 1981 (report No. UCRL-50025-81-3).

A

Ables, E., 80-1
 Alexander, E., 75-1
 Alpha emitters, long-lived, 80-1
 Alrick, K., 75-1
 Aluminum-air battery, 82-1
 Ames, H. S., 76-2, 79-3
 Analyses, automated
 chemical, 75-3
 geological, 78-3
 Analysis and management, 79-3
 Analyzer,
 chlorine, 79-1
 Dunegan 920, 77-1
 radioisotope, 76-3
 Anesthesia, 80-2
 Antenna, unique directional, 81-3
 Argus laser, 77-2
 Arming, 77-3
 Armstrong, G. H., 79-3
 Artificial people, 80-3
 Axelrod, M. C., 78-3

B

Baker, J., 76-1, 78-3
 Balch, J. W., 75-2, 81-1
 Barlow, O. M., 75-3
 Barton, V., 75-3
 Baseball-II, 76-1
 Battery, aluminum-air, 82-1
 Behrin, E., 82-1
 Bell, H. H., 79-2
 Bengel, W. L., 75-3
 Bishop, S. R., 78-2
 Bogdanoff, A., 76-1
 Bourret, S., 75-3
 Bozorgmash, H., 81-1
 Bradley, R. T., 75-4, 76-2
 Braille, 82-1
 Brase, J., 84-3
 Brazing furnace, induction, 75-1
 Breitenbucher, P., 84-1
 Brown, B. J., 79-1
 Brown, D. R., 81-1
 Bryant, R., 84-2
 Buettner, H. M., 81-3
 Burgess, T. J., 77-2
 Bus, general purpose interface, 80-1
 Bus structure, 76-2
 Butner, D. N., 77-3

C

CAIN, 76-2
 CAMAC, 80-3, 83-3

CATV, 78-1
 CMOS, 77-2
 CTR, see Controlled thermonuclear
 Calibration, automatic, 74-4
 Candy, J., 82-2
 Carbon dioxide sensor, 79-2
 Casterson, R., 77-1, 83-1
 Castleton, R. N., 84-1
 Chau, H. H., 79-2
 Chlorine analyzer, 79-1
 Christie, D., 84-2
 Ciarlo, D., 75-1, 81-1
 Circuit diagnostics, 84-2
 Clark, J. C., 77-2
 Cleland, L. L., 77-1
 Clendenen, L. D., 77-2
 Coal, high speed spectroscopy
 for process control, 81-1
 Coffield, F. E., 84-3
 Communications cards, LSI-11, 84-2
 Communications link, fiber optics, 80-2
 Computer model, 77-2
 Control system, isolation, 78-1
 Control systems, MFTF, 83-1
 Controlled thermonuclear research, 76-1
 Copper resistivity, 77-2
 Coradetti, T., 84-1
 Coutts, G. W., 75-1
 Crates, CAMAC, 80-3
 Criminal diversion of
 nuclear materials, 77-1
 Criticality false alarm, 76-1
 Cross-borehole, 79-1, 81-3
 Cruise missile, computer-based
 testing of, 82-3

D

DASLL, 80-3
 Danielli, F., 80-1
 Data
 acquisition, 77-1, 80-1
 collection, 76-1
 gathering, 76-1
 handling, 79-3
 low-level signal, 82-3
 Davis, G. E., 81-2
 Deadrick, F. J., 75-2
 Delay generator, 78-3
 Detectors, time-resolved radiation, 75-2
 Diagnostics, 77-1, 79-2
 2X11B, 76-1
 Digital techniques, high speed, 78-2
 Distributed instrumentation control, 83-1
 Drill press, 79-1
 Druce, R., 84-2
 Dye lasers, 78-2

E

Electron Cyclotron Resonant
Heating, 84-3
EPA lab, 76-2
Editing, text, 77-3
Effluent characteristics, 75-3
Ekstrom, M. P., 75-1
Electro-optics, 76-3, 79-2
Electromagnetic
cross-borehole, 79-1
railgun, 80-1
Energy storage, 77-3
Equations-of-state, 79-2
Ewins, J. H., 75-2
Explosive, 79-2, 79-1

