Producing Unipolar Lightning Waveforms to Satisfy MIL-STD-1757A

The effects of lightning strikes on aircraft can be duplicated in a specially designed test facility.

JAMES L. PRESS, R & B ENTERPRISES and
MONTY LEHMANN, CONSULTANT

INTRODUCTION

MIL-STD-1757A details a set of standard test waveforms and techniques for lightning qualification testing of aircraft. The document presents waveforms intended to represent different phases of an actual lightning strike. For qualification testing, four current waveforms, designated Components A, B, C and D, are used to determine direct effects. Component E is used to determine indirect effects. Test Method TO2 of the standard applies to structures and components in zones of the aircraft for which there is a high probability of initial lightning flash attachment, and to structures and components in the zone to which a flash will likely be swept.[1] RTCA/DO-160C, Section 23[2] specifies the same waveforms and procedures except that it does not address the Component E waveform.

A full threat lightning test facility has been developed to meet the requirements of these two standards. The design was based upon available capacitors, power supplies, and additional hardware that would allow the requirements to be met. The pulser was designed to supply the desired action integral without undue strain to components. Additional safety items, such as large volume dump resistors and heavier connections, were incorporated into the pulser design so it could better withstand the heating effects of the Component A waveform. The pulser has been tested and numerous MIL-STD-1757A and DO-160C, Section 23, tests have been performed with reliable and repeatable results.

The Component A pulser, powered by a Marx generator, is capable of driving 200 kA at 80% peak rating. The pulse is fired by pneumatic switches and arc-over spark gaps to provide a waveform whose action integral meets or exceeds the requirements of MIL-STD-1757A Component A (Figure 1). The output waveform is reproducible and is designed to perform with minimum overshoot to increase reliability and minimize maintenance. Component B is achieved using a small discrete pulser, and Component C is achieved using a standard dc power supply. Component D is achieved with an easily installed modification to the Component A Marx generator.

MIL-STD-1757A REQUIREMENT

COMPONENT A - INITIAL HIGH PEAK CURRENT

Component A has a peak amplitude of 200 kA ±10% and an action integral of $2 \times 10^6 A^2$ seconds ±20%, with a total time duration not exceeding 500 µs. These values represent a stroke whose intensity is known to be exceeded only by 0.5% of the known strikes at the time of the promulgation of MIL-STD-1757A (20 July 1983). A unidirectional waveform is preferred but oscillatory waveforms are acceptable. For maintenance and reliability reasons, a Marx generator design was used for a unipolar pulse. Component A is responsible for the blast, magnetic force, and acoustic shock effects on structures and components, so these physical constraints were accounted for in the design.

COMPONENT B - INTERMEDIATE CURRENT

Component B has an average amplitude of 2 kA ±10% flowing for a maximum duration of 5 ms and

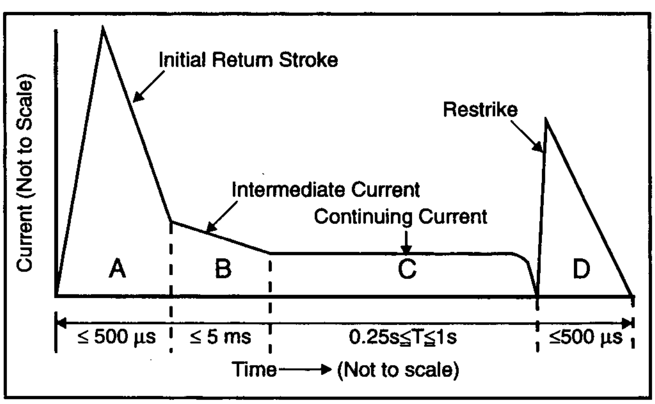

***Figure 1.** Current Waveforms.*[3]

a maximum charge transfer of 10 coulombs (C). The waveform is required to be unidirectional. An exponential decay waveform was utilized for its simplicity. The effects of the intermediate current are primarily thermal, resulting in melting of metals and burning of nonmetallic components. The main severity factor of Component B lies in the deposition of the energy in a relatively short time to simulate one lightning attachment point on a swept stroke path.

COMPONENT C - CONTINUING CURRENT

Representing the continuing current in a severe lightning flash, Component C transfers a charge of 200 C ± 20% in a time span between 0.25 and 1 second. The waveform is required to be unidirectional. A dc power supply was selected as a source of Component C due to the ability to control and regulate the waveform using this method.

