ORNL/Sub--84-89642/1

DE86 007069

ORNL/Sub/84-89642/1
Dist. Category UC-97

DESIGN CONCEPTS FOR A PULSE POWER TEST FACILITY
TO SIMULATE EMP SURGES IN OVERHEAD POWER LINES

PART I
FAST PULSE

A. Ramrus

Prepared for the U.S. Department of Energy, Assistant
Secretary for Conservation and Renewable Energy, Office
of Energy Storage and Distribution, Electric Energy
Systems Program.

Date Published - February 1986

Report Prepared by

Maxwell Laboratories, Inc.
8888 Balboa Avenue
San Diego, California 92123-1577
under
Subcontract No. 19X-89642V

for

P.R. Barnes, Technical Manager
Power Systems Technology Program
Energy Division
Oak Ridge, Tennessee 37831
operated by
Martin-Marietta Energy Systems, Inc.
P.O. Box M
Oak Ridge, Tennessee 37831
for the
U.S. Department of Energy
Under Contract No. DEAC05-84OR21400

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.

i/ii

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

1
2
3

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION -- FAST PULSE EMP	1-1
1-1 Background	1-1
1-2 Specifications	1-5
1-3 Report Organization and Approach	1-7
1-4 Summary of Results	1-7
2 REVIEW OF TECHNICAL OBJECTIVES	2-1
2-1 Electrical Parameters	2-1
2-2 Simulation Concepts	2-5
3 Pulser Design for Components Testing	3-1
3-1 General Discussion on Design	3-1
3-1.1 Exponential Decay	3-1
3-1.2 Marx Pulser	3-1
3-1.3 Peaking Circuit	3-2
3-2 Unpowered Components	3-5
3-2.1 High Voltage Interface	3-5
3-2.2 Marx Energy versus Pulser Impedance	3-8
3-2.3 Effect of Long Pulse on Design	3-8
3-2.4 Conformity with Specifications	3-14
3-2.4.1 Impedance	3-16
3-2.4.2 Jitter	3-16
3-2.4-3 Prepulse	3-17
3-2.4-4 Rise Time	3-18
3-2.4-5 Reproducibility	3-19
3-2.4-6 Pulse Rate	3-21
3-2.4-7 Variability	3-22
3-2.4.8 Test Object Excitation	3-22
3-2.4.9 Polarity	3-23
3-2.4.10 Multi-Point Testing	3-23
3-3 Powered Components	3-24
3-3.1 Effect of Long Pulse (10 to 30 μ s) on Design ...	3-32
3-3.2 Conformity with Specifications	3-36
3-3.2.1 Decay Time	3-36
3-3.2.2 Overshoot	3-36
3-3.2.3 Rise Time	3-36
3-3.2.4 Multi-Point Tests	3-37

TABLE OF CONTENTS (Concluded)

<u>Section</u>	<u>Page</u>
4 PULSER DESIGN FOR POWER LINE TESTS	4-1
4-1 Tests on Unpowered Tests	4-1
4-1.1 General Considerations	4-1
4-1.2 Impedance	4-2
4-1.2.1 High-Voltage Properties	4-5
4-1.2.2 Multiline Tests	4-10
5 SYSTEM CONSIDERATIONS	5-1
5-1 Summary of Test Objectives	5-1
5-2 Test Configuration	5-1
5-3 Diagnostics	5-2
6 REVIEW OF STATE OF THE ART	6-1
6-1 Pulser Technology	6-1
6-2 EMP Testing	6-2
6-3 Facilities	6-3
7 CONCLUSIONS AND RECOMMENDATIONS	7-1
7-1 General	7-1
7-2 Program Plan	7-3
7-2.1 Component Tests - Pulser	7-3
7-2.2 Coupling Devices	7-3
7-2.3 Long Pulse Decay	7-3
7-2.4 Long Pulse Coupling	7-4
7-3 Power Line Testing	7-4
7-3.1 Wire Line Transition	7-4
7-3.2 Electromagnetic Modeling	7-4
7-3.3 Coupling the 1 μ s Decay to AC or DC Lines	7-4
7-3.4 Long Decay	7-4
7-3.5 Long Decay Coupling on Powered Lines	7-4
8 BIBLIOGRAPHY	8-1

LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1-1. Power lines and components exposed to effects of EMP	1-2
1-2. Capacitive source C discharges into a load resistance R_L which is small compared to the output impedance Z_O	1-4
1-3. Conceptual design of a 4 to 5 MV oil-immersed pulser consisting of a Marx generator, a peaking capacitor, and a resistant network for appropriate V_{OC} and I_{SS}	1-8
2-1. Definition of rise time, first decay, and second decay	2-2
2-2. Waveshape is generated at a resistance (R_L) low compared to the output pulser impedance, Z_O	2-3
2-3. Simulator concept in which a free-field radiating pulser exposes the power line and components to EMP	2-6
2-4. Transformer for current injection into a conducting cable ..	2-8
3-1. Simplified peaking circuit	3-3
3-2. Typical bushing design for oil-to-air high-voltage interface	3-6
3-3. Typical field plot to evaluate high stress areas in an oil-to-air bushing	3-7
3-4. Energy versus load resistance for a 5 MV pulser with 1 and 2 μs decay times	3-9
3-5. Marx peaking circuit and auxiliary pulser to generate second decay	3-10
3-6. Computer simulation of $V_{OC}(t)$ showing the blending of a waveform with fast rise time and 1 μs decay, followed by a 30 μs decay	3-13
3-7. Laser triggered crowbar switch operated at Sandia and Maxwell	3-15
3-8. Conceptual design of a 5 MV, coupling capacitor	3-25

LIST OF ILLUSTRATIONS (Concluded)

<u>Figure</u>		<u>Page</u>
3-9.	Circuit consisting of Marx peaking capacitor long pulse shaping and coupling capacitor	3-27
3-10.	Output current through short-circuited coupling capacitor for comparison with capacitively coupled waveforms to follow	3-28
3-11.	Short-circuit current through 5 nF coupling capacitor, showing reduction of pulse width compared to Figure 3-10 ...	3-29
3-12.	Short-circuit current through 20 nF coupling capacitor showing slight reduction in pulse width compared to Figure 3-10	3-30
3-13.	Voltage across 5 nF coupling capacitor due to output current pulse	3-33
3-14.	Voltage across 20 nF coupling capacitor due to output current	3-34
3-15.	A coupling capacitor connected to each of three powered-up terminals on a test object	3-38
3-16.	A spark-gap switch and interrupter connected to each of three powered-up terminals on a test object	3-38
4-1.	Waveshape when pulser discharges into a 100 ft section of 400 ohm transmission line	4-3
4-2.	Conceptual design of an overhead power line test configuration	4-4
4-3.	Waveshape when pulser discharges into a nonuniform line with 11 sections of $350 \text{ ohm} < Z < 400 \text{ ohms}$	4-6
4-4.	Cylinder-over-plane impedance versus height	4-7
4-5.	Electric field on inner conductor with 5 MV applied to inner conductor with radius r_1 surrounded by insulating sheath ($k = 2.5$) with radius r_2 within outer conductor of radius r_3	4-9
4-6.	Electric field at outer insulator surface	4-11

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1-1. Original specifications	1-5
1-2. Detailed specifications	1-6
3-1. Pulser parameters with decay variation	3-12
3-2. Capacitance and energy for the long decay pulser	3-12
4-1. Comparison of coax and cylinder-over-plane peak field and impedance 5 MV on coax	4-8
5-1. Summary of recommended diagnostics	5-3
6-1. List of Laboratories with data or equipment related to power line tests	6-4
7-1. Summary of Coupling Techniques	7-2

10

ABSTRACT

This report presents the results of a study conducted by Maxwell Laboratories, Inc., under Contract No. 19X-89642V with Martin Marietta Energy Systems, Inc., for the Oak Ridge National Laboratory (ORNL). The objective was to create conceptual designs of high voltage pulsed capable of simulating two types of electromagnetic pulses (EMPs) caused by a high-altitude nuclear burst; the slow rise time magnetohydrodynamic (MHD-EMP) and the fast rise time high-altitude EMP (HEMP). The pulser design was directed towards facilities capable of performing EMP vulnerability testing of components used in the national electric power system.

Maxwell conducted two distinct studies for ORNL during the same period; one on fast-pulse EMP and the other on slow-pulse EMP. The principal authors were A. Ramrus for fast-pulse and R. Dethlefsen for slow-pulse. The slow-pulse study is contained in a separate report to ORNL. The technical contact for this project was P. R. Barnes of Oak Ridge National Laboratory.

SECTION 1
INTRODUCTION -- FAST PULSE EMP

1-1 BACKGROUND

The electromagnetic pulse from a high-altitude nuclear burst (at the height of 50 km and up) can induce large voltage and current transients in the electric power system.¹ In this process the high altitude EMP (HEMP) propagates towards the ground as a radiated wave as shown in Figure 1-1. The wave then couples to the power lines of an electric power system inducing current in the conductors and the earth. This problem is potentially most severe for the long high-voltage transmission lines which conduct power over long distances. In contrast to the distribution lines, the relatively greater length and height of the transmission lines accentuates the EMP coupling. Once the current is induced, the overhead transmission line and ground constitutes a two-conductor, glossy waveguide along which the electromagnetic wave propagates.

The effects of the induced wave on components which are connected to the power system can be studied in an appropriate pulser or simulator. The purpose of this report is to establish the feasibility and conceptual design of such a simulator. In one particularly attractive approach, this simulator consists of a high-voltage capacitive source which discharges into the component under test. The simulator creates the same amplitude and waveshape for voltage and current as that which the component would receive if connected to a power line subject to HEMP. The definition of this HEMP induced waveshape is based on combined theoretical and experimental considerations and, for purposes of this report, was supplied to Maxwell by written and verbal communications from the Oak Ridge National Laboratory (ORNL).²

This study, conducted by Maxwell for ORNL was directed towards the definition and analysis of pulsed sources and integrated test facilities capable of simulating HEMP waveforms specified by ORNL. In this regard, we envision a facility to which components and subsystems are brought for test. Therefore, portability is discussed but not emphasized. In this report, we

Figure 1-1. Power lines and components exposed to effects of EMP.

consider pulser designs which span a range of operating voltage and currents in order to develop design concepts suitable for use in a realistic parameter range.^{3,4}

After review of the options, the most promising is a generator consisting of a capacitive source discharging into a load resistor, the output terminal of which is connected to a resistive element equal to the specified generator impedance, Z_0 . Much of this study consists of a review of the detailed analysis conducted during this program in order to make a capacitive pulser system meet the requirements of a test facility for power system components.

To simulate waveshapes one can imagine a pulser circuit which is the approximate Thevenin equivalent of the HEMP charged power line over perfectly conducting ground. The induced power line open-circuit voltage waveshape is known or assumed, and the power line surge impedance is calculated from geometric considerations. For example, consider a power line with open-circuit time-dependent voltage $V_{oc}(t)$. Consider $V_{oc}(t)$ to be a double exponential consisting of a fast rising portion rise time to $(1-1/e)$ of peak of 20 to 30 ns, followed by a decay (to $1/e$ of peak) of 1 μ s. The appropriate simulator could contain a capacitive source of capacitance C_0 , charged to the required peak open-circuit voltage of the power line. To generate the appropriate exponential decay, the capacitive source discharges into the load resistance R_L and generates the decay time of $R_L C_0$. This circuit consisting of the source and load resistance would be placed in series with a relatively high impedance, Z_0 equal to the power line impedance.

Appropriate adjustments may be made to this impedance to adjust for ground and conductor losses. The assumption of perfectly conducting ground is reasonable throughout the 100 Hz to >1 MHz frequency range. The impact of imperfectly conducting ground is taken into account when the long pulse (10's of microseconds) is considered. In a simplified case of practical use to the simulator designer, this impedance may consist of a linear resistance R_{pL} equal in value to the surge-impedance of the power line Z_{pL} . The load resistance R_L is small compared to Z_{pL} . Then the waveshape across R_{pL} is the same for both the open-circuit case and the short-circuit case. A simplified circuit for the capacitive source is shown in Figure 1-2.

MLA-10,208

Figure 1-2. Capacitive source C discharges into a load resistance R_L which is small compared to the output impedance Z_o .

1-2 SPECIFICATIONS

The specifications listed in Table 1-1 were contained in the original RFQ as guidelines, subject to change by ORNL as understanding of the problem progressed during the program.

Table 1-1. Original specifications.

Parameter	Specified Range
Peak Open-Circuit Voltage, V_{oc}	1 to 3 MV
Short-Circuit Current, I_{ss}	10 to 15 kA
Internal Impedance, Z_o	300 ohms
Rise time (10-90%), t_r	5 to 30 ns
Decay time, t_d	2 to 5 μ s
Rep-rate	Single pulse

During the course of this program, analysis was conducted by Lutech Inc., and Pulsed Sciences, Inc., under separate contract with ORNL and directed, in part, towards the improvement in definition of simulator properties. This resulted in the more detailed specifications shown in Table 1-2.^{5,6}

Table 1-2. Detailed specifications.

Parameter	Specified Value(s)
Peak open-circuit voltage, V_{OC}	4 MV
Internal impedance, Z_O	400 + or - 100 ohms
Rise time (1-1/e) of peak, t_r	20 to 30 ns
Decay time (to 1/e of peak), t_{1d} $t_{2d(1)}$ $t_{2d(2)}$	1 μ s to 0.8 MV, then 30 μ s for σ (earth) = 3×10^{-3} mho/m or 10 μ s for σ (earth) = 1×10^{-3} mho/m
Prepulse	<10%
Jitter, one standard deviation	<20 ns
Variability	3:1 (10:1 desired)
Reproducibility	5%
Test object operational excitation	500 kV ac or dc and 30 kV ac
Polarity	+ or -
Test object configuration	single or multi conductor
Pulse Rate (estimated)	2 pulses, 1 min apart, 8 times/day

The following study deals with pulser capable of satisfying all the above requirements with a practical and reasonably economical system using, wherever possible, equipment within the state-of-the-art. We point out where higher accuracy in meeting a specification may significantly increase pulser complexity and cost. Cost is not specifically addressed in this report. Variability is considered to be of particular importance in the sense that one simulator should be useable to explore the response to a variety of conditions. Therefore, in our interpretation of the specifications, the optimum pulser is capable of being varied throughout the indicated parameter range and components may be added to the simulator to extend the available test options.

1-3 REPORT ORGANIZATION AND APPROACH

This report was prepared by considering the logical sequence which the pulser designer must follow in order to successfully meet the given specifications. We start with a discussion of specifications and follow with a detailed section on pulser design. We first consider meeting the main specifications, in particular, those on peak amplitude and early time waveshape (first decay) for voltage and current. This is followed by a discussion of variation in the main pulser design necessary to meet the remaining specifications such as the long delay associated with the late-time (see specifications above). We also study coupling to components charged with their normal ac and dc excitation.