F

Fiber optics, 77-2, 80-2, 83-3
Fiber-optic data links, 81-2
Fiber-test facility, 77-1
Field-compression devices, 77-2
Fisher, E. R., 75-3
Flow cell analyzer, 75-1
Fluorometric, 78-2
Follow-up systems design, 82-3
Framing camera, 75-4
tube, 78-3
Francis, F. D., 80-3
Friesen, R. D., 76-1
Fuels, alternative transportation, 75-4
Fusion, laser, 77-2
Fuzing, 77-3

G

Gadd, T. J., 76-3
Gages, talking, 83-1
Gas-pressure diagnostic system, 81-2
General Purpose Interface Bus, see GPIB
Geologic, 78-3
Geology, 79-1
Geophysical probing, 75-2
Goerz, D., 79-1
Gordon, L., 84-2
Gozani, T., 81-1
GPIB, 80-1
Graphics, computer, 79-2
Gunn, R. C., 81-1, 82-3

H

Hasbrouck, R. T., 85-1
Hawke, R. S., 80-1
Herget, C., 80-2, 82-2
Hersey, R. J., 76-1
High voltage test stand, 78-2
High-speed photography, 75-4
High-speed radiation camera, 75-1
Hill, C., 79-3
Holloway, F. W., 75-2
Hollstein, R. B., 77-2
Huebel, J. R., 75-4
Huen, T., 75-2

Hunt, D. N., 83-1
Hunt, G. F., 80-2
Hydrodiagnostic, 77-3
Hydrodynamic test data, 79-3
Hydrogen, compressed, 80-1

I

IC, 80-1
IC, 80-3
Image intensifiers, pulsed, 75-4
Image processing, digital 75-1
Imaging, 77-1
Imaging gamma-ray cameras, tumor, 75-2
Imperial Valley, California, 78-3
Induction brazing furnace, 75-1
Interferometer phase detection, 78-2
Interferometer, microwave, 75-1
Interlocks, CAMAC-based, 83-3
Ion-implantation, 81-1
Isocon camera, 80-3

J

Jaroska, M. F., 75-4, 77-3, 82-1
Jensen, C. W., 75-3
Johnson, B. C., 76-3
Johnson, G. W., 84-1

K

Kalibjian, R., 78-3, 75-4
Kaser, J. B., 78-3
Kaufman, A. M., 81-2
Koo, J. C., 84-3
Krausse, G. I., 85-1
Kuramoto, A., 79-3

L

LGF data acquisition system, 84-1
LSI development, 75-2
LSI-11, 84-2
Lager, D. L., 75-2, 80-2
Laine, E. F., 81-3
Language aids, 77-2
Large optics diamond turning
machine, 84-1
Laser, 75-2, 75-4, 76-3, 77-2, 78-1,
79-2, 78-2, 80-2
optics, 83-1
Lathe, LeBlond, 79-1
Latorre, V. R., 80-1
Lawson, J. C., 77-3
LeBlond lathe, 79-1
Lee, F. D., 75-3, 79-2
Leighton, J., 77-1
Lightning vulnerability of nuclear
explosive test systems, 85-1
Liston, D., 77-1
Long, J. R., 76-2
Low-level signal data acquisition, 82-3
Lytle, R. J., 75-2, 79-1