Component C can cause melting of metals and burning of composites. The average rate of charge delivery is less than Component B; therefore, the amount of damage per unit of time is less than that produced by the intermediate current. This implies that Component C is more damaging to structures or components in aircraft zones 1B or 2B than elsewhere, since only the trailing edges have sufficient dwell time for the full 200 C of charge to enter the aircraft.

COMPONENT D - RESTRIKE CURRENT

Component D has a peak amplitude of 100 kA ±10% and an action integral of $0.25 \times 10^6 A^2$ seconds (±20%). This component may either be unidirectional or oscillatory with a total time duration not exceeding 500 µs. As stated, the unidirectional waveform is most desirable. Component D represents a severe restrike and its parameters are based upon data available when MIL-STD-1757A was released.

GENERATOR DESCRIPTION

DESIGN CONCEPTS

Forty-eight 500-µF, 10-kV Maxwell Model No. 32259 capacitors, along with twenty 2-µF Aerovox, 50-kV Model PX190D21 capacitors and two power supplies rated at 100 kV, 0.3 A, and 10 kV, 2 A were available. With this equipment, a Marx generator capable of an output of 200,000 A requires an erected voltage of 51 kV into the estimated circuit inductance. A design was developed in accordance with Test Method TO2 of MIL-STD-1757A. After completion of the initial design, an inventory of existing equipment indicated that only a few other items needed to be modified or reconfigured. Once the Component A generator was designed, the Component D generator would essentially be the Component A generator with modified capacitance and output resistance. The Component B generator was designed using two of the 500-µF capacitors charged to the desired voltage and discharged through an air gap. The Component C generator was essentially a Sorensen 1200-A dc power supply with appropriate switches and timing circuits.

COMPONENT A GENERATOR DETAILS

The main objective of the circuit design of the 200-kA Component A pulser was to protect and extend the useful life of the high energy capacitors. In particular, the design team was concerned with keeping the maximum charge of each capacitor to 10 kV or less and limiting the output voltage reversal during pulsing to less than 10%. If these capacitors were used to develop an oscillatory waveform, the usable life of the capacitors would be dramatically reduced. Since the replacement cost of each capacitor is approximately $1,500 and would contribute to the maintenance cost and operational capability of the pulser, an oscillatory waveform was ruled out at the early design phase of the generator.

Once the oscillatory waveform was ruled out, the next design criteria that was examined was the peak current rating of the Model 32259 capacitors. Each capacitor had a maximum rating of 100 kA. Using six capacitors in parallel for each stage of a Marx generator effectively divides the erected current by a factor of six. Therefore, each capacitor is subjected to a level of 34 kA, well below its maximum rated current. This level extends the useful life of the capacitor and reduces maintenance costs.

Based on the Component A parameters, the Marx generator produces a unidirectional pulse that rises quickly to 200 kA and then decays in less than 500 µs. The estimated inductance for the six-stage Marx generator was taken into account and additional resistance added to prevent the waveform from overshooting.

The selected charge voltage on each Marx stage is 8.5 kV to produce an erected voltage of 51 kV. Calculations showed that the action integral of this setup is $2.6 \times 10^6 A^2$ seconds. The PSpice output is shown in Figure 2 and the overall schematic is shown in Figure 3. The pulser is triggered by a pneumatic switcher built out of existing hardware.

COMPONENT B GENERATOR DETAILS

In order to meet the Component B requirements of up to 10-C charge transfer and 2-kA average waveforms, it was determined that a 1,000-µF capacitor charged to 6.5 kV would be sufficient. Since the Component A Marx required only thirty-six of the available forty-eight 500-µF capacitors, two of the spare capacitors were configured in parallel to achieve the 1,000-µF capacitance with a total charge of 6.5 kV. Monel 2-1/2" diameter threaded spheres were used as an over-voltage gap for the Component B setup. Figure 4 shows a schematic of the Component B pulser.