The pulser design section is followed by a summary of the main issues associated with the incorporation of the pulser into a facility, complete with a summary on diagnostics and data processing. Finally, we review the state-of-the-art in pulser and facility design. One of the objectives of this section is to show the main areas where the pulser design is based on experience and to compare that with areas in which proof-of-design experiments would be desirable. This section also contains a list of major domestic facilities in which EMP and lightning testing is conducted.

1-4 SUMMARY OF RESULTS

On the basis of this study, the author concluded that an oil-immersed, Marx-type pulser, equipped with a peaking capacitor to sharpen the output rise time, is the appropriate pulser to meet the requirements on peak amplitude, rise time, and first decay, shown in Table 1-2. In this design, the waveshape is generated in a load resistance whose value is small compared to the specified pulser impedance. This conceptual design is shown in Figure 1-3. This approach is suitable for the required 3 to 5 MV range, (and beyond) and to a first approximation, the size (linear dimensions) of the equipment can be scaled in direct proportion to pulser peak output voltage.

Special components can be added to this basic machine, to enable it to generate a second decay on the tail of the first waveform. Specifically, a lower-voltage high capacitance Marx (with output voltage much smaller than the pulser voltage associated with the first peak) is used to superimpose the long decay (10 μ s to 30 μ s) onto the fast decay (1 μ s) described above. Other components enable the pulser to be coupled to test components excited with

MLA-10,244

Figure 1-3. Conceptual design of a 4 to 5 MV oil-immersed pulser consisting of a Marx generator, a peaking capacitor, and a resistant network for appropriate V_{OC} and I_{SS} .

their normal (operational) ac or dc voltage. (In this report, test objects are said to be energized or powered up if they are charged with their normal operating ac or dc voltage). Capacitive coupling is suitable for the 1 μ s range and a spark gap is an attractive option for coupling the 10 to 30 μ s pulse onto an operating line. Coupling these long pulses has not been demonstrated and therefore, limited proof-of-design experiments may be desirable. Coupling is discussed in Section 3, and experiments in Section 7.

SECTION 2

REVIEW OF TECHNICAL OBJECTIVES

In this section those specifications which bear most heavily on basic pulser design are reviewed. In general terms, broad design principles for meeting overall system requirements are described. Considerations that lead to the selection of a Marx-type pulser are summarized.

2-1 ELECTRICAL PARAMETERS

The simulator requirements call for a fast rise time, followed by an exponential decay for the open-circuit voltage waveshape and the same waveshape for the short-circuit current as shown in Figure 2-1. These are the approximations of the waveforms which would be expected at the two terminals of a semi-infinite power line of characteristic surge impedance Z_0 . In an ideal circuit consisting of a zero-impedance voltage source in series with a pure resistance R_0 , the ratio of the open-circuit voltage $V_{OC}(t)$ with the short-circuit current $I_{SS}(t)$ should yield the constant ratio R_0 . Then R_0 would be a real valued quantity, which is the effective Thevenin-equivalent impedance of the EMP charged power line.⁷

This method of specifying the required output waveforms, which establishes the open-circuit voltage and internal impedance is important to the pulser design. Maintaining the exact similarity in waveshape (i.e., the same time dependence) for the open-circuit voltage $V_{OC}(t)$ and the short-circuit current $I_{SS}(t)$ can impose stringent requirements on the pulser. In effect, this specification corresponds to a pulser (or general waveshape generator) with internal impedance very low compared to Z_0 . The equivalent circuit shown in Figure 2-2 shows this concept. In that circuit, the waveshape is generated in R_L where $R_L \ll Z_0$. Since the appropriate decay occurs across R_L , the requirement that the exponential decay of open-circuit voltage and that of short-circuit current be the same is satisfied; as R_L approaches Z_0 , a larger deviation in the ratio $V_{OC}(t)/I_{SS}(t)$ occurs. Figure 2-2 also shows the effect of using a capacitive source without a low resistance R_L .

Figure 2-1. Definition of rise time, first decay, and second decay.

Figure 2-2. Waveshape is generated at a resistance (R_L) low compared to the output pulser impedance, Z_0 .

This method of specifying V_{OC} , I_{SS} and Z_O is appropriate since it corresponds to the case in which a power line of impedance Z_O , which is energized by EMP, would in effect have an equivalent circuit consisting of a zero impedance voltage source which generates the appropriate exponential waveform, connected in series with geometric impedance of the line, Z_O . Usually, pulser systems are designed using specifications on the actual load current and voltage. In those cases, a substantial amount of knowledge about the load exists. In the case of present interest, the character of the load test object is not well known and components subject to test are expected to have a variety of properties. These considerations establish the necessity to specify the pulser on the basis of its open-circuit voltage, and internal impedance.

The circuit design which generates the proper waveform and has the proper impedance calls for the creation of the waveform in the low impedance load, R_L . Much of the pulser energy is, therefore, dissipated in that load and is never delivered to the output. This is important since it leads to the trade-off of pulser energy versus the ratio of pulser load resistance to Z_O . As this ratio goes down, (ideally to zero, but to about 0.1 in practice) pulser energy and associated size, complexity, and price tend to rise. This trade-off will be discussed later in this report.

Another important requirement calls for the test of ac (or dc) energized components. In effect, this requirement calls for the ability to superimpose the EMP waveform onto the normal operational excitation. Based on discussions with our consultant, Edward Vance, it appears that many meaningful tests can only be conducted when the components are energized with the normal voltage (see Appendix). We should emphasize that important data is obtainable without such ac (or dc) excitation, but tests related to the operation or characteristics of the component under test in its normal system environment should be conducted when it is under normal power. We have therefore considered equivalent circuits in which the pulser is capacitively isolated from the component under test. This capacitor acts as a high-frequency-pass filter and blocks the relatively low 60 Hz (or dc) voltage from the pulser. Although this capacitor introduces a complication to the test configuration, and if not properly sized, can distort the exponential waveshape of the applied pulse, we have concluded that this test is important. In practice this capacitor would be portable and be used only for tests involving powered-up (ac or dc) components or power lines. Otherwise it would be removed from the test setup and

replaced by an appropriately insulated conductor. Also the use of coupling capacitors is not the only approach to the isolation problem. To test powered-up components a self-breaking output switch in series with a circuit interrupter shows promise especially for coupling the long pulse (10's of microseconds to ac charged lines). This will be discussed in Section 3.

2-2 SIMULATION CONCEPTS

In this subsection we summarize background considerations which lead to the Marx pulser approach emphasized in this report. Initially we studied two broad classes of test configuration. These were 1) Integrated System Test and, 2) Components and Power Line Test.

In the first category, we envisioned an operating segment of a power system subject to a radiated EMP. This segment would consist of power lines and their appropriate attachments such as surge arresters, transformers and controls. The free-field source of EMP would be in the form of a radiating dipole deployed nearby. This configuration is similar to that used over the past twenty years by several major laboratories in the U.S. and Europe, (Air Force Weapons Laboratory, Albuquerque, Harry Diamond Laboratories, Maryland, and Naval Surface Weapons Center, Maryland and Virginia). This concept is shown in Figure 2-3. This could be done in a dedicated facility built for this purpose, consisting of all appropriate power generating, transforming, and transmitting components. This would have to simulate, as closely as possible, a fully operational section of a public utility substation.

Further consideration of the practicality of a dedicated facility in which such a test could be conducted led us to tentatively conclude that it was beyond the scope of the present work to pursue this approach, and this was confirmed by the sponsor of this work, ORNL. It was more in the interest of ORNL that Maxwell concentrate on components and power line testing rather than the integrated facility outlined above. However, at a future time such a facility does make sense because it creates the proper electromagnetic environment by introducing transients with their proper time phase throughout the various parts of the system.

MLA-11,741

Figure 2-3. Simulator concept in which a free-field radiating pulser exposes the power line and components to EMP.

Technical issues and problems associated with this technique were not explored in depth. For example, the Thevenin-equivalent circuit parameters described previously are not directly applicable to this configuration since the pulser is a separate circuit which is radiatively coupled to the power system. Also, the practicality of attaining microsecond decay time with a purely radiating pulser would need further study. A hybrid system consisting of a combined radiator and a direct injection pulser for the long decay appears to be called for (as in the TORUS concept described in the AFWL High Altitude EMP series of notes).

In the second category, which is the component and power line test facility, we envisioned two techniques for introducing the specified transient. In one technique we considered a transformer coupling wherein a power line or wire would have induced in it the specified transient. In this mode, the line acts as a secondary in a single-turn current transformer. This configuration is desirable because the wire or line need not be broken in order to introduce the transient. This technique is growing in use today, especially for injection of transients in below and near-ground cables. This concept is shown in Figure 2-4. The problems associated with this technique to meet the present specifications are formidable. The development of 3 to 5 MV on the power line means the transformer would be required to withstand that voltage. This would be a large, multi-segment pulse transformer beyond the present state-of-the-art.⁸

Furthermore, the fast rise time (10's of nanoseconds) combined with slow decay (at least 1 μ s) is difficult to attain with a transformer. These difficulties would be compounded by the requirement for the dual decay specified in Table 1-2.

The main advantage of this approach is that it applies to unbroken lines. There is not a major motivation at this time to inject pulses into an unbroken line (as in existing facilities equipped with fixed power line components). Further consideration of this approach, although of potential interest in future test facilities, is not recommended for the present application. The relative merits of the concept to be described provided the motivation to abandon the transformer approach for the present. This selection of technical approach was discussed with representatives of ORNL who concurred.^{9,10,11,12}

Figure 2-4. Transformer for current injection into a conducting cable.

SECTION 3

PULSER DESIGN FOR COMPONENTS TESTING

This section develops the design of pulsers suitable for testing components as opposed to overhead power lines which are treated in the next section. Components subject to normal powered-up ac or dc excitation are considered.

3-1 GENERAL DISCUSSION ON DESIGN

3-1.1 Exponential Decay

The requirement on open-circuit voltage waveshape calls for a fast rise time (10's of nanoseconds) followed by a $1\ \mu\text{s}$ decay which may, in turn, be followed by a second still slower decay. The latter decay will be covered later in this report. Consider the waveform derived from an ideal capacitive high-voltage source C_p which discharges into a pure load resistance R_L . The decay time of voltage across the load R_L is $R_L C_p$ (to $1/e = 1/2.72$ of peak) and this provides the appropriate first exponential decay. For example, consider a numerical example; let $R_L = 50\ \text{ohms}$. To obtain a $1\ \mu\text{s}$ decay, $C_p = 20\ \text{nF}$.

3-1.2 Marx Pulser

In practice, Marx inductance is important because it limits rise time of a Marx discharging into a load impedance. Marxes attain high voltage utilizing a circuit in which capacitors are charged in parallel then switched into series. A combination of capacitor and spark gap is called a stage. Practical Marxes have inductance approximately proportional to the erected voltage of the Marx, nV_c , where n is the number of Marx stages and V_c is the charge voltage per stage. Realistic Marxes have inductances approximately $1.5\ \mu\text{H}$ per MV; i.e., a 4 MV Marx can have $6\ \mu\text{H}$. If the Marx were discharged directly into R_L the rise time would be on the order of $(L_M/R_L) \sim 100\ \text{ns}$ which exceeds the requirements.

Raising the load resistance would not help. As the resistance approaches the required output impedance Z_o , the differences between wave shapes for the open-circuit voltage and short-circuit becomes larger. (See Table 1-2 specifications calling out internal impedance as 400 ohms + or - 100 ohms which corresponds to + or - 25 percent). A peaking circuit is needed to overcome this problem.

In summary a Marx pulser can be designed to provide the needed capacitive voltage source using technology within the state-of-the-art. This Marx must be connected to a peaking circuit which, when appropriately timed, discharges into the load resistance with a fast rise time. Following is a summary of a peaking circuit. (See the facility design shown in Figure 1-2 for a view of the Marx and peaking circuit.) In this design, a Marx, which acts as a capacitive source, discharges into a load impedance which is small compared to Z_o , where $Z_o = 400$ ohms.

3-1.3 Peaking Circuit

To attain fast rise times, peaking circuits are often used and have been used in many EMP pulsers. A simplified peaking circuit is shown in Figure 3-1. The peaking capacitance is estimated with the formula:

$$C_p \approx L_M / R_L^2 \quad .$$

As described previously, $R_L \ll Z_o$ to assure similarity of the open-circuit voltage and short-circuit current. For example, to attain the decay of 1 μ s, with the Marx inductance L_M of 6 μ H and a $Z_L = 0.2 \times Z_o$ or 80 ohm, the capacitance C_M obtained from the 1 μ s decay time is:

$$C_o = t_d / R_L = 1 \mu s / 80 \text{ ohms} = 12.5 \text{ nF}$$

$$C_p = L_M / R_L^2 = 6 \mu H / (80 \text{ ohms})^2 \approx 1 \text{ nF} \quad .$$

The pulser stored energy is a useful parameter for comparison with existing state-of-the-art Marxes. For the erected Marx capacitance of 12.5 nF, energy is given by the equation:

$$E = 1/2 C_M V_o^2$$

MLA-11,742

Figure 3-1. Simplified peaking circuit.

$$\begin{aligned}
&= 1/2 \times 12.5 \text{ nF} \times (4 \text{ MV})^2 \\
&= 100 \text{ kJ} \quad .
\end{aligned}$$

This is considered a modest sized Marx from the standpoint of its stored energy, comparable to many pulsers operating in the field. (For Maxwell systems, this implies a standard Marx capacitor contained within a standard Marx tray.) Now consider the variation in decay time for the short-circuit current.

The new decay time for the above example will be governed by the effective load impedance, given by the parallel combination of the 400 ohm with the 80 ohm pulser load. This new resistance is:

$$R_{SS} = R_L Z_0 / (R_L + Z_0) = (80 \times 400) / (80 + 400) \text{ ohms}$$

$$R_{SS} = 67 \text{ ohms} \quad .$$

The new decay time is:

$$\begin{aligned}
t_d &= R_{SS} \times C \\
&= 67 \text{ ohms} \times 12.5 \text{ nF} \\
&= 0.84 \text{ } \mu\text{s} \quad .
\end{aligned}$$

This Marx capacitance may be selected to provide a decay time in the 1 to 2 μs range. The variation from open-circuit voltage to short-circuit current is a measure of the extent to which the pulser impedance appears to be resistive and simulates an EMP excited transmission line.

$$\begin{aligned}
\text{deviation} &= [t_d(\text{oc}) - t_d(\text{ss})] / t_d(\text{mean}) \\
&= (80 - 67) \text{ ohms} / 74 \text{ ohms} = 18 \text{ percent}
\end{aligned}$$

where t_d is the average of $t_d(\text{oc}) - t_d(\text{ss})$.

Other effects on the waveform will also occur to the variation of load impedance in the peaking circuit.

For optimum waveshape of $I_{ss}(t)$ and $V_{oc}(t)$, the peaking capacitance would be calculated using a resistive impedance midway between the short-circuit impedance R_{ss} and R_L observed in the open-circuit case. Therefore:

$$C_p = 6 \mu H / [(80 + 67)/2]^2 \text{ ohms}^2 = 0.8 \text{ nF}$$

A peaking capacitor can be readily designed to meet these pulser requirements.

3-2 UNPOWERED COMPONENTS

This section discusses the techniques by which a high voltage connection can be made between the pulser output and the component under test. Since the component under test is assumed to be unpowered, a conductor which extends from the output of the pulser resistance R_o to the test object is feasible. The main design objective is to provide an interface with the required high voltage integrity and with minimum stray capacitance and inductance.

3-2.1 High Voltage Interface

The EMP industry has paid substantial attention to the generator-to-air interface problem because most lightning and EMP must undergo this interface in order to test components in air. An important consideration is to hold the electric field at electrode surfaces below 2 MV/m (which corresponds to testing seal temperature and pressure.) At higher altitudes this field must be reduced. Reducing the pulse width allows this stress to be increased. For pulse width on the order of 1 μs , air undergoes discharge and breakdown in the range of 3 MV/m. For safe operation in the ORNL case, the air/plastic interface should have a surface field still further below the 2 MV/in; the final value depending on decay time.

For given voltage, a geometry must be found in which the surface and interfacial field is below the breakdown value. For voltage scaling, it is necessary to vary the size of the interface, roughly in proportion to the peak voltage. Detailed design of this interface is beyond the scope of this report, and we show in Figure 3-2 a typical bushing design (used in Maxwell's lightning generator now being constructed for the Boeing Corporation). Also, the equipotential distribution of this bushing is shown in Figure 3-3 to clarify the

MLA-10,217

Figure 3-2. Typical bushing design for oil-to-air high-voltage interface.

GIVEN FIELDS BASED ON AN APPLIED VOLTAGE OF 1.76 MV

Figure 3-3. Typical field plot to evaluate high stress areas in an oil-to-air bushing.

technique of determining the field strength used in designing such an interface. It is important to note that the interface problem is an air breakdown problem and refers to the external interface of the pulser. The internal interface is usually not a problem because the internal dielectric strength of oil or other pulser insulator, is usually far greater than that of air. For example, oil has a breakdown strength on the order of 30 MV/m, in contrast to the 2.5 to 2.3 MV/m of air.

3-2.2 Marx Energy versus Pulser Impedance

Ideally, the pulser impedance would be purely resistive and the ratio $V_{OC}(t)/I_{SS}(t)$ would not vary. To approximate that condition, $R_L \ll Z_O$, the value of R_L determines the Marx capacitance needed to attain given decay time, $R_L C_M$. When this Marx capacitance and the required test voltage is established, then the Marx energy is determined. (Energy is $0.5 C_M V^2$). Figure 3-4 shows the required energy versus load resistance for a 1 and 2 μs decay assuming a 5 MV Marx. As shown, a 1 μs decay with a 60 ohm load resistance (which is 15 percent of the output 400 ohm impedance), yields a 200 kJ Marx energy. If desired, this can readily be scaled to other energies by means of the energy equation above. A 4 MV Marx would contain 125 kJ.

3-2.3 Effect of Long Pulse on Design

The specifications in Table 1-2 call for an interruption in the first decay (of 1 μs), at the levels of either 0.8 or 0.4 MV, at which time a new decay of either 30 or 10 μs begins. Various techniques are available to accomplish this dual decay waveform. The following meets the requirements in a reasonably efficient manner.

The preferred approach which appears most promising calls for the use of a second pulser which at the appropriate time is electrically connected in parallel with the pulser which generates the first, 1 μs decay. This circuit is shown schematically in Figure 3-5. (The added circuit is shown in the dashed rectangle.) In operation this added circuit is initially insulated from the first circuit by means of the switch, S_D . During the period the switch is open, the peaking circuit generates the fast rise time pulse followed by the 1 μs decay. Prior to firing that peaking circuit, the second pulser circuit is erected to a voltage approximately equal to the voltage at which the second slow decay will begin. After the first transient has decayed to the desired

Figure 3-4. Energy versus load resistance for a 5 MV pulser with 1 and 2 μs decay times.

5 MV MARX/PEAKING CIRCUIT, FOR FAST RISE AND $1 \mu\text{s}$ DECAY.
AUXILIARY MARX FOR $30 \mu\text{s}$ DECAY.

Figure 3-5. Marx peaking circuit and auxiliary pulser to generate second decay. (Dashed capacitor is for coupling to be discussed in Section 3-3.)

level, S_D is triggered. This connects the second Marx bank to the output load through the 400 ohm resistance.

The 400 ohm resistance continues to provide the required isolation of the output so that the waveshapes of the open-circuit voltage and the short-circuit current will be the same, depending on the ratio of the load resistance to the output resistance, as previously. To attain the long decay, the Marx capacitance should be t_{D2}/R_{LP} where t_{D2} is the new long decay and R_{LP} is the pulser load ($\ll R_O$).

To show the manner in which the parameters would be estimated, we will consider some examples. Table 3-1 shows a comparison of 5 and 4 MV pulsers in which a 30 μs decay is generated at the level of one-third of peak voltage. Therefore, the 4 MV peak voltage calls for a second Marx bank charged to 1.3 MV. To generate the 30 μs decay into the 50 ohm load assumed for that example, a 600 nF Marx bank is required. This added Marx bank has the substantial energy of 500 kJ.

In contrast, consider the specifications in Table 3-2 in which a 4 MV pulser operates into an 80 ohm load. The late time pulse begins at 0.8 MV. Then, the added Marx bank generates the required 30 μs decay into 80 ohms. The required capacitance is:

$$\begin{aligned} C_D &= T_D/R_{LP} = 30 \mu s / 80 \text{ ohm} \\ &= 0.375 \mu F \end{aligned}$$

The Marx energy is:

$$\begin{aligned} E &= 1/2 C_D U^2 = 1/2 \times 0.375 \mu F \times (0.8 \text{ MV})^2 \\ E &= 120 \text{ kJ} \end{aligned}$$

(By normal standards in the pulse power industry this is a relatively modest pulser). The following table shows capacitance and energy for other specifications.

For comparison, the Marx required to generate the 4 MV peak amplitude into an 80 ohm, with a 1 μs decay time is 12.5 nF, 100 kJ. Figure 3-6 shows a typical computer calculation of the output when the second Marx is fired 1 μs after the first Marx.

Table 3-1. Pulser parameters with decay variation.

Fast rise time, 1 μ s initial decay, 30 μ s late decay			
Marx			
Erected voltage	5 MV	4 MV	V_M
Inductance	7.5 μ H	6 μ H	L_M
Capacitance	20 nF	20 nF	C_M
Energy	250 kJ	160 kJ	E_M
Peaking Section			
Capacitance	2.6 nF	2.1 nF	C_p
Pulse shaping load	50 ohm	50 ohm	R_L
Output switch time	200 ns	170 ns	t_s
switch rise time (10-90%)	11 ns	9 ns	t_R
Long Pulse Section			
Marx voltage	1.7 MV	1.3 MV	V_D
Switch time	1 μ s	1 μ s	t_{DS}
Initial switch voltage	3.3 MV	2.7 MV	V_{DI}
Marx capacitance	600 nF	600 nF	C_{MD}
Energy	870 kJ	500 kJ	E_{MD}

Table 3-2. Capacitance and energy for the long decay pulser.

V_{pk} MV	T_1 μ s	T_2 μ s	V_{LD} MV	R_{pl} ohms	C_{LD} μ F	E kJ
4	1	10	0.4	80	0.125	20
4	1	30	0.8	80	0.375	120

Figure 3-6. Computer simulation of $V_{oc}(t)$ showing the blending of a waveform with fast rise time and 1 μs decay, followed by a 30 μs decay.

An important technical issue is associated with this circuit. Gas insulated spark-gaps are planned for this application. These tend to be difficult to close reliably when the voltage across them is below ~40 percent of their self-break value. Recently, laser triggered switches operated at Sandia National Laboratories and at Maxwell Laboratories have attained excellent performance in crowbar service and we therefore recommend that approach. Computer runs on the influence of switch timing on the output waveform has shown the output $V_{oc}(t)$ and $I_{ss}(t)$ is not a sensitive function of the second switch closure time. Therefore, firing times can be selected at which the voltage across the second switch S_{LD} (Figure 3-6) is 30 to 40 percent of its self-break value. Laser triggering of a 2 MV crowbar switch has been reliably accomplished at Maxwell and if significantly higher voltage is required, this technique should be tested experimentally to establish its performance when triggered at low ratios of triggered to self-break voltage. (Laser triggering of switches with applied voltage over 4 MV has been accomplished at Sandia, but these were not used in crowbar service.) A drawing of a laser triggered switch recently tested at Maxwell is shown in Figure 3-7.

To review this crowbar requirement, consider the example in which a 4 MV Marx and an 0.8 MV Marx (see specifications) are simultaneously erected. After the peaking switch fires the voltage across S_{LD} is 3.2 MV. Therefore, it should have a self-break voltage of about 4 MV to reliably withstand the 3.2 MV. Then, S_{LD} voltage decays during the $1 \mu s$ decay. This decay can progress until pulser load voltage decays to 2 MV. Since the other electrode of S_{LD} is held at 0.8 MV, the voltage across S_{LD} is 1.2 MV corresponding to 30 percent of the 4 MV self-break. Laser triggered switches can be operated at this level. Computer circuit analysis includes this early triggering of S_{LD} showing that output waveforms blend well from the 1 to 30 μs decay over a substantial range of firing times.

3-2.4 Conformity with Specifications

This section reviews a pulser at 4 to 5 MV, configured to drive components which are not charged with their normal ac or dc voltage. We sequentially consider the capability of the pulser to meet the specifications listed in Table 1-2.

Figure 3-7. Laser triggered crowbar switch operated at Sandia and Maxwell.

3-2.4.1 Impedance. The pulser is equipped with a series impedance R_O equal to the desired Thevenin-equivalent impedance Z_O . If the pulser load resistance were made arbitrarily small, the pulser's Thevenin-equivalent impedance could also be made arbitrarily close to Z_O . This is not practical because of the large pulser energy lost in the pulser load R_L .

Two approaches may be used to analyze the pulser's equivalent impedance. In one the ratio of $V_{OC}(t)$ to $I_{SS}(t)$ is considered and this ratio is allowed to vary between specified limits. In another approach, the spectra of $V_{OC}(t)$ and $I_{SS}(t)$ are analyzed and the quantity $V_{OC}(\omega)/I_{SS}(\omega)$ are plotted versus frequency.

In this report, we consider the former approach, using the ratio of $V_{OC}(t)$ and $I_{SS}(t)$ because we can conveniently compare pulser waveshape parameters directly. For example, we can calculate peak values V_{OC} and I_{SS} , and compare them to $V_{OC}(T)$ and $I_{SS}(T)$ where T is the decay time to $1/e$ of peak. Also, the difference in decay time between $V_{OC}(t)$ and $I_{SS}(t)$ can be calculated which provides a guide to the effective impedance into which the pulser discharges since the decay time for $V_{OC}(t)$ is:

$$\begin{aligned} T_{OC} &= C_O R_L \\ T_{SS} &= C_O (R_L R_O / R_L + R_O) \end{aligned} .$$

A guide to the deviation of R_p from R_O can be obtained by considering the ratio:

$$R_L / (R_L R_O / R_L + R_O) = 1 + R_O / R_L .$$

To a first approximation, if $1 + R_O / R_p = 1.2$, the specification on 400 ohm + or - 100 ohm, i.e., (400 + or - 25 percent) can be met. The above considerations are intended to provide guidance for the selection of R_L , for a given R_O .

3-2.4.2 Jitter. Modern Marx pulsers of the required size have the capability to erect with jitter of 20 to 30 ns within a voltage range of 3:1. The jitter tends to increase as a given Marx pulser is operated at the lower extreme of their voltage range.

In the circuit under consideration, a peaking capacitor in the 2 nF range is required. The charging time on this capacitor is estimated from the formula:

$$t_c = \frac{\pi (L_M C_{eq})^{0.5}}{4} ,$$

where T is the period at resonance, L_M the Marx inductance, and C_{eq} is the equivalent series capacitance of the Marx and peaking capacitor. For example, consider a 4 MV pulser which calls for a 70 ohm pulser load. To meet the 1 μ s decay time, a 14 nF Marx is required. This Marx may have an inductance of about 6 μ H. The peaking capacitance is given from the formula:

$$C_p \sim L_M / R_L^2 .$$

In this case, $C_p = 1.2$ nF .

The equivalent series capacitance is:

$$C_{eq} = C_M C_p / (C_M + C_p) = 1 \text{ nF} .$$

Often in discussing gas breakdown during a pulse charging waveform, the concept of effective time t_{ef} is used (after C. Martin of AWRE). This is the time during which the charging waveform exceeds 63 percent of the breakdown value. For example, if the 1.2 nF peaking capacitor charged with a $(1 - \cos \omega t)$ waveshape attains breakdown in 128 ns from start charge, the t_{ef} is about 40 ns.

Jitter has been found to be approximately proportional to t_{ef} and tends to be in the range of 5 to 10 percent. Therefore, a jitter of less than 5 ns in the output switch is expected. In this type of peaking circuit, the system jitter is therefore primarily caused by the Marx. Therefore, a jitter of about 20 ns is expected, and this should hold throughout the Marx output range of 3:1.

3-2.4.3 Prepulse. Prepulse is caused by the flow of displacement current through and around stray capacitance of the peaking switch and the peaking

capacitor. The value of stray capacitance depends on the specific design but ~100 pF is not unusual. The prepulse current can be readily estimated.

The charging voltage has the form of $nV_C (1 - \cos 2\pi ft)$ where n is the number of Marx stages and V_C is the Marx dc charge voltage per stage. The time rate of rise of the voltage is:

$$dV/dt = nV_O (2\pi f) \sin (2\pi f)t \quad ,$$

and the peak (which occurs near the switchout time) is:

$$dV/dt \text{ (peak)} = nV_O 2\pi f = nV_O / (L_M C_{eq})^{0.5} \quad .$$

At 4 MV, for $L = 6 \mu H$ and $C_{eq} = 1 \text{ nF}$ the prepulse current is:

$$\begin{aligned} I_{pp} &= C dV/dt = 100 \times \text{pF} \times 5 \times 10^{13} \text{ v/s} \\ &= 5 \text{ kA} \quad . \end{aligned}$$

This is compared to the normal discharge current of 60 kA at 4 MV through a 70 ohm load and is less than 10 percent. Prepulse can be further reduced by increasing Marx inductance artificially, i.e., by deliberately installing inductors in series with the Marx. This would slow the Marx discharge rate and may necessitate increase in tank dimensions. Also, the peaking capacitance would have to be increased to compensate for this increase in inductance. It appears the 10 percent prepulse requirement is readily met with standard Marx peaking circuit components.

3-2.4.4 Rise Time. The pulse voltage rise time is initiated by the closure of the peaking switch; the peaking capacitor then rapidly applies voltage to the load resistor R_{p1} . A low inductance output switch and peaking capacitor is important to establish fast rise time. The peaking capacitor also contributes to the shaping of the early time of the pulse, i.e., the first 10 to 20 ns. Ignoring electromagnetic propagation effects for the moment, the inductance of the output switch and the peaking capacitor is approximately proportional to rise time. The rise time is estimated with the equation:

$$t_R \sim (L_p + L_s) / R_L \quad ,$$

where t_R is the output rise time, L_p and L_s is the inductances of the peaking capacitor and the effective inductance of the output switch. The requirements (Table 1-2) call for t (rise) to be 20 to 30 ns. This rise time would be generated across the pulser load of 50 to 80 ohms. Therefore, $L_p + L_s$ in the range of $\sim 1 \mu\text{H}$ and is allowable in the peaking circuit. In fact, the peaking capacitor and output switch will have below one-half that value. Spark gaps in the 4 MV class have effective inductances in the range of 300 nH and the peaking capacitor inductor can be held to about 100 to 200 nH. The required rise time can readily be generated by the switch and peaking capacitor.

This rise time must be propagated through the 400 ohm resistor and along the cylinder-over-plane geometry which extends to the test object or transmission line, while still preserving the high frequency components of the rise time. This requires careful design and several losses will increase this rise time. Radiation of these high-frequency components tends to be worse as the ratio of the interelectrode spacing to the propagating wavelength exceeds one. A 10 to 20 ns rise time contains wavelength components of 5 ft in oil which is comparable to the interelectrode spacing at the pulser output in and around the 400 ohm resistor and the oil/air interface. Therefore, careful design is required in that region to minimize radiation losses and maintain constant impedance. Since the required rise time is 20 to 30 ns and that launched is less than 10 ns, it is feasible to meet the requirements despite these electromagnetic effects which tend to increase rise time.

3-2.4.5 Reproducibility. Shot-to-shot reproducibility of the open-circuit voltage and the short-circuit current depends mostly on the reproducibility in the closure delay of the peaking switch with respect to the Marx firing. A small dependence on the charging voltage and on the long-time variation of the components is present but those effects are small.

The percent variation in peak output voltage due to peaking switch jitter may be calculated to obtain the voltage amplitude variation. Reproducibility is given by the definition:

$$R = (dV/dt)Dt_s/nV_C \quad ,$$

where nV_C is the voltage at which the output switch closes, and Dt is the rms time deviation in closure decay (or jitter). The quantity, dV/dt is time voltage ratio-of-rise at the switchout time. Consider a resistance-free resonant circuit in which a Marx capacitance C_M charges a peaking capacitance C_P . The charging waveshape is:

$$V(t) = (nV_C) (1 - \cos(2\pi f)t) ,$$

where V and dV/dt are evaluated at the switchout time.

Consider an ideal resonance charging circuit in which the Marx capacitance C_M greatly exceeds the peaking capacitance, C_P . The optimum switchout time occurs at $T/4$, which is the peak dV/dt . (T is the resonant period).

The charging waveform is:

$$V(t) = nV_C (1 - \cos \omega t) ,$$

$$\text{Charging rate is: } dV/dt = nV_C \omega \sin \omega t$$

$$\text{Peak Rate is: } (dV/dt)_{\text{peak}} = nV_C \omega .$$

$$\text{Reproducibility: } dV/dt (Dt)/nV_C .$$

To obtain the jitter expressed as a percentage of t_{eff} calculate the time difference between $T/4$ (the switchout time) and the time t_1 at which the voltage is $0.63 V_S$.

$$V(t) = nV_C (1 - \cos \omega t)$$

$$0.63 nV_C = nV_C (1 - \cos \omega t_1)$$

Therefore, solving for t_1 ,

$$t_1 = (1/\omega) \cos^{-1} (0.37) .$$

The time difference to reach $T/4$ is obtained from the waveshape:

$$V(t) = nV_C (1 - \cos \omega t)$$

$$t_2 = (1/\omega) \cos^{-1} (0) .$$

Then, t_{eff} is:

$$t_{\text{eff}} = (T/4) - t_1 = T/4 - \left[(1/\omega) \cos^{-1}(0.37) \right] = 0.06T \quad .$$

The jitter is taken to be a fixed percentage P of t_{eff} (normally P falls in the range of 5 to 10 percent). For $T = 2\pi \sqrt{LM_{\text{eq}}} = 0.7 \mu\text{s}$. Jitter (Dt) is 5 to 10 percent of t_{eff} at worst, $10\% \times 0.06 \times 0.7 \mu\text{s} = 4 \text{ ns}$.

Reproducibility, i.e., the percent variation amplitude due to jitter is:

$$R = (1/V) dV/dt (Dt) = \frac{\omega \times 0.379P}{\omega}$$

$$= \omega (Dt) = (2\pi/T)Dt = 4\% \quad .$$

Another effect which tends to increase rise time is the stray capacitance at the pulser output. This stray may be expressed in terms of the reduced surge impedance of the section of transmission line extending from the pulser output to the load. If the impedance of the conductors extending from the output end of the 400 ohm resistor to the load were perfectly uniform, the fast rise time would propagate virtually unchanged from the output resistor R_0 to the test component. The need for corona shields and their associated large radii introduces these stray capacitive effects which can slow the $V_{\text{oc}}(t)$ rise time over 10 ns. Although not a serious problem, careful design will be needed to control these effects.

3-2.4.6 Pulse Rate. The pulse rate requirements (Table 1-2) call for a series of two pulses, about one minute apart. This is then repeated up to eight times per day. Most pulsers made today are capable of meeting this requirement. Three main limitations influence pulse rate. These are 1) component heating due to high average power, 2) switch clearing (opening) in the Marx and peaking circuit, and 3) power supply size. The low average power will not create excessive heating in the Marx because the average power is low, in a system which is double-pulsed only eight times per day. If, for example, the Marx stores 200 kJ then eight double pulses per day (8 hours) corresponds to an average power of about 100 W.

To maintain that schedule with minimum maintenance, components are designed to avoid long term deterioration (especially if liquid resistors are used for charging the Marx and controlling pulse shape) but these do not present major technological limitations. Also, switch clearing between pulses will not present a limitation because with modest gas purging the Marx and output switch can be cleared in 10's of seconds or less.

The power supply will be selected to charge the Marx in 30 to 40 s, regardless of whether or not a repeat shot after one minute will occur. This charge-time is normally chosen to avoid shortening capacitor life by applying extended dc stress. Power supply cooling can also be designed for higher than one shot per minute if desired.

3-2.4.7 Variability. Extensive experience with Marxes and spark gaps, both of which are normally equipped with fixed-electrode, gas pressurized spark gaps, has demonstrated good performance throughout the voltage range of 3:1. For example, a 4 MV Marx could be operated in the 1 to 1.5 MV range with limited increase in gap jitter at the lower portion of this range. In the case of the output switch electrode adjustment, a mechanism may be included in the switch electrode structure to extend that range substantially beyond 3:1. Other options are available but may entail some down time between adjustments. For example, disconnecting the charging resistors on the higher Marx stages, then connecting three stages together has been successfully done to lower Marx voltage below normal range.

Techniques can be envisioned which can extend the Marx range to the desired 10:1, although they are not convenient to implement. The Marx gaps may be replaced by ones with smaller spacings but this requires substantial disassembly and may not be considered convenient. The best option may be simply to have the Marx replaced by one which is one-third the size of the main one. This smaller Marx may be installed with an appropriate inductor to accurately simulate the electrical characteristics of the full size Marx.

3-2.4.8 Test Object Excitation. The subject of components which are powered up will be considered in Section 3-3 in which a dc or 60 Hz ac capacitor which passes the high frequency pulse with decay time is discussed.

3-2.4.9 Polarity. The Marx/peaking circuit can be designed for operation in either polarity. Negative Marx charge and erection polarity is more often chosen because it is appropriate for electron beam machines. Also, a negative polarity is preferred because the electrical breakdown of the negatively charged Marx components will occur at significantly higher breakdown strength than positively charged Marx. Insulation strength in areas free of support structures are about 2 MV/ft for a negative Marx, and about 1 MV/ft in areas where supports exist. The stress would be reduced by about 40 percent to accommodate positive polarity.

3-2.4.10 Multi-Point Testing. The specifications call for the ability of the pulser to drive either one or more conductors at the pulser output. As the number of driven conductors increases, improved simulation may result if the series impedance is decreased from the nominal 400 ohms. The appropriate impedance would depend on the new conductor configuration and may be in the 200 to 300 ohm range for 3 or 4 conductors. This does not present a serious design problem because the effective pulser impedance consists of a series resistance. This will probably be an aqueous CuSO_4 resistor which can be readily changed by altering the resistivity of the electrolyte to accommodate a range of load resistance.

Preserving the same ratio, $V_{oc}(t)/I_{ss}(t)$ as with the higher load, throughout the frequency range would necessitate a reduction in the value of the load impedance R_L below that used with the 400 ohm series resistance. In practice this may require special consideration because the peaking capacitance would require modification also to preserve the same exponential decay. One alternative is to start out in the initial design with a lower value of load impedance, perhaps in the 50 ohm range. Then the specifications on output impedance could be met as Z_o varied from 400 down to 200 ohm. This design approach may be more costly, since the Marx energy is higher than that required for higher R_L (for the RC decay time). Also, the peaking capacitor would be larger for a 50 ohm load compared to the 70 to 80 ohm load.

Much of the design considerations used to this point assume a pulser is 400 ohm, and we will continue with that assumption, with the understanding the pulser design can, be designed with larger energy and then be capable of driving a substantial range of impedances and still meet all other specifications.

3-3 POWERED COMPONENTS

To this point, the discussion addressed the case in which the component under test is in its unpowered state. That allows a direct connection of the pulser to the component under test. The following discussion addresses the case in which the component under test is powered with its normal operational ac or dc excitation. This voltage can be up to 500 kV ac or dc. Necessarily, a coupling component or circuit is required between the pulser and the test component.

The coupling function can be performed in several ways. A spark gap with a circuit interrupter located between the output of the 400 ohm resistor and the test object is one attractive possibility. The spark gap would decouple the pulser from the load prior to the pulse since the gap is initially open-circuited. The spark gap would self close during the pulse rise time thereby providing the path for injection of the EMP into the test object. Then, the problem of disconnecting the pulser would occur. The residual current flowing through the coupling is the excitation voltage divided by the pulser impedance. For 500 kV excitation and 400 ohms resistance current, 1 kA (ac or dc) would pass through the 400 ohm resistor and the pulse load, R_L . For both ac and dc, circuit interrupters are commercially available which could break this circuit.

An important advantage of this coupling technique is that no other filtering components are needed. One consideration in the use of this component is that it must withstand the pulsed high voltage as well as the power excitation voltage. Therefore, preliminary testing would be desirable prior to placing such a device in the field. In other configurations to be discussed a coupling capacitor is used. As will be shown, this capacitor is ideal for coupling to dc lines and is attractive for the 1 μ s decay range when coupling to ac lines. The approach calling for a coupling capacitor may not prove as attractive for pulses in the 10 to 30 μ s decay applied to ac lines.

Consider a high voltage coupling capacitor connected between the pulser and load. This component has the advantage of being passive and consists of relatively standard, available parts. Figure 3-8 shows a concept of a 5 MV coupling capacitor. This concept shows a coupling capacitor contained within a 5-foot diameter tube. A 17 nF, 50 kV ac capacitor is assumed as the building block of the coupling capacitor. The total capacitance is inversely proportional to the number of series capacitors in a string and directly

Figure 3-8. Conceptual design of a 5 MV, coupling capacitor.

proportional to the number of parallel strings. The number of series capacitors is determined by the line voltage to which the coupling capacitor is connected. For example, a 500 kV ac line would require a series string of 10 capacitors. A 5 nF capacitor would use 3 parallel strings and a 25 nF capacitor would use about 16 parallel strings.

The inductance of a capacitor with relatively low capacitance can be made comparable to that of a large capacitor, if desired, by separating the axes of the parallel strings. The three axes of the 5 nF coupling capacitor are shown separated compared to the densely packed capacitor of 25 nF of the end view in the figure. This assembly, with the dimensions shown, will withstand 500 kV ac or dc (neglecting severe environmental effects due to extremes in atmospheric pressure, weather, or dirt, etc.)

Peaking capacitor performance is shown by the computer analysis of the circuit in Figure 3-9. Consider a 5 nF coupling capacitor for a pulse with 1 μ s decay time. The output current waveform, assuming C_C is short-circuited, as shown in Figure 3-10. An output pulse with a $V_{OC}(t)$ decay time of 1 μ s has the $I_{SS}(t)$ of 0.9 μ s. This reduction of 1 to 0.9 μ s is caused by the parallel combination of the 50 ohm pulser load with the 400 ohm output impedance R_O . Now compare the $I_{SS}(t)$ with the current through the 5 nF capacitor as in Figure 3-11. The decay time has been reduced to 0.6 μ s and overshoot has appeared due to the differentiating effect of the 5 nF capacitor. The reduction in pulse width and the overshoot is much less apparent in the waveform of Figure 3-12 in which a 20 nF coupling capacitor is used. There the pulse width is 0.8 μ s, only 11 percent below the 0.9 μ s injected pulse and the overshoot is less than 10 percent.

In order to perform its function the capacitor must block ac (or dc) current passing back through the isolation resistor from the test object. In the case of dc, the coupling capacitor C_C will provide complete blockage. Then, the minimum required capacitance depends on the transmitted pulse width. It would be desirable to minimize the capacitance size of C_C to minimize the stored energy since cost and physical size of the bank is a function of stored energy.

Figure 3-9. Circuit consisting of Marx peaking capacitor long pulse shaping and coupling capacitor.

MLA-11,543

Figure 3-10. Output current through short-circuited coupling capacitor for comparison with capacitively coupled waveforms to follow. See text for discussion of 0.9 μ s pulse width.

MLA-11,545

Figure 3-11. Short-circuit current through 5 nF coupling capacitor, showing reduction of pulse width compared to Figure 3-10.

MLA-11,542

Figure 3-12. Short-circuit current through 20 nF coupling capacitor showing slight reduction in pulse width compared to Figure 3-10.

In the case of ac, isolation occurs if C_C is small enough to pass negligible (or manageable) leakage current I_{ac} through the capacitive reactance. This current is:

$$I_{AC} = (2\pi f)C_C V_{AC} \quad ,$$

where f is the excitation frequency and V_{AC} is the line ac voltage.

A second criterion calls for the time $R_O C_C$ to be large compared to the decay time of the pulse to be transmitted in order to transmit the waveshape $I_{ss}(t)$ with acceptably small distortion:

$$R_O C_C \gg t \text{ (decay)} \quad .$$

Consider these criteria as applied to a 1 μs decay. In that case:

$$R_O C_C \gg \sim 10 \mu s \quad .$$

Since R_L is the series resistance, 400 ohm,

$$C_C > 10 \mu s / 400 \text{ ohm} = 25 \text{ nF} \quad .$$

In this example, $25 \text{ nF} < C_C < 38 \text{ nF}$ as $R_O C_C$ varies between 10 and 15 μs .

This capacitance would pass the 1 μs decay with low distortion, and would effectively block ac current from passing back through the series resistance R_L . This can be seen by calculating the capacitive reactance at 60 Hz.

$$\begin{aligned} X_C &= (2\pi f C_C)^{-1} \\ &= (377 \times 30 \text{ nF})^{-1} \\ &\approx 90 \text{ kilohms} \quad . \end{aligned}$$

Since $R_L = 50$ to 80 ohms and R_O is only 400 ohms, the capacitive reactance provides the main impedance to limit the current.

The current passed back to the pulser is:

$$I \approx V_{ac} / X_C = 500 \text{ kV} / 90 \text{ k}\Omega = 5.6 \text{ A} \quad .$$

This current is dealt with by cooling the series 400 ohm resistance since it dissipates 10 kW average power. Using this capacitive coupling, this power is dissipated both before and after the output (peaking) switch closes. After the switch closes, the ac current will tend to keep the switch closed. However, with only modest gas flow through the peaking switch to purge the switch products, the peaking switch will quench, near the first a current zero crossing.

In the case of dc excitation, capacitive current goes to zero after the pulse, (zero frequency) and the peaking opening switch problem does not occur at all; from that standpoint, the configuration for pulse injection into a dc line problem is simplified. In summary, this concept appears to be particularly effective for the transmission of pulses with 1 μ s decay. When this decay exceeds that value, as in the case of interest calling for 10's of microseconds, the conduction of ac power back through the load complicates the test setup. Then adequate power in the source which powers the load (test object) is required and cooling R_0 becomes more involved. In that case, a switch and circuit breaker concept would be the best alternative. This subject will be considered in the next section.

3-3.1 Effect of Long Pulse (10 to 30 μ s) on Design

The discussion above dealt with coupling a pulse with 1 μ s decay time from the pulser to a test object, where the test object is excited with its operational (power up) ac or dc voltage. To accomplish this a coupling capacitor is installed between the pulser and the test object. The pulser then consists of the combined pulser and coupling capacitor. The open-circuit voltage of this pulser $V_{oc}(t)$ is the same whether or not C_C is in place, since the capacitor is assumed to pass no current. Only the short-circuit current is affected by the presence of the capacitor. The larger the capacitance, the smaller the distortion of the short-circuit current. Also, the larger the capacitance the smaller the pulser voltage which actually appears across the capacitor. The design objective is to have the $R_0 C_C \gg T_d$ where T_d is the decay time of the pulse.

This motivates the use of a 20 nF capacitor for this 1 μ s decay. It is of interest to compare the stored energy due to the pulse in the 5 nF and the 20 nF case. The peak voltage in the 5 nF case is shown in Figure 3-13 at 950 kV. This is 2.3 kJ. As in Figure 3-14, the peak voltage in the 20 nF

MLA-11,544

Figure 3-13. Voltage across 5 nF coupling capacitor due to output current pulse.

MJA-11,541

Figure 3-14. Voltage across 20 nF coupling capacitor due to output current.

capacitor is 345 kV, corresponding to 1.2 kJ. In summary, these energy calculations indicate the elements which constitute the 20 nF capacitor would actually be smaller, lighter, and more easily designed than the 5 nF capacitor. The coupling capacitor must withstand the test object voltage so its length would be the same in both cases, since the length is determined by the test object excitation voltage.

Therefore, if the test object is powered up to 500 kV ac or dc, that voltage is the overriding concern for the coupling design, not the pulser voltage. (In practice, careful high voltage design is also required to provide adequate insulation of the capacitor from the surroundings. This view of the coupling capacitor as being simply a pure capacitor is deliberately simplified. Also, stray capacitance and inductance must be considered to fully analyze the optimum configuration).

Now consider the effect on the coupling capacitor of passing a 10 to 30 μ s pulse. A 200 nF is needed for a pulse ten times the width of that considered above. This coupling capacitor must still connect to 500 kV ac. That represents a substantially larger capacitor bank than that considered for the 1 μ s pulse, and one that passes much more ac current. (For dc, there is no power transmitted back and, in principle, this concept is acceptable).

For the 60 Hz case the capacitive reactance is $1/\omega C_C = 13$ kilohms. This would pass 38 amps back through the 400 ohm resistor and the ≈ 80 ohm pulser load (assuming 500 kV ac the test object). Therefore, these resistors must dissipate hundreds of kilowatts. That is not practical. The alternative design for coupling to 500 kV ac calls for a spark gap and a circuit interrupter to be used. This would be required to interrupt over 1 kA (500 kV/400 ohm). Commercial designs are available for this purpose.

To complete this discussion of coupling capacitors for 1 μ s decay on ac lines and all pulse widths on dc lines, consider the feasibility of constructing the 20 nF, 500 kV ac coupling capacitor. Capacitors are available which are 20 kV rms and up to 1 μ F each. These capacitors can be contained in steel cases about 2 x 1 x 0.5 ft and weigh less than 100 lbs each. A 20 nF capacitor could be constructed from a single series string of 25 units. The structure might be enclosed in a cylinder and insulated with one atmosphere of freon.

Another aspect of feasibility is the inductance contribution of the capacitor and the effect of this inductance on the pulse. Expected peaking

capacitor total series inductance is $\sim 1.5 \mu\text{H}$. To assess its impact in the short-circuit current, consider the L_C/R_O time. That provides a measure of the increased rise time to be expected. The effect is a rise time slowing of less than 5 ns. During actual design a more careful investigation into the effects of stray inductance and capacitance is required but, in summary, this coupling device appears to be feasible for the 1 μs decay.

3-3.2 Conformity with Specifications

This section addresses those specifications which may be influenced by the coupling components.

3-3.2.1 Decay Time. The open circuit voltage has the same decay time with or without the coupling capacitor. The short circuit current decay time is reduced by the coupling capacitor as shown previously (Figures 3-10 through 3-12). The decay time is met by appropriately sizing the coupling capacitance and the Marx capacitance for the 1 μs in the ac or dc case. For the 10 to 30 μs case, we distinguish between ac and dc power lines. For dc, use a $>200 \text{ nF}$ coupling capacitor which preserves the pulse shape. For ac, use a circuit interrupter and an output switch. The output switch breaks on the pulse rise time, thereby connecting the pulser to the powered-up load. Flowing SF_6 in the circuit interrupter and/or a mechanical separation in the current path (as with commercial vacuum interrupters) will stop the current at the first zero crossing after the pulse with no adverse effects on the decay.

3-3.2.2 Overshoot

A small overshoot (or reversal) is experienced in the short circuit current due to the coupling capacitance. This overshoot occurs relatively late in time after the e-fold decay time has been completed (Figure 3-13).

3-3.2.3 Rise Time

The coupling capacitor has only a minor adverse affect on rise time due to the stray series inductance. Care must be exercised to minimize shunt capacitive effects also. With careful design, the adverse affects of these strays may be minimized. We conclude that a 20 ns e-fold rise time may be transported through the coupling capacitors described above with only minimal distortion of rise time.

3-3.2.4 Multipoint Tests

This deals with the simultaneous injection of pulses into two or more points on the test object. The test object may be a 3-phase transformer, for example, and an important test may involve the simultaneous injection of a pulse into all phases. The concept for a 1 μ s decay is shown in Figure 3-15. Each individual phase is separately isolated with a coupling capacitor before being connected to the pulser output terminal. The coupling capacitor concepts discussed to this point are applicable to each single-phase coupling capacitor. It is important to note that currents will now be circulated between phases if the test object is energized with ac. These currents can be kept acceptably small, if the coupling capacitors are properly selected. For example, a 20 nF coupling capacitor will transmit about 4 A from phase to phase. In most test facilities, this would be acceptable.

It is feasible to inject pulses into more than one phase. For good simulation, this may require a reduction in the pulser driven impedance R_0 to take into account the parallel connection of resistors to each phase.

For the 10's of microseconds decay, a separate switch and circuit interrupter must be connected to each phase. In that case, prior to the pulse, no phase-to-phase current would circulate. During and immediately after a pulse, current would begin to circulate until the interrupter opened the circuit. This is shown in Figure 3-16.

Figure 3-15. A coupling capacitor connected to each of three powered-up terminals on a test object.

MLA-11,743

Figure 3-16. A spark-gap switch and interrupter connected to each of three powered-up terminals on a test object.

SECTION 4

PULSER DESIGN FOR POWER LINE TESTS

4-1 TESTS ON UNPOWERED LINES

4-1.1 General Considerations

To this point we considered test objects in the form of components such as surge arresters or transformers. If the component is not powered up, a direct connection is made from the pulser to the test object. If the test object is powered up, a coupling device such as a capacitor is required. In case of components which are charged with their operational ac or dc voltage, the coupling for a 1 μ s pulse width is made through a coupling capacitor which isolates the components ac or dc voltage from the pulser. For longer pulses, a capacitor is used for dc and a spark gap and interrupter is used for ac.

Now we consider the injection of pulses into overhead power lines. In this concept, the pulser described above is connected to a transition section. This section is in the general form of an insulated cable which slopes upwards from the pulser to the overhead power line. This insulated cable has an impedance due to its geometry. This impedance should closely match that of the pulser and the power line under test. In the case in which the pulser is 400 ohms and the power line is also 400 ohms, the surge impedance of the insulated cable should be approximately that value also. However, calculations to be discussed have shown that deviation from that ideal is possible without major impact on the quality of the pulse injected into the power line.

In this test configuration, the pulser and pulse shaping circuit is considered to extend up to the interface between the insulated cable of the transition section, and the power line itself. The criteria on open-circuit voltage and short-circuit current now apply to the output of the insulated wire where it meets the power line.

As before, two cases are relevant. In one, the line is not powered, and the insulated cable directly connects to the power line. In the second case, the power line is powered with its normal ac or dc voltage. In that case

the insulated cable and the power line. Either the coupling capacitor or a switch/circuit breaker would require an insulating support structure to hold it at an optimum point along the 15 to 35 m sloped length of the connection to the power line. The location of these components depends on considerations of safety and operating convenience.

4-1.2 Impedance

Consider the electrical effects of extending an insulated cable from the pulser to the overhead power line. We first take the case in which no coupling component is used. Simply extending a cable consisting of a 1 to 5 cm radius conductor from the pulser to the power line creates an impedance mismatch due to the varying proximity of the conducting ground along the cable. (An inner conductor of this relatively large radius is desirable to ensure that the configured insulation will survive the voltage. This will be discussed further in 4-1.2.1. This impedance variation affects the open-circuit voltage or short-circuit current waveforms applied to the interface between the cable and the power line.

Computer simulation were performed to show this effect. Figure 4-1 shows the output from an ideal 400 ohm pulser. The waveform is nearly ideal despite the extension of the 400 ohm cable. This is expected, and to explain this effect consider the case of a square pulse of amplitude V from a 400 ohm pulser injected into a 400 ohm cable. The open-circuit output voltage is a square pulse of exactly V and no reflections appear at the output. If any impedance mismatches were present, reflections with periods of two pulse-transit times would occur. The same reflection-free current waveforms occur if the output of the cable were short-circuited. Then, the current is V/Z_0 and is free of reflections. In the same sense, injecting a pulse into the input of the 400 ohm series resistor, passing it through an ideal 400 ohm cable, then observing the open-circuit voltage and short-circuit current would be the same as if the insulated cable were not present. Therefore, if the pulser met the requirements for component testing using the output of the resistor as the interface, then it also meets the requirements with an ideal 400 ohm cable extending from the pulser to the power line. A conceptual design of a pulser connected to the power line is shown in Figure 4-2.

Figure 4-1. Waveshape when pulser discharges into a 100 ft section of 400 ohm transmission line.

Figure 4-2. Conceptual design of an overhead power line test configuration.

These considerations do not include the electromagnetic properties of the transmission line formed by the cable and ground. Such effects are important when analyzing the electromagnetic environment created at the interface with the overhead power line and many of those effects could be analyzed experimentally using low voltage apparatus. The short-circuit current waveshape with this impedance mismatch is shown in Figure 4-3. An impedance distribution of a conductor over ground for wire radii of 0.01, 0.05, and 0.1 m is shown in Figure 4-4. A distribution of this type was used to define the non-uniform line used in the previous figure.

4-1.2.1 High-Voltage Properties. An important consideration in designing the cable is its high-voltage design. Careful design can eliminate breakdown of the cable in the air. This can be done by using large diameter cable and by enclosing it in an insulating sheath.

In order to evaluate feasibility of this approach, preliminary estimates of the dimensions of the insulating sheath were obtained. Also, the dependence of the electric fields at the conductor surface and at the insulator-to-air interface was estimated using a coaxial approximation. The coaxial fields are slightly higher than those of the cylinder-over-plane so that the coaxial approximation provides a worse than actual case. For convenience in design calculations, the coaxial approximation for the peak fields was used. As shown in Table 4-1 coaxial peak fields are 10 percent higher than the cylinder-over-plane peak fields. The coaxial approximation is convenient to generate worst-case estimates of the effect of an insulating sheath on the peak fields. To avoid electrical breakdowns, the field must be identified at two points; it must be held below breakdown at the conductor surface inside the dielectric, and at the interface between the dielectric and air. To generate examples, these calculations were done assuming a 5 MV applied voltage to an insulated cable.

Special high-voltage cables have been known to withstand 50 MV/m (400 kV/cm) within the dielectric although the life of cables subject to that stress is limited under some conditions. Such a cable shows promise because the stress is attained for a 1 cm radius conductor within a plastic sheath of about 1 m. A configuration of this kind could meet this criteria. Consider a 0.1 m radius conductor with varying plastic sheath diameters. (These are the primed curves in Figure 4-5). These internal peak stresses of below 10 MV/m

MLA-10,226

Figure 4-3. Waveshape when pulser discharges into a nonuniform line with 11 sections of 350 ohm $< Z < 400$ ohms.

MLA-10, 214

Figure 4-4. Cylinder-over-plane impedance versus height.

Table 4-1. Comparison of coax and cylinder-over-plane peak field and impedance 5 MV on coax.

r_i m	r_o m	COAX		CYL/PLANE		ΔE	ΔZ OHMS
		$E_{pk}^{(1)}$ MV/m	$Z^{(2)}$ Ω	$E_{pk}^{(3)}$	$Z^{(4)}$ Ω		
0.01	2	94.0	318.0	85.0	360	10%	42
	10	72.0	415.0	65.0	456	10%	41
1.00	2	7.2	41.6	6.5	79	10%	37
	10	2.2	138.0	2.0	180	10%	42

$$^{(1)} V/[r_i \ln (r_o/r_i)] = E_{pk}$$

$$^{(2)} (60/k^{0.5}) \ln (r_o/r_i) = Z_{COAX}$$

$$^{(3)} 0.9 V/[r_i \ln (r_o/r_i)] = E_{c/p}$$

$$^{(4)} (60/k^{0.5}) \ln \{[(r_o/r_i) + [(r_o/r_i)^2 - 1]^{0.5}]\} = Z_{c/p}$$

$$\text{FOR LARGE } (r_o/r_i), Z_{c/p} = 60/k^{0.5} [\ln 2 + \ln(r_o/r_i)] = 42 + Z_{COAX} \text{ OHMS}$$

Figure 4-5. Electric field on inner conductor with 5 MV applied to inner conductor with radius r_1 surrounded by insulating sheath ($k = 2.5$) with radius r_2 within outer conductor of radius r_3 . This calculation is used to estimate fields at sheathed conductor.

(100 kV/cm) are manageable in one of numerous dielectrics including transformer oil. In that concept, an oil-filled dielectric cylinder would contain the conducting tube along a common axis). This cylinder need only extend a short distance from the pulser, until the fields were reduced to the point that the conductor could be in air with only limited corona. The outer fields can readily be maintained below 2 MV/m, an important criterion to avoid corona. As shown, the critical area is near the pulser, about 2 to 4 m off ground, which is the vicinity of the pulser oil-to-air interface. Typical design curves are plotted in Figure 4-6. The curves shown are not accurate in the critical area near the pulser because the bushing size will be large compared to the cable diameter in order to reduce these interface fields. Other field plotting techniques are used in that area for high accuracy. (Design considerations of this interface were discussed in Section 3.)

To summarize, designing and constructing a 300 to 400 ohm cable connection for a transition between the pulser and the power line is feasible. With care taken to minimize the impedance variation from the nominal value (400 ohms) a design can be developed to create the appropriate waveshape at the power line while avoiding serious waveform perturbations due to the transition.

4-1.2.2 Multiline Tests. As discussed previously, multiline tests can be conducted, although the pulser internal impedance R_0 should be adjusted to account for the lower common mode impedance of the power lines. Regarding the transition section, one convenient method for testing multiple power lines may be to use multiple cables from the pulser to the overhead line. The reduced impedance of the several cables could be arranged to approximately match the lower impedance of the two or more cables in the power line.

MLA-10,213

Figure 4-6. Electric field at outer insulator surface.
For coaxial cylinders:
 r_1 = inner conductor radius
 r_2 = insulating sheath radius
 r_3 = outer conductor radius.

SECTION 5

SYSTEM CONSIDERATIONS

5-1 SUMMARY OF TEST OBJECTIVES

This section discusses, in general terms, typical test objectives, test configuration, and diagnostic practices.

To this point in the discussion the concept of test facility is one in which power system components are brought to a final location for EMP vulnerability tests. The test objectives may be, for example, to determine the external or internal high-voltage failure levels of power system components such as surge arresters. Other components such as transformers, may be subject to test to qualify them at a specified level of threat; in that case, the objective may be to establish their capability to withstand a specified level without electrical failure due to high-voltage stress breakdown (analogous to Basic Impulse Level (BIL) testing).

Power lines may be erected at such a facility to test their response and the response of attached components to the simulated EMP voltage.

5-2 TEST CONFIGURATION

The equipment under test is generally operated in atmospheric air environment. The pulser contains the wave shaping components which provide the required pulse shape at an air interface. In the case of test components which are not energized with voltage, direct connection is made from the pulser to the test component.

If the test component is energized, a coupling capacitor or switch/interrupter is required between the pulser and the test component. The coupling capacitor is in the form of an insulating cylinder, with conducting end caps. A series/parallel set of capacitors is contained within this cylinder. Capacitor size depends on the voltage of the test component and on the decay time of the pulse to be coupled. The switch/interrupter may be simply an SF₆-purged spark gap or a spark gap in series with a commercial vacuum interrupter.

The pulser is contained in a steel oil-filled enclosure. We distinguish between the multi-megavolt (4-5 MV) pulser which generates the 1 μ s decay time and the lower voltage (0.8 MV) pulser which generates the 10 to 30 μ s decay time. It is likely the latter would be contained in a compact second enclosure located at one side of the first enclosure. The 4 to 5 MV, 1 μ s pulser is contained in a 8 to 10 m long, 3 to 4 m wide, 3 to 4 m high steel oil tank. The output structure of this pulser would be in the form of a hemispherical insulator with a conducting central conductor. The test object would be located directly outside of this interface. The smaller pulser contains a 0.8 MV pulser for 10 to 30 μ s decay of about 2 to 3 m in length, 2 m in width, and 2 m in height.

A double screen-room should be located near the pulser and test object. One screen room would contain all command and control equipment for the pulser and the test object control; and the other would contain diagnostic measurement and recording equipment.

The pulsers described in this report require oil handling and storage facilities.

5-3 DIAGNOSTICS

The pulser itself should be equipped with performance diagnostics such as resistive load voltage and current. This will monitor pulser performance only. To monitor the electrical performance of the test object, the voltage at the output terminal of the 400 ohm series resistor should be monitored. This resistor may be an aqueous CuSO_4 resistor connected between ground and the output side of the series resistor.

The pulse current which flows through both the 400 ohm series resistor and the output load should also be monitored. This current also flows from the test object to facility to the ground. Two locations are possible for this load current monitor. In one, the current probe is located in the 400 ohm series resistor. The data from that sensor may be converted to an optical signal and transmitted away from the high-voltage region by means of optical fibers. A second photodiode in the screen room converts the signal to analog voltage waveforms. Another alternative is to connect current-shunt monitors in the ground plane which connects the pulser to the test object. The selection of this current monitor may depend on the nature of the component under test. Certain components limited in size and complexity may allow the use of a

diagnostic loop such as a Pearson current transformer. A summary of recommended diagnostics is shown in Table 5-1.

Table 5-1. Summary of recommended diagnostics.

Diagnostics	Purpose
DC charge voltage	Marx voltage
Pulse voltage at R_{p1}	Marx output waveform
Pulse voltage at C_p	Pulser performance diagnostics
Test object voltage	Test object performance
Test object current	Test object current after breakdown
Electromagnetic field sensors	Measure propagated wave

SECTION 6

REVIEW OF STATE OF THE ART

This section provides background data on simulators currently in use for EMP and lightning testing of military and civilian equipment potentially vulnerable to high-voltage transients. We begin the discussion with a summary of high-voltage Marx pulsters because these are the most commonly used in modern high-voltage simulators, at least in this country. This is followed by a listing of the various facilities at which testing has been conducted. We include in this category, lightning test facilities because many similarities exist between EMP and lightning, from the standpoints of equipment requirements and test object vulnerability.

6-1 PULSER TECHNOLOGY

Pulsters in the 10's of kilojoule, 5 MV class have been available for EMP testing over the past 15 to 20 years. Often these create fast rising (<10 ns rise time, 10 to 90 percent) pulses with exponential decay on the order of 100's of nanoseconds. Therefore, from the standpoint of the high-voltage source itself, the required 4 MV with 10's of microseconds decay is well within the state-of-the-art.

For generating fast rise times, alternative electrical circuits were compared over the years. A so-called transfer circuit appeared to be an attractive candidate for many applications. This circuit operates by transferring the stored Marx energy into a large high-voltage capacitor which is then discharged into the output load. The main difference between the transfer circuit and the peaking circuit is discussed in this report. The capacitance of the high-voltage capacitor in the transfer circuit exceeds that of the peaking circuit. Also, sustained high-voltage is much greater in the transfer circuit. The industry ultimately favored the peaking capacitor primarily because these factors result in a high-voltage design substantially simpler than that of the transfer capacitor. In virtually all cases the use of a peaking capacitor to

store the transient energy needed for the rise time was found to be the preferred design.

The dual exponential decay described previously is created with two separate Marxes. The use of the second Marx to create the second slow decay may represent a new arrangement of Marxes. Usually paralleled Marxes are used in order to store larger amounts of energy to create lower inductance. Low inductance Marxes have the advantage of discharging relatively quickly thereby holding high-voltage on the charged components for the minimum time. In EMP testing no system known by this author calls for a double decay time as indicated in these specifications.

The output load resistor allows the Marx/pulser assembly to provide the same waveshape for the open-circuit voltage and for the short-circuit current.

6-2 EMP TESTING

Limited testing has been performed using circuits which allow pulses to be injected into power lines and components although at substantially lower voltage and energy than that indicated in the present requirement. Theory and practice of such testing is in the EMP Handbook for Electric Power Systems by E. Vance. Such testing has been conducted at Culham Labs in England. This laboratory, though not known for big machines, has devised simple, relevant experiments to evaluate coupling. Tests have been conducted on F16 aircraft.

Details on equipment and tests are available from:

Brian Burrows
Culham Labs.
Ebbington, Oxford UK
Telephone: (235) 464 1000

A component injection test was conducted by E. Vance for AFWL under the Minuteman program. For this test, the EMP pulser was capacitively coupled to the line. A variant of this configuration included a diesel engine generator as the power source for tests on military equipment. Other elements were basically the same in both experiments. An air core choke served as a filter to protect the generator from the simulated EMP pulse. (The diesel

Metal oxide varistors and spark gaps were considered for injection of the simulated EMP pulse onto the power line if the pulse amplitude is much larger than the peak ac amplitude. MOV's have been used to test C³ systems (by Mission Research Corp. for the Air Force Weapons Lab, Albuquerque). It has only been used for injection on the low voltage side of the transformer. Spark gaps are also appropriate for this application, although they might be noisier. The MOV/SG is non-conducting at line voltage, but fully conducting at EMP-induced voltage.

6-3 FACILITIES

In summary, it is noted that no background on the response of power system equipment to fast rising, megavolt EMP, with microsecond decay has been found. Megavolt level data has been acquired in the simulation of EMP fast rise (~10 ns) and decay of 100's of nanoseconds. Also, data has been acquired in the simulation of lightning (μ s rise, 10's of microsecond decay). Limited data has been obtained at ~100's of kV with rise and decay times of interest to this study. These tests were performed on military systems which included small, portable power system components. Table 6-1 lists laboratories generally involved in power systems and EMP testing.

Table 6-1. List of Laboratories with data or equipment related to power line tests.

Laboratory	Test Voltage	Facility Type
Boeing	to 2 MV	Lightning impulse
Westinghouse	to 5 MV	Lightning impulse
McDonnell Douglas	1.6 MV	Lightning impulse
Georgia Light and Power	1.5 to 5 MV	Lightning impulse
Biddle		Mfg. of impulse generators
Lockheed		Lightning facility planned
Maxwell Laboratories		Mfg. of EMP & lightning generators
Air Force Weapons Lab	to 5 MV	Fast pulse EMP
University of Waterloo	1.2 MV	Lightning & switching
Physics International Co.		Mfg. of EMP equipment
PSI, Inc.		Analysis of EMP requirements
Northrup	1.6 MV, 4 kJ Marx Full set of 500 kV, 100 kJ lightning pulses, A thru D	Lightning & current injection
Bonneville Light & Power	5.6 MV	Lightning impulse

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7-1 GENERAL

This report describes conceptually the methods by which the specifications listed in Table 1-2 may be accomplished. An important underlying theme was to establish techniques by which the objectives can be met with design principles within the state-of-the-art. Perhaps the best example of this is the high-voltage equipment which generates the fast rise time followed by the 1 μ s decay. Many such pulser have been constructed and a large body of data is available describing their function and performance.

In the case of the coupling techniques for powered-up components and transmission lines, the design principles are within state-of-the-art but proof-of-design experiments are recommended prior to installation in a power system test facility. Of special interest in this regard is the interrupter used to disconnect the pulser from the test object at the conclusion of the pulse. (The initiating of the pulse can be done with a conventional gas-insulated spark gap.) This is an important problem in the coupling of long pulses (10's of microseconds) into powered-up ac lines. In principle, a simple SF₆-purged spark gap may perform this interrupt function without the need for commercial circuit interrupters although, if needed, those are indeed available and within the state-of-the-art. Table 7-1 summarizes the coupling techniques appropriate for each of the specified delay times.

The use of the second Marx to generate the second decay (10's of microseconds) also is a case in which all required principles are within state-of-the-art although proof-of-design tests are recommended. Recent developments in laser triggered crowbar switches at Maxwell (in the 2 MV range) point to the use of this type of switch to command fire the second pulser into the output load at the desired time to create a smooth blend of the 1 μ s decay with the 10's of microsecond decay.

The high-voltage design of the transition section between the pulser and the test component or power line is attained with well developed

Table 7-1. Summary of Coupling Techniques.

Decay μ s	Test Object Power (Component or Power Line)	Coupling
1	None	Conductor
1	AC	Capacitor (gas switch/ interrupter also feasible)
1	DC	Capacitor
10-30	None	Conductor
10-30	AC	Gas switch and interrupter
10-30	DC	Capacitor

computerized field plotting techniques. Multimegavolt transitions from oil insulation to air have been made in the voltage range up to 5 MV, although these tend to be somewhat large. To reduce their dimensions, and thereby reduce their cost while enhancing the portability of the system, some developmental work would be required. This would address the influence of the long pulse on the acceptable field strengths in air as they are now understood by the EMP industry.

An area of concern for the pulser/air interface is its affect on the rise time of the pulse as it propagates through the interface and to the component. This concern is also important for the transition from the pulser/air interface to the insulated wire transmission line which extends up to the overhead transmission line. Electromagnetic effects in this transition are not expected to lengthen the pulse beyond the specified range but limited testing would be desirable to verify and strengthen mathematical models used in the estimation of the influence of this transition on the waveshape.

In review, although the required designs are within current practice, we recommend a scaling in the voltage below the 4 to 5 MV discussed in this report. Many of the main features can be studied in the 1 to 2 MV range in a cost-effective manner and in shorter periods than can be accomplished at the higher voltages. For powered-up components and power lines, a scaling of the

component ac or dc voltage is called for. The range of 100 kV may be of interest because it would then be scaled down in the same measure as the pulser voltage.

7-2 PROGRAM PLAN

A program to systematically develop the equipment to meet all the objectives can be defined. Following is an approach which calls for the use of a Marx pulser in the 1 to 2 MV range to provide the first building block.

7-2.1 Component Tests - Pulser

Consider a 1 to 2 MV pulser consisting of a Marx and peaking capacitor. Construct a resistive network to provide appropriate open-circuit voltage and short-circuit current. Set the component values for the 1 μ s decay time. Select a load suitable for test, such as a large insulator or a gas pressurized spark gap capable of withstanding the open-circuit voltage and the short-circuit current of the pulser. Fire the pulser into this load and study the open-circuit voltage and short-circuit current to establish the effective electrical parameters of the pulser.

7-2.2 Coupling Devices

Construct and test a capacitive coupling for use with dc powered test components. Evaluate effect of dc on component flashover.

Modify the coupling capacitor (if necessary) for ac operation. Test and compare this coupling approach with that calling for a switch/circuit interrupter. To start, the switch/circuit interrupter may consist of a single SF₆-purged spark gap.

7-2.3 Long Pulse Decay

Construct the auxiliary pulser to provide the 10 to 30 μ s decay. Use laser triggered switch as developed at Sandia and Maxwell. Study the effect of switch firing points on waveform quality. Apply dual-decay waveform, (1 μ s followed by 10 to 30 μ s), to an arbitrary test object using direct conductive coupling.

7-2.4 Long Pulse Coupling

For dc powered components, evaluate capacitive coupling of the long pulse. (The capacitance of the coupling must be increased compared to that used above due to the extended decay.)

For ac powered components, use switch/circuit interrupter, such as SF₆-purged gas switch. Investigate and compare commercial vacuum interrupters.

7-3 POWER LINE TESTING

7-3.1 Wire Line Transition

Use the 1 to 2 MV pulser with peaking circuit and resistive network as described above. Set up for 1 μ s decay. Evaluate high-voltage performance of several insulated lines extending arbitrary distances and heights from the pulser transition section. Determine influence of corona on propagated waveshape. Evaluate effect of transition shape on the waveshape.

7-3.2 Electromagnetic Modeling

Perform low voltage scale model studies to measure the effect of geometry on the waveshape of the propagating waveform. (This can be done using convenient laboratory dimensions for the pulser interface, the transition section and a segment of power line.)

7-3.3 Coupling the 1 μ s Decay to AC or DC Lines

For ac power, compare performance of a coupling capacitor with a switch/interrupter.

For dc power use coupling capacitor. Confirm waveshape of power line pulses after transmission through the coupling devices.

7-3.4 Long Decay

Configure pulser for 10 to 30 μ s decay, as described above. Pulse through conductive coupling into power line to evaluate effect on corona of wave propagation for long pulses.^{13,14}

7-3.5 Long Decay Coupling on Powered Lines

AC Lines. Use coupling capacitor with sufficient capacitance for low distortion. (A 200 nF capacitor may be used here.)

DC Lines. Install, test, and compare switch/interrupter with capacitive coupling.

Once this sequence of tests is performed, continued development for higher voltage equipment can be performed by repeating the sequence of experiments with larger pulsed, transitions, and coupling capacitors. However, the equipment developed above is ready for the performance of important tests on actual power lines. Experiments can be envisioned in which the pulser injects high-voltage waveforms into one end of a power line, which is either powered-up or not. Components which are attached to the line would be exposed to EMP in order to evaluate the impulse response. This would provide an extension of the Basic Impulse Level (BIL) data used by the power industry to grade the impulse response of power line components.¹⁵ The propagation characteristics can be measured with electromagnetic field sensors deployed at various points down the line. Effects of corona, dispersion due to ground resistivity, and radiation from the line can be studied to assess EMP threat as a function of distance from the injection point. This is viewed as a critical vulnerability experiment.

SECTION 8
BIBLIOGRAPHY

1. Klein, Barnes, P.R. and Zaininger, H.W., "EMP and the Electric Power Network," ORNL Report, February 1984.
2. Barnes, P.R., Vance, E. and Askins, H.W. Jr., "Nuclear EMP and Electric Power Systems," ORNL-6033, April 1984.
3. Oak Ridge National Laboratory, "Program Plan for Research and Development of Technologies and Systems for Electric Power Systems Under the Influence of Nuclear Electromagnetic Pulses," May 1983.
4. Marable, J.H., Barnes, R. et al., "Power System EMP Protection," ORNL-4958, March 1975.
5. Tesche, F.M., "Excitation of Overhead Lines by Alternate HAEMP Environments," LuTech, Inc., PSA Memos #15, October 10, 1984.
6. Smith, I., "Further Studies of the Response of Power Lines to High Altitude EMP, PSI Interim Report to ORNL, October 1984.
7. Vance, E., "EMP Handbook for Electric Power Systems," Stanford Research Institute, Menlo Park, California, December 1984.
8. Baum, C.E., "EMP Simulators for Various Types of Nuclear EMP Environments: An Interim Categorization," July 1976.
9. Lee, K.S.H., Yang, F.C. and Engheta, N., "Interaction of High-Altitude EMP with Transmission and Distribution Lines," Interaction Note 435, December 1983.
10. Sharfman, W.E. and Vance, E., "EMP Coupling and Propagation to Power Lines: Theory and Experiments," AFWL Report TR-73-287, February 1974.
11. Whitson, A.L., "Engineering Techniques for EMP Hardness Testing," September 1973.
12. Sharfman, W.E. and Vance, E., "EMP Coupling to Power Lines."
13. Ramrus, A. and Clark, W. "Corona from a Pulsed Wire Transmission Line, Unpublished Internal Report, 1970.
14. Book, P.S. and Harold, J.P., "A Transmission Line Corona Experiment," Interaction Notes, Note 313, October 1976.
15. Westinghouse Electric Corporation, "Electrical Transmission and Distribution Reference Book," East Pittsburgh, Pennsylvania, Chap. 18.

APPENDIX

TESTING OF ENERGIZED SYSTEMS

1. INTRODUCTION

When systems are tested with high-voltage transient excitation, it is usually easier to couple the source and measurement instruments to the system if the normal operating power is turned off. For making diagnostic measurements, such as passive transfer function measurements in which energization of the circuits is not a factor, it is usually not necessary to perform the measurement with the system energized. However, when the purpose of the test is to evaluate the performance of the protection system or to evaluate the performance of the protected system, it is usually important to have all parts of the system energized and operating normally.

2. PURPOSE OF TEST

If the purpose of the test of a system with high level transients is to determine whether or not the system will perform as intended when it is operating in the field and exposed to an actual EMP or lightning transient, it is important that the system tested be constructed like a production system, and that it be operating like an operational system when it is exposed to the transient stress. While it is possible in some cases to deduce the effects of minor differences between the test conditions and the actual field operating conditions, this usually requires a thorough understanding of all of the possible responses of the system - nonlinear as well as linear - to the transient excitation. On the other hand, if we really possessed such an understanding, we would not need to test the system at all. Of course, one reason for performing a test is to verify our understanding of the system performance.

Furthermore, the reliance on understanding minor differences is often overworked, because the excitation is not an exact simulation of the threat transient, and the system under test is frequently not a production unit but a prototype or preproduction unit. Thus, there are significant differences between the test and an operational situation even if the system is energized

and functioning in some expected operating state. When the differences between the simulated transients and the real EMP or lightning, the differences between the test system and production units, and the variation from unit to unit are combined, the number of uncertainties is already too large to be completely accounted for.

Finally, it should be noted that high level transient tests of systems almost always demonstrate that some aspect of the system response was overlooked or incorrectly assessed. Frequently, the "surprise" response involves the differences in performance or response when the system is energized. Evidently, one important purpose of the test is to discover these unexpected responses. Some of these responses are described below.

3. RESPONSES OF ENERGIZED SYSTEMS

The responses of energized systems differ from those of de-energized systems primarily because the impedances differ and because the transient can trigger the release or switching of system energy. The switching of system energy is usually the more spectacular effect, since this mechanism can cause damage well beyond that possible with the energy in the excitation pulse alone. Furthermore, it is an effect that is often overlooked in the analysis of system failure through transient-induced damage. Some examples will illustrate this point.

ESA Damage: An electric surge arrester (ESA) installed in a system functioned appropriately under transient excitation when the de-energized system was tested. When the energized system was tested, however, ac power applied across the ESA caused it to remain conducting for several microseconds each time the transient was applied. This additional conduction and energy dissipation caused the ESA to fail after several exposures to the transient. Failure was caused by sputtered electrode material building up until the spark gap was closed permanently. This result had not been previously suspected, and it would not have been detected without testing the energized system.

Insulation breakdown: There have been several cases in which air or solid insulation breakdown have occurred with the system energized, but did not occur (or was not noticed) when the system was not energized. In these cases, the transient voltage superimposed on the system operating voltages was sufficient to cause the insulation to fail, while the transient voltage alone did not produce a noticeable failure. Frequently, such failures occur at flaws

that do not meet the system specifications - for example, they might occur at a point where wire insulation is damaged adjacent to a metal structure or on a terminal strip whose screws are too long and are almost penetrating the insulation between the strip and the supporting metal structure. Sometimes the transient alone produces a very weak short breakdown that is hardly noticeable, but when the system is energized a destructive high power arc is triggered. As suggested, these malfunctions often occur at flaws that should not be present but usually are present in practical systems.

Energy dump: Occasionally a circuit or device is destroyed in a test in which a pretest analysis had predicted that the transient energy in the test source "could not possibly harm the test circuit." The explanation of these unexpected failure is often found in a post-test analysis to be that the transient allowed a charged filter or power supply capacitor to discharge through the damaged device, thereby delivering much more energy to the device than the transient alone could provide. In complex circuits with many modes for abnormal excitation, it is almost impossible to identify all of the modes, let alone accurately predict the system response to each.

Saturation: Ferrous cores in inductors and transformers are nonlinear and are frequently operated in or near their nonlinear range. Particularly in power equipment, the impedance and the linearity may change significantly when the system is energized. Although the effect of saturation is usually not dramatic, it has been a concern in power system components, such as line filters, because the insertion loss measured without power frequency current flowing through the filter is sometimes quite different from the insertion loss measured with rated current flowing.

Synergistic effects: There are other more complicated combined effects that can occur and have occasionally been observed. These often involve nonlinear elements, such as surge arresters, that interact with other elements of the system to produced unexpected responses. For example, a nonlinear device, such as an activated surge arrester can interact with the energy radiated by transmitting antennas to produce harmonics or intermodulation that affect another unrelated subsystem. In another example, the test of a surge arrester system with power applied demonstrated that the surge arrester performed properly, but when this test was conducted with all of the electronic circuits energized, it was found that some digital circuits were triggering on the surge arrester transient (the circuits functioned properly when the test

transient was just below the surge arrester firing threshold.) In a third example, it was observed that a filter and isolation transformer combination allowed more differential-mode transient through than had been anticipated. This appeared to be caused by surge arresters placed across the filter input terminals that, when activated, effectively shorted one phase and allowed a large differential current to flow through the transformer windings.

4. CONCLUSIONS

As these examples illustrate, it is almost impossible to predict some of the responses of a complicated system to transient excitation that drives some parts of the system into nonlinear states. This is further exacerbated by the flaws that are present in all systems, and by synergistic effects that occur when two or more phenomena are present simultaneously, but do not occur when any one phenomenon alone is present. It is to discover these unpredicted responses that we test the system under conditions as nearly approximating the operating conditions as possible. Since experience shows that the system response when it is energized is often significantly different from its response when it is not energized, it is important to test the system in the energized condition (and in any other condition that the system is expected to survive and function.)

INTERNAL DISTRIBUTION

1. R. L. Anderson	35. J. W. Michel
2-25. P. R. Barnes	36. M. O. Pace
26. R. S. Carlsmith	37. R. A. Stevens
27. L. G. Christophorou	38. J. P. Stovall
28. S. J. Dale	39-43. Z. E. Whitson
29. W. Fulkerson	44-45. Central Research Library
30. P. A. Gnad	46. Document Reference Section
31. J. A. Hawk	47-48. Energy Information Library
32. H. W. Hoffman	49. Laboratory Records - RC
33. F. C. Maienschein	50-51. Laboratory Records Department
34. V. C. Mei	52. ORNL Patent Section

EXTERNAL DISTRIBUTION

- 53. V. D. Albertson, Department of Electrical Engineering, 123 Church Street, S.W., University of Minnesota, Minneapolis, MN 55455
- 54. H. W. Askins, Jr., The Citadel, Charleston, SC 29409
- 55. C. E. Baum, AFWL/NTAAB, Kirkland AFB, NM 87117-6008
- 56. R. Bellem, Director for Radiation, Defense Nuclear Agency, Washington, DC 20305
- 57. J. N. Bombardt, R&D Associates, 105 E. Vermijo Street, Suite 450, Colorado Springs, CO 80903
- 58. G. E. Brackett, Code H25, Navy Surface Weapons Center, 1091 New Hampshire Avenue, Silver Springs, MD 20903-5000
- 59. E. H. Brehm, Department GK/CN32, Brown, Boveri, and Cie, Aktiengesell Schaft, Postfach 351, D-6800 Mannheim 1, WEST GERMANY
- 60. F. C. Buchholz, Pacific Gas & Electric Co., 77 Beale Street, Room 2933, San Francisco, CA 94106
- 61. J. F. Buck, Wisconsin Electric Power Company, 231 W. Michigan, Milwaukee, WI 53201
- 62. L. M. Burrage, McGraw-Edison, P.O. Box 100, 11131 Adams Road, Franksville, WI 53126

63. H. S. Cabayan, Lawrence Livermore Laboratory, P.O. Box 5504, Livermore, CA 94550
64. F. L. Cain, Georgia Institute of Technology, Engineering Experiment Station, Atlanta, GA 30332
65. J. G. Carbonell, Associate Professor of Computer Science, Carnegie-Mellon University, Pittsburgh, PA 15213
66. R. N. Carlile, Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721
67. I. J. Carney, Nuclear Survivability Organization, Boeing Aerospace Company, P.O. Box 3999, Seattle, WA 98124
68. V. L. Chartier, Bonneville Power Administration, P.O. Box 491-ER, Vancouver, WA 98666
69. K. K. Chen, Sandia National Laboratory, Drawer 1333, P.O. Box 5800, Kirkland AFB, NM 87185
70. R. F. Chu, Philadelphia Electric Company, 2301 Market Street, MS 10-1, P.O. Box 8699, Philadelphia, PA 19101
71. H. E. Church, Aluminum Company of America, 1501 Alcoa Building, Pittsburgh, PA 15219
72. B. Cikotas, DCES (R-620), Defense Communications Agency, 1860 Wiehle Avenue, Reston, VA 22090-5500
73. C. F. Clark, Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208
74. R. E. Clayton, Power Technologies, P.O. Box 1058, 1482 Erie Boulevard, Schenectady, NY 12301-1058
75. A. Clerici, Sanelmi, Via Pergolesi 25, 20124 Milano, Italy
76. H. W. Colborn, North American Electric Reliability Council, Research Park, Terhume Road, Princeton, NJ 08540-3573
77. P. L. Collins, VP-TP0, Defense Intelligence Agency, Washington, D.C. 20301-6111
78. D. E. Cooper, Southern California Edison Company, P.O. Box 800, 2244 Walnut Grove Avenue, Rosemead, CA 91770
79. R. Cortina, ENEL-Centro Ricerca, Automatica, VIA Volta 1, Cologno Monzese (MI), ITALY
80. G. Dahlen, Royal Institute of Technology, S-100-44, Stockholm, SWEDEN

81. J. Darrah, Headquarters NORAD/G5, Peterson AFB, CO 80914
82. Defense Technical Information Center, Cameron Station,
Alexandria, VA 22314
83. J. J. Dougherty, Electric Power Research Institute, P.O. Box 10412,
Palo Alto, CA 94303
84. W. M. Druen, 8200 South Memorial Parkway, Suite D, Huntsville,
AL 35802
85. J. C. Engimann, Commonwealth Edison, 1319 S. First Avenue,
Maywood, IL 60153
86. D. M. Ericson, Jr., Sandia National Laboratory, Division 6414,
Kirkland AFB, NM 87185
87. W. E. Ferro, Electric Research and Management, Inc., P.O. Box 165,
State College, PA 16804
88. W. G. Finney, Project Manager, Stanley Consultants, Inc., Stanley
Building, Muscatine, IA 52761
89. M. Fitzgerald, MITRE Corp., P.O. Box 208, Bedford, MA 01730
90. F. Fisher, General Electric Corporation, Electric Utility Systems
Engineering Department, Building 5, Room 306, Schenectady, NY 12345
91. P. B. Fleming, Science and Engineering Associates, Inc., Mariners
Square, Suite 127, 1900 North Northlake Way, P.O. Box 31819,
Seattle, WA 98103
92. R. Fullwood, Science Applications, Inc., 5 Palo Alto Square, Suite
200, Palo Alto, CA 94304
93. R. Gates, Federal Emergency Management Agency, Research
Division, 500 C Street, S.W., Washington, DC 20472
94. M. R. Gent, North American Electric Reliability Council, Research
Park, Terhume Road, Princeton, NJ 08540-3573
95. S. M. Gillis, Economic and Public Policy, Department of Economics,
Duke University, 4875 Duke Station, Durham, NC 27706
96. W. Graham, R&D Associates, P.O. Box 9695, Marina Del Rey, CA 90291
97. J. J. Grainger, 5004 Hermitage Drive, Raleigh, NC 27612
98. I. S. Grant, Power Technologies, Inc., 1482 Erie Blvd.,
Schenectady, NY 12305
99. A. R. Gritzke, U.S. Department of Navy, Theater Nuclear Warfare
Project Office, Washington, DC 20360

100. J. Gut, Research Intitute for Protective Construction, Auf der Mauer 2, CH-8001 Zurich, SWITZERLAND
101. V. Guten, R-52, National Security Agency, Fort G. Mead, MD 20755
102. M. H. Hesse, JEC 5008, Rensselaer Polytechnic Institute, Troy, NY 12181
103. D. Higgins, JAYCOR, Santa Barbara Facility, P.O. Box 30281, 360 South Hope Avenue, Santa Barbara, CA 93105
104. D. W. Hilson, Tennessee Valley Authority, 1100 Chestnut Street, Tower 2, Chattanooga, TN 37402
105. F. C. Holdes, Pacific Gas & Electric Company, 3235-18th Street, San Francisco, CA 94110
106. W. S. Howington, Noranda Aluminum, Inc., P.O. Box 70, New Madrid, MO 63869
107. R. Hutchins, BDM Corporation, 1801 Randolph, S.W., Albuquerque, NM 87106
108. J. Hunt, Emergency Preparedness Administrator, San Diego Gas and Electric Company, P.O. Box 1831, San Diego, CA 92112
109. V. Inkis, Ontario Hydro, U7E1, 700 University Avenue, Toronto, Canada M5G1X6
110. Wasyl Janischewskyj, Electrical Engineering Dept., University of Toronto, Toronto, Canada M5S1A4
111. H. P. Johnson, Georgia Power Company, 270 Peachtree Street, 11th Floor, Atlanta, GA 30303
112. V. K. Jones, Science and Engineering Associates, Inc., Mariners Square, Suite 127, 1900 North Northlake Way, P.O. Box 31819, Seattle, WA 98103
113. F. R. Kalhammer, Vice-President, Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303
114. W. Karzas, R&D Associates, P.O. Box 9695, Marina Del Rey, CA 90291
115. R. E. Kasperson, Professor of Government and Geography, Graduate School of Geography, Clark University, Worcester, MA 01610
116. K. W. Klein, Forrestal Building, Room 5E-052, 1000 Independence Avenue, S.W., Washington, DC 20585
117. J. Koepfinger, System Planning Department 21-2, Duquesne Light Company, 1 Oxford Centre, Pittsburgh, PA 15279

118. N. Kolcio, American Electric Power, 1 Riverside Plaza,
Columbus, OH 43216
119. J. Labadie, IRT, 6800 Poplar Place, McLean, VA 22131
120. H. T. Lam, South Carolina Public Service Authority, 1 Riverwood
Dr., Monks Corner, SC 29461
121. T. R. LaPorte, Professor, Political Science, Institute of Government
Studies, University of California, 109 Moses Hall,
Berkeley, CA 94720
122. R. C. Latham, Duke Power Company, P.O. Box 33189, Charlotte, NC 28242
123. A. Latter, R&D Associates, P.O. Box 9695, Marina Del Rey, CA 90291
124. J. S. Lawler, Department of Electrical Engineering, University of
Tennessee, Knoxville, TN 37916
125. K. S. H. Lee, Dikewood Division of Kaman Science Corp., 2800 28th
Street, Suite 3780, Santa Monica, CA 90405
126. J. R. Legro, Westinghouse Electric Corporation, Advanced Systems
Technology, 777 Penn Center Boulevard, Pittsburgh, PA 15235
127. M. Lessen, Consulting Engineer, 12 Country Club Drive,
Rochester, NY 14618
128. Library, JAYCOR, 205 S Whiting Street, Alexandria, VA 22304
129. J. Lloyd, ED-SD, U.S. Army Engineering, USAEDH, P.O. Box 1600,
Huntsville, AL 35087
130. J. Locasso, Rockwell International, 3370 Meraloma Avenue, P.O. Box
4192, Mail Code 031-BB17, Anaheim, CA 92803
131. C. L. Longmire, Mission Research Corporation, P.O. Drawer 719,
Santa Barbara, CA 93102
132. W. C. Maklin, IRT Corporation, 6800 Poplar Place, McLean, VA 22101
133. R. M. Maliszewski, American Electric Power Service Corp., 1 Riverside
Plaza, P.O. Box 16631, Columbus, OH 43216-6631
134. J. N. Mallory, Southern California Edison Co., P.O. Box 800,
Rosemead, CA 91770
135. J. D. Martin, Harris Corporation, PRD Electronics Division, 6801
6801 Jericho Turnpike, Syosset, NY 11791
136. P. S. Maruvada, Hydro-Quebec Institute of Research, 1800 Montee
Ste-Julie, Varennes, Quebec, CANADA J0L2P0

137. R. G. McCormack, CERL, Corps of Engineers, P.O. Box 4005,
Champaign, IL 61820
138. G. F. Meenaghan, Vice President for Academic Affairs and Dean of the
College, The Citadel, Charleston, SC 29409
139. C. Menemenlis, University of Patras, Patras, GREECE
140. I. N. Mindel, IIT Research Institute, 10 West 35th Street,
Chicago, IL 60616
141. D. L. Mohre, Cajun Electric Power Corp., P.O. Box 15440,
Baton Rouge, LA 70895
142. B. B. Mrowca, Baltimore Gas & Electric Co., P.O. Box 1475,
Baltimore, MD 21203
143. K. Muller, IABG, Einsteinstrasse 20, 8012 Ottobrunn, WEST GERMANY
144. E. M. Murtha, Booz Allen and Hamilton, General Services
Administration, 18th & F Streets, N.W., Washington, DC 10405
145. H. P. Neff, Department of Electrical Engineering, University of
Tennessee, Knoxville, TN 37916
146. B. O. Nettles (Code 203), Naval Electronic Systems Engineering
Center, Charleston, 4600 Marriott Drive, North Charleston, SC 29418
147. D. R. Nevius, North American Electric Reliability Council, Research
Park, Terhume Road, Princeton, NJ 08540-3573
148. G. B. Niles, Baltimore Gas & Electric Company, Principal Eng. Room
1020, P.O. Box 1475, Baltimore, MD 21203
149. B. Noel, Los Alamos National Laboratory, Mail Station 5000, P.O. Box
1663, Los Alamos, NM 87545
150. B. Nowlin, Arizona Public Service Company, P.O. Box 21666,
Phoenix, AR 85036
151. R. Oats, Atomic Weapons Research Establishment, Building D57,
Aldermaston, Reading, RG74PR, England
152. G. Orrell, Dep. Associate Director for National Preparedness,
Federal Emergency Management Agency, 500 C Street, S.W.,
Washington, DC 20555
153. L. Paris, University of Pisa, Via Diotisalvi 2, 56100 PISA, ITALY
154. R. Parker, RDA, P.O. Box 9335, Albuquerque, NM 87119

155. R. Parkinson, Science Applications, Inc., 5150 El Camino Real, Suite B-31, Los Altos, CA 94022
156. A. Pignini, CESI-Via Rubahimo 59-Milano, ITALY
157. J. B. Posey, Ohio Brass Co., 380 N. Main Street, Mansfield, OH 44903
158. M. Rabinowitz, Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303
159. W. A. Radaski, Metatech Corp., 358 South Fairview Avenue, Suite E, Goleta, CA 93117
160. Al Ramrus, Maxwell Laboratories, Inc., 8835 Balboa Avenue, San Diego, CA 92123
161. J. J. Ray, Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208
162. T. J. Reed, Westinghouse Electric Corporation, Advanced Systems Technology, 777 Penn Center Boulevard, Pittsburgh, PA 15235
163. R. L. Retallach, American Electric Power, 1 Riverside Plaza, Columbus, OH 43216
164. J. Richardson, National Academy of Science, 2101 Constitution Avenue, Washington, DC 20418
165. F. Rosa, Nuclear Regulatory Commission, Division of Systems Integration, MS P1030, Washington, DC 20555
166. D. H. Sandell, Harza Engineering Co., 150 South Wacker Drive, Chicago, IL 60606
167. J. A. Sawyer, MITRE Corp., MS-H070, P.O. Box 208, Bedford, MA 01703
168. R. A. Schaefer, Metatech Corp., 20 Sunnyside Avenue, Suite D, Mill Valley, CA 94941
169. M. Schechter, A.D.A., P.O. Box 2250(81), Haifa, 31021, ISRAEL
170. D. Serafin, Lawrence Livermore Laboratory, P.O. Box 5504, Livermore, CA 94550
171. H. Singaraju, Air Force Weapons Laboratory, Kirkland AFB, NM 87117
172. A. C. Smith, Jr., Beam Research Program, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
173. J. C. Smith, McGraw-Edison Company, Power Systems Group, P.O. Box 440, Canonsburg, PA 15317
174. R. Smith, DNA, RAEE, 6801 Telegraph Road, Alexandria, VA 22310
175. W. Sollfrey, RAND Corp., 1700 Main Street, Santa Monica, CA 90406

176. H. Songster, Electric Power Research Institute, Electrical Systems Division, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303
177. G. K. Soper, Defense Nuclear Agency, Washington, DC 20305
178. S. Spohn, DB-6E2, Defense Intelligence Agency, Washington, DC 20301-6111
179. J. R. Stewart, Power Technologies, Inc., P.O. Box 1058, 1482 Erie Boulevard, Schenectady, NY 12301-1058
180. R. L. Sullivan, Department of Electrical Engineering, College of Engineering, University of Florida, Gainesville, FL 32611
181. I. O. Sunderman, Lincoln Electric System, P.O. Box 80869, Lincoln, NE 68501
182. R. W. Sutton, Science Applications, Inc., 1710 Goodridge Drive, P.O. Box 1303, McLean, VA 22102
183. F. M. Tesche, LuTech, Inc., 3742 Mt. Diablo Boulevard, Lafayette, CA 94549
184. L. Thione, CESI-Via Rubattino 54 20734, Milano, ITALY
185. R. J. Thomas, 302 Phillips Hall, Cornell University, Ithaca, NY 14853
186. R. Torres, BDM Corporation, 1801 Randolph, S.W., Albuquerque, NM 87106
187. W. Tyler, NT, Kirkland AFB, NM 87117
188. M. A. Uman, Department of Electrical Engineering, University of Florida, Gainesville, FL 32611
189. E. F. Vance, Route 3, Box 268A, Fort Worth, TX 76140
190. D. R. Volzka, Wisconsin Electric Power Company, 231 West Michigan Street, Milwaukee, WI 53201
191. J. Vora, Nuclear Regulatory Commission, MS 5650 NL, Washington, DC 20555
192. C. D. Whitescarber, Martin Marietta Orlando Aerospace, Sandlake Road Complex (SLRC), Mail Point 399, P.O. Box 5837, Orlando, FL 32855
193. W. P. Wigner, 8 Ober Road, Princeton, NJ 08540
194. M. W. Wik, Forsvarets Materielverk, S-11588 Stockholm, SWEDEN
195. C. B. Williams, IRT Corp., 7650 Convoy Court, P.O. Box 80817, San Diego, CA 92138

196. W. H. Williams, Division Manager, AT&T Information Systems,
Building 83, Room 1B23, 100 Southgate Parkway, Morristown, NJ 07960
197. D. D. Wilson, Power Technologies, Inc., P.O. Box 1058,
Schenectady, NY 12301
198. U. P. Wissmann, AEG-Telefunken, General Electric Company,
1 River Road, Building 36-444, Schenectady, NY 12345
199. H. W. Zaininger, Zaininger Engineering Company, 3408 Vance Court,
San Jose, CA 95132
200. Institute for Energy Analysis, ORAU - Library
201. Assistant Manager for Energy Research & Development, DOE/ORO
Oak Ridge, TN 37830
- 202-357. Given for distribution as shown in DOE/TIC-4500 under
Category UC-97 (Electric Energy Systems)