M

MACRO2, 81-1
 MFECC, see NMFECC
 MFTF, 81-2, 81-3, 82-1, 82-3, 83-3
 MFTF-B power supply,
 computer model, 85-1
 MGX, 83-3
 MOS fast-switching techniques, 85-1
 MOS time-resolved radiation
 detectors, 75-2
 MOS/LSI facility, 75-1
 Machine-control system,
 programmable, 75-3
 Macro, structured, 77-2
 Magnet, superconducting, 82-3
 Magnetic fusion, 76-1
 energy, 78-3,
 Magnetic mirror fusion, 78-1
 Magnets, 79-1
 Magnuson, W. G., 80-3
 Maiten, M. S., 80-3
 Maples, M. D., 75-3
 Mass storage, 78-3
 McConaghy, C., 75-1, 75-2, 81-1
 McCue, H. K., 84-1
 McGibbon, A. L., 76-3
 McQuaid, J. H., 75-2, 79-2, 81-1
 Meeker, D. J., 75-1
 Mendell, D. S., 78-2
 Message processing system,
 automated, 75-3
 Microchannel plate x-ray spectrometer,
 ultrafast gating, 85-1
 Microcomputer, 77-2, 78-2, 79-1, 82-3
 Microcomputer, special issue, 75-3
 Microcomputer system, modular, 75-3
 Micropellet guidance, 76-1
 Microprocessor, 79-2
 LSI-11, 77-1
 Microstructure fabrication, 81-1
 Mihalka, A. M., 81-3
 Miller, E. K., 75-2
 Minicomputer, 77-3
 bus structure, 76-2
 D112, 77-1
 Minor, E. G., 82-3
 Monitor, fast scan, 78-1
 Montoya, C., 82-3
 Mooney, L. J., 78-1
 Moore, T. L., 84-3
 Morrison, J., 75-1
 Mullenhoff, D., 81-3
 Multiprocessor, debugging, 81-2

N

NAD system, 75-1
 NC machine tool, see Numerically
 controlled
 NC, see Numerically controlled
 NMFECC, 77-1
 NTS diagnostics, 75-1
 NURE program, 78-3
 National MFE computer network, see
 NMFECC

Networking microcomputers, 80-1
 Neutral beam, 82-1
 injectors, 76-1
 ion-density profile, 78-1
 power supply, 78-1, 81-3
 protection circuits, 83-3
 Neutron monitoring, 76-1
 Neutron, portable spectrometer, 80-2
 Neutron-gamma field, 80-2
 Newton, L. E., 76-2, 79-1
 Niven, W. A., 82-1
 Nova laser, 80-2, 84-2
 Nuclear science data production
 facility, 83-1
 Nuclear test, underground, 77-1
 Nuclear waste repository, 81-2
 Numerically controlled machine
 tool, 76-2, 76-3

O

O'Brien, D. W., 83-1
 Octopus, line switching
 Oicles, J. A., 85-1
 Oil shale, 82-1
 Olk, L. B., 75-1
 Olken, H., 75-3
 Optics, high power laser, 83-1
 Oscilloscope,
 dual raster, 77-3
 fast-transient, 75-3
 Oxidants, photochemical, 78-3

P

Pavel, G., 84-2
 People, artificial, 80-3
 Peratt, A. L., 75-2
 Phase detection interferometer, 78-2
 Photochemical oxidants, 78-3
 Photodetector, 79-2
 Photometer, a scanning reflection
 transmission, 83-1
 Plasma diagnostics, 82-1
 Pocha, M., 81-1, 84-3
 Pockels cell, 76-3
 Pollock, G. G., 76-1
 Pomernacki, C. L., 79-1, 80-1
 Portnoff, M., 82-2
 Power supplies, 82-1
 Pressure switch, subnanosecond
 MOS, 75-4
 Printed circuit board, 77-1,
 layout, 80-3
 Pulse generator, 84-2
 Pulse height analyzer, high speed, 82-1
 Pulse-power, 78-1
 Pulsed image intensifiers, 75-4

R

Rabbit, 75-3
 Radiation camera, high-speed, 75-1
 Radiation detectors, time-resolved, 75-2
 Radioisotope analyzer, 76-3
 Rail-gap switch, 84-2