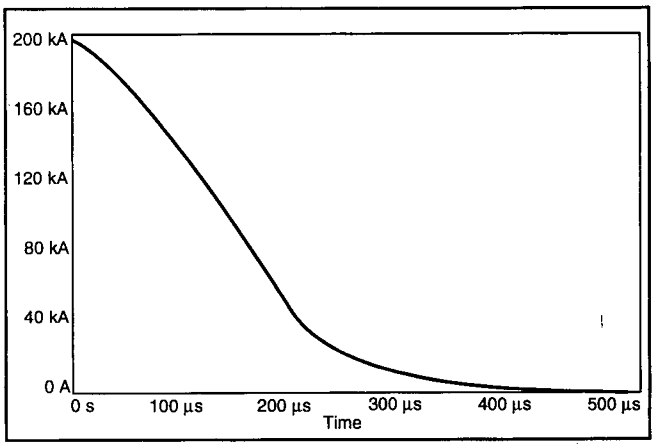

Figure 2. *Computer Simulated Output For Marx.*

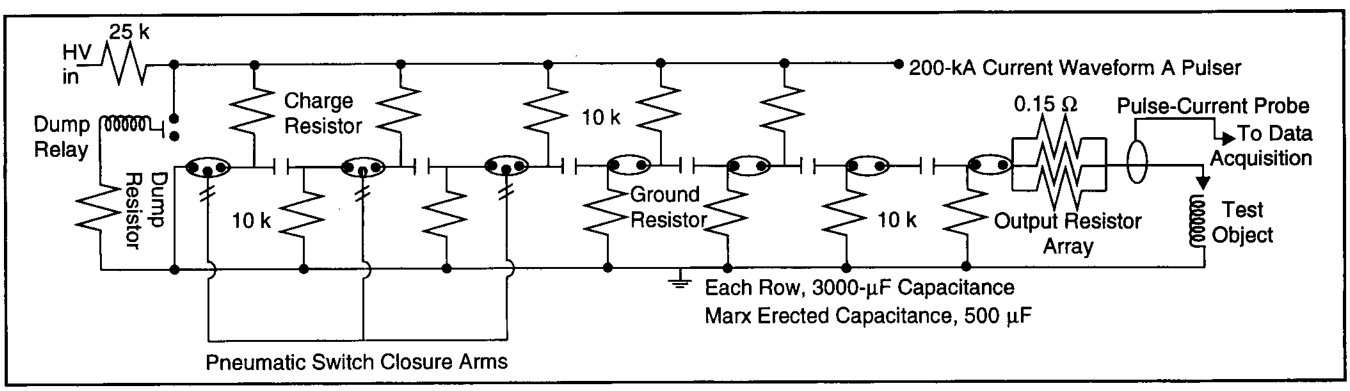

Figure 3. *Component A Marx Generator.*

COMPONENT C GENERATOR DETAILS

After review of initial designs using the forty-eight 500-µF capacitors, it was determined that using the capacitors in a bank involved both extensive reconfiguration from the Component A design and high maintenance costs. In addition, large resistors and inductors had to be constructed to keep the peak currents below 800 A and the discharge time between 0.25 and 1 second. It was quickly realized that an alternative method to a charge-and-dump type simulator was desirable. A Sorenson Model DCR20-1000A was procured after determining that this power supply was capable of supplying up to 1200 A when shorted by heavy-duty welding cables. The main difficulty was the ramp-up of the power supply, which was solved by obtaining the required current through a dummy load and then switching the output of the dc power supply to the item under test. After the output was switched from the dummy loads to the test item, a timer was set to shut down the power supply after the proper dwell time had expired. Figure 5 shows a block diagram of the Component C test setup.

COMPONENT D GENERATOR DETAILS

It was initially decided that the Component D generator would essentially be the Component A generator, modified and charged to a lower voltage, and equipped with proper resistors to meet the action integral requirement. After preliminary testing, it was determined that the Component D requirement could be met using the modified design of the Marx stages instead of the Component A configuration. This reduces the capacitance of each stage, and the erected capacitance of the Marx generator is thereby reduced. Figure 6 shows a schematic of the Component D Marx generator.

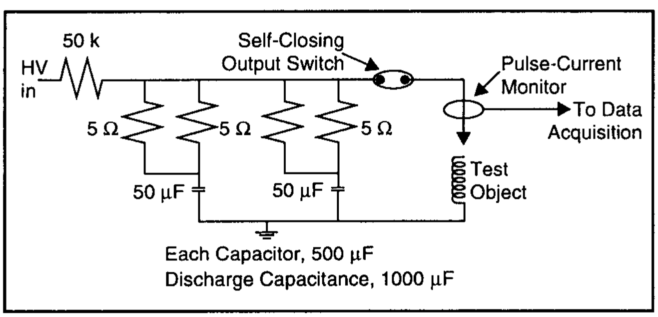

Figure 4. *Component B Pulser.*

SAFETY AND COMPONENTS

To reduce costs, pulse power resistors were not purchased. Resistors were manufactured using plastic tubing cut to a length of approximately 1 meter. The diameter of the hose was approximately 5 cm, allowing for a volume of 7,800 cm^3. By mixing the proper amount of copper sulfate with distilled water, high-power resistors were produced for a few dollars. Resistance values range from 50 Ω to 200 kΩ. The tubes have metal ends that act as electrodes and are held in place by hose clamps for ease of maintenance. These resistors are extremely cost-efficient and allow for flexible resistance values

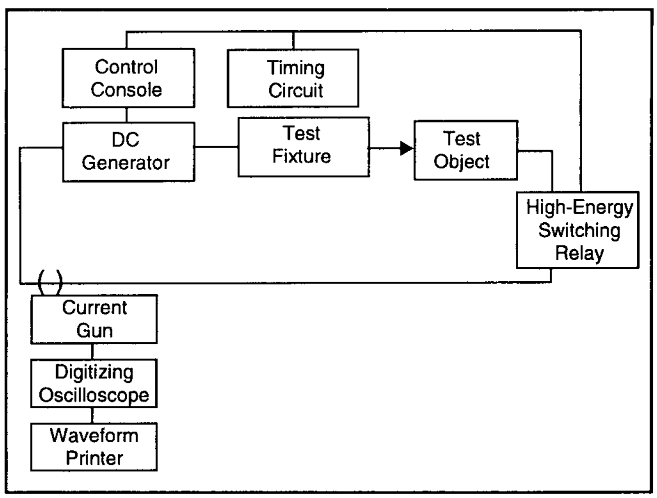

Figure 6. *Component D Marx Generator.*

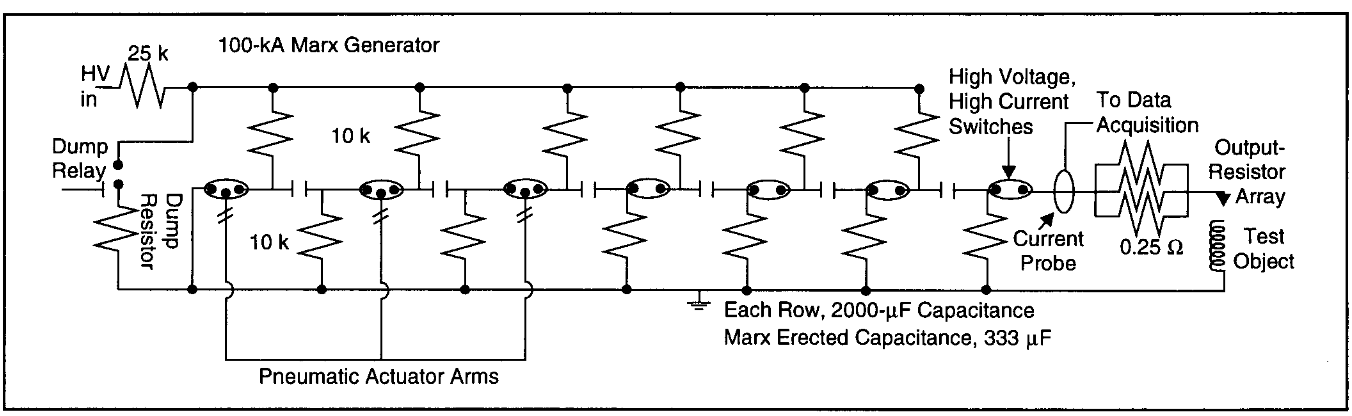

Figure 5. *Component C Diagram.*

with high wattage at a low cost.

Over-voltage spark gaps with monel electrodes are used to switch stages three through six with pneumatic actuators used to trigger the initial stages. Monel equipment is capable of handling the rapid temperature changes and shock blasts that occur during Marx erection. The heavy-duty switches allow for minimum maintenance costs and provide increased reliability and repeatable waveforms.

To prevent unauthorized personnel from entering the pulser chamber during operation, all doors are interlocked to a main safety relay. If any door is opened, the main dump relay is closed, effectively shorting the Marx to ground. Since the Marx is capable of holding over 1 MJ of energy, a 90-ohm discharge resistor is used to discharge the generator in a short time interval. This resistor is made using copper sulfate and 2.5 cu.ft. of water. Emergency stop buttons are placed throughout the lab area and inside the pulser area and target area. Engaging any of these emergency stop relays will cause the safety relay to discharge the Marx generator. An overall illustration of the direct lightning test facility is shown in Figure 7.

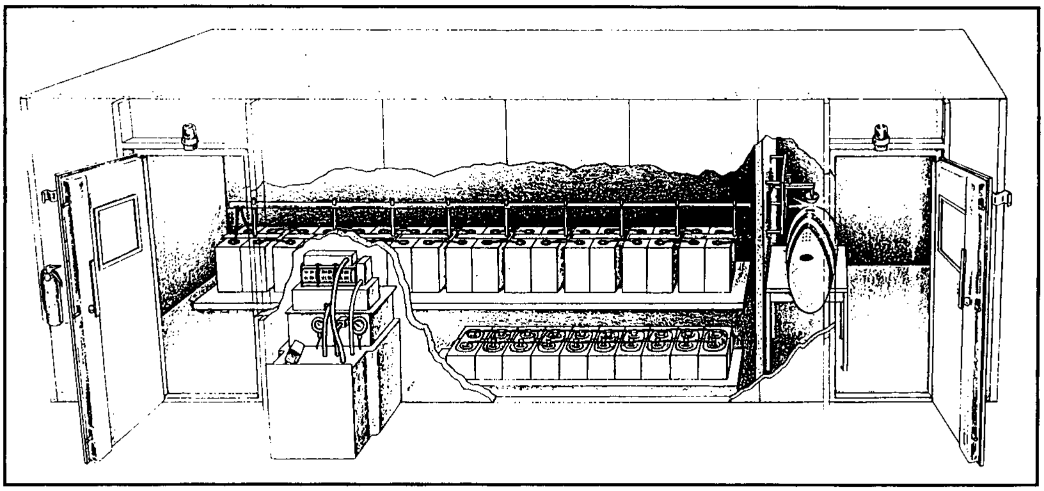

Figure 7. *Lightning Facility - Marx Room and Test Room.*

RESULTS

Figure 8 shows the final configuration of the Component A Marx generator. Figure 9 shows the waveform output of the Component A Marx generator. The output is 200 kA. A slight overshoot was adjusted by adding an additional 100 mΩ to the output section of the pulse generator. The action integral exceeds MIL-STD-1757A requirements with the generator operating at approximately 80% of full voltage capability. The Component A pulser posed a problem due to the output arc which exhibits a great deal of arc blast pressure. If the test sample was mounted on a flat plate, the arc blast could affect the status of the test sample. Test samples are therefore mounted on an elevated pedestal with a sharply pointed output electrode placed approximately 5 cm above the test object as per Test Method TO2. The pulser is charged with the 10-kV, 2-A dc power supply. Charging takes approximately 8 minutes through the charging resistor array.

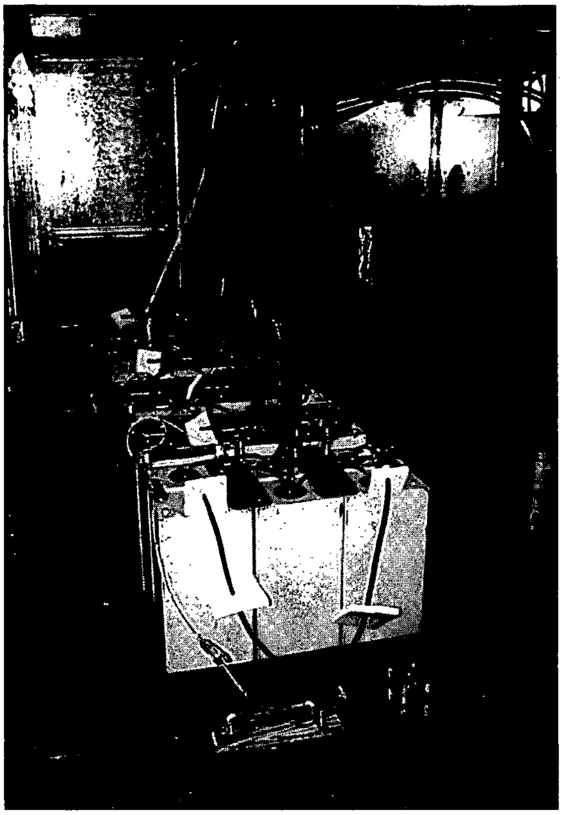

Figure 8. *The Final Configuration of the Component A Marx Generator.*

Figure 10 shows a typical output for the Component B generator, which has a peak amplitude of 4 kA and a total charge transfer of 10 C. The

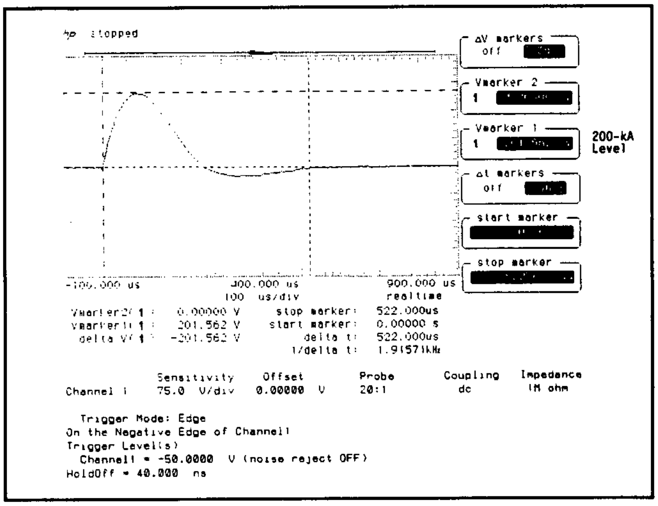

Figure 9. Component A Marx Output.

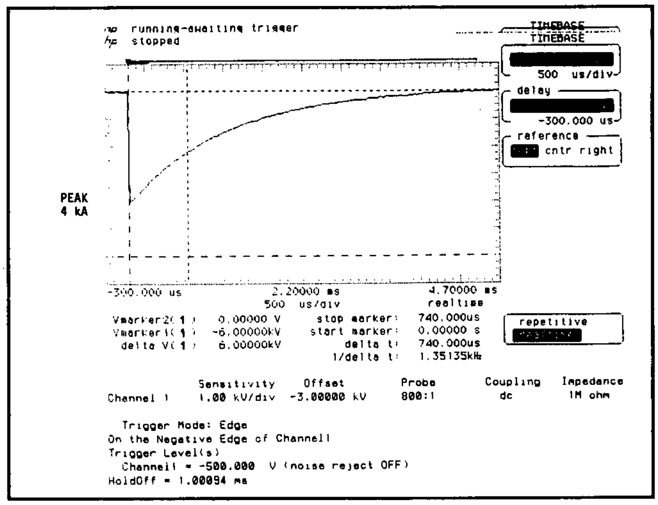

Figure 10. Component B Pulser Output.

waveform has a duration of approximately 4.7 ms. The capacitor bank shown in Figure 4 is charged to 6.5 kV, then discharged through an output probe placed over the face of the test object. The pulser is charged with the 10-kV, 2-A dc power supply.

Figure 11 shows the output waveform obtained from the Component C generator. The waveform supplies a 200-C energy transfer by generating a 200-A dc level for 1 second. A 1-second time relay is attached to a larger switching relay allowing for

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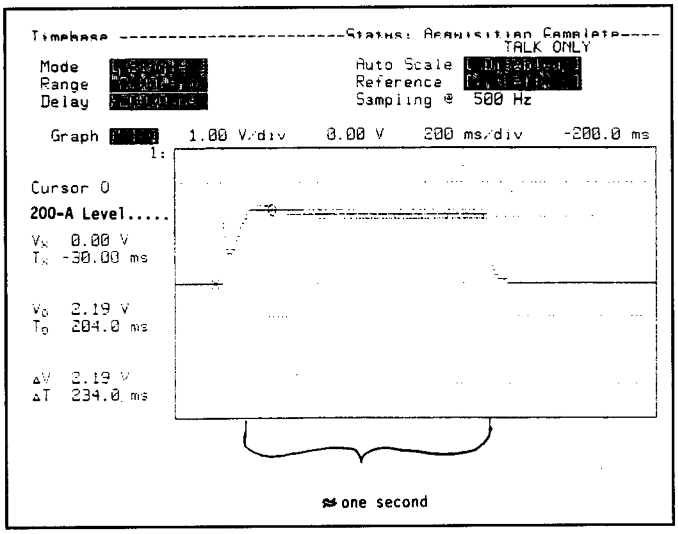

Figure 11. *Component C Test Setup Output.*

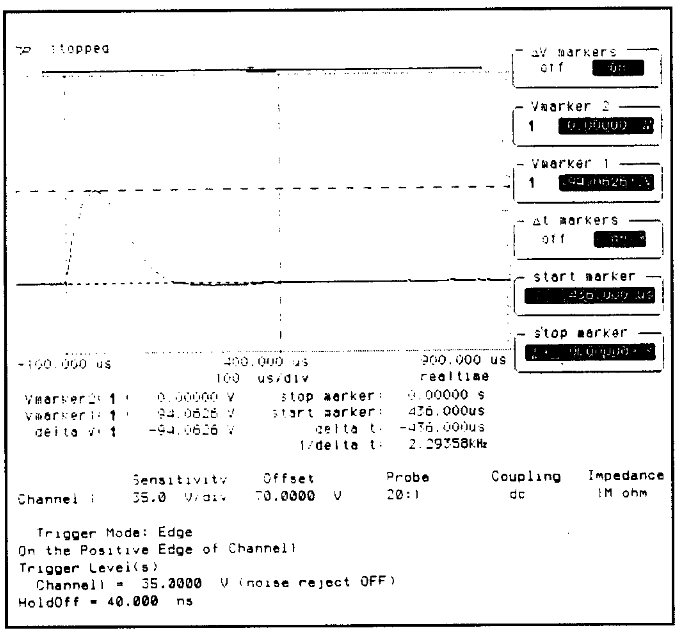

Figure 12. *Component D Marx Output.*

the test object and the load to be switched at the required 1-second intervals. This method proves to be capable of generating the waveform required and is very repeatable. An 800-A level for 0.25 seconds can also be developed for satisfying Component C requirements.

Figure 12 shows the output of the Component D Marx generator with a peak amplitude of 100 kA. The action integral exceeds MIL-STD-1757A requirements. The same injection technique used for Component A test samples is also employed for Component D testing.

FUTURE DESIGNS

With the completion of the Components A, B, C, and D test generators, and successful completion of testing for various commercial customers, a Component E waveform can now be built to meet the requirements of MIL-STD-1757A. To meet this requirement, the 50-kV, 2-μF capacitors that are presently available in the lightning facility will be used. In addition, an investigation into using inductor storage techniques for meeting Components A and B voltage requirements of MIL-STD-1757A is underway. A new design is also presently being developed for a 300-kV ESD generator per MIL-STD-331A.

CONCLUSION

A lightning test facility capable of meeting all the requirements of MIL-STD-1757A, Components A, B, C, and D, has been successfully designed, constructed and finalized. The design allows for repeatable test waveforms with a minimum maintenance time required on each generator. The test facility has been successfully utilized to meet the MIL-STD-1757A requirements. Future plans include Component E test generators, voltage Components A and B test generators, and a MIL-STD-331A, 300-kV ESD pulser.

REFERENCES

1. MIL-STD-1757A, Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware: DoD, June 17, 1990.
2. RTCA/DO-160C, "Environmental Conditions and Test Procedures for Airborne Equipment," Section 23- Lightning Direct Effects:September 27, 1990.
3. MIL-STD-1757A, p. 9.

JAMES L. PRESS *is the engineering services manager at the EMC Science Center, Inc., West Conshohocken, PA. He oversees over 300 projects each year involving EMI, lightning, EMP and other EMC related disciplines. Projects involve analysis, design, testing, and documentation of various commercial and government programs. He has designed numerous EMI, EMP, lightning, and other transient test equipment throughout his career. He has a Bachelor's degree from Temple University, Philadelphia, PA and a Master's degree from Iowa State University, both in Physics.*

MONTY LEHMAN *is a senior consultant to the EMC Science Center, Inc., West Conshohocken, PA. He has over 20 years of experience in pulse power and has designed, built, and tested many high current, high voltage pulse generators. He designed and implemented the MIL-STD-1757A lightning test facility at the EMC Science Center lightning test laboratory. Prior to this position, he was the lead contract engineer at the Naval Lightning Laboratory, Patuxent River, MD, operated Hermes II at the Sandia National Laboratory and worked on various programs for Maxwell Laboratory, San Diego, CA.*