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MARTIN MARIETTA

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

Part II
SLOW PULSES

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

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Part II
SLOW PULSES

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KEY WORDS

Electric Power Systems
Electromagnetic Pulses (EMP)
Magnetohydrodynamic EMP (MHD-EMP)
Slow EMP
Nuclear High Altitude Burst
Magnetic Core Saturation
Harmonics
Pulser
DC Power Supply
Pulse Power Test Facility
Lead Acid Batteries

Executive Summary

This report reviews the applicable technology for simulating the slow electromagnetic pulse effects of high altitude nuclear detonations on electric power transmission systems.

A nuclear high altitude