- Railgun, 80-1
- Reactors, 80-1
- Recorder, on-board, 82-1
- Recording, high-velocity, impact, 82-1
- Rectifier transformer, 81-3
- Relativistic beam, 77-2
- Retorts, 82-1
- Ring seating, 84-1
- Robinson, W. F., 83-1
- Ronchetto, J. J., 82-1
- Rotating turbine camera controller, 84-1
- Rotter, M. D., 81-2, 83-3
- Route profile analysis, 81-3
- Rufe, R. P., 78-1
- Rupert, P. R., 78-1

S

- Safety, machining 79-1
- Safing, 77-3
- Scarafioti, J. J., 83-3
- Scarpetti, R. D., 83-3
- Sensor, carbon dioxide, 79-2
- Severyn, J. R., 77-2, 80-2
- Sewall, N. R., 75-4, 77-1
- Shaker control, 75-2
- Shiva, 78-1
- Shock-wave-velocity measurements, 75-4
- Signal and Control Engineering, 82-2
- Smith, B. H., 76-1
- Smith, M. E., 78-2
- Smith, R. J., 77-1
- Software debugging tool, 81-2
- Solder-joint reliability, 76-1, failures, 76-1
- Spann, J. M., 75-3, 81-2
- Sparks, D. F., 80-3
- Spectrometer,
 - gamma ray, 76-3,
 - portable neutron, 80-2
 - x-ray, 76-3
- Spectroscopy, 81-1
- Sphere-winding machine, 75-4
- Spracklen, H. P., 82-1
- St. Leger-Barter, G., 75-1, 75-4
- Steinmetz, L. L., 75-1, 79-2, 78-2
- Strauch, M. S., 83-3
- Streak camera,
 - isocon, 80-3
 - x-ray, 75-1
- Substation, 230-kV, 81-3
- Superconducting cable, 79-3
- Surgery, 80-2
- Switches, high speed, 84-3
- Switching, high power, 76-2
- Synthesizer, voice, 83-1

T

- TMX, see Tandem Mirror Experiment
- Tandem Mirror Experiment,
 - 79-1, 81-2, 84-3
- Technology transfer, 75-3
- Temperature control, 75-1
- Test, nuclear, 79-2
- Testing, short circuit, 81-3
- Text editing, 77-3
- Thermometry, 82-1
- Thomson scattering, 75-2

- Three-dimensional images, 75-4
- Thrust area, 82-2
- Time-resolved radiation detectors, 75-2
- Transient
 - electromagnetics measurement, 75-2
 - high-speed recording of, 81-1
 - output current, 82-3
 - recorder, 79-3
- Transportation, alternative fuels, 75-4
- Transuranics, 80-1
- Tumor, 75-2
- Twogood, R., 82-2
- Tyler, G. C., 76-1

U

- U. S. Postal Service, 81-3
- Ultrasonic, 82-1
 - inspection of superconducting cable, 79-3
 - test bed, 84-3
- Underground caverns and tunnels, 81-3

V

- Van Ness, H., 82-3
- Victor, R. A., 76-2, 79-3
- Video playback facility, 81-1
- Vogtlin, G., 84-2
- Voice synthesizer, 83-1

W

- Warhus, J., 82-3
- Water samples, 79-3
- Waugh, A. F., 78-1
- Weapon control, 75-2
- Weiskamp, T., 75-3
- Wentz, D. L., 78-3
- Werner, R. E., 82-1
- Whelan, H. A., 76-3
- Whitham, K., 77-3
- Wiedwald, J. D., 85-1
- Willows, J. L., Jr., 82-1
- Wilson, J. H., 81-3, 85-1
- Wind calculations, NTS, 75-3
- Woodruff, J., 82-1

X

- X-ray
 - medical, 75-4
 - monitor and control, 79-3
 - pulse calorimeter, 75-2
 - spectrometer, 76-3, 85-1
 - streak camera, 75-1

Y

- Young, R. H., 75-3

Z

- Zoret, R. E., 75-4

Numeric

- 2XIB diagnostics, 76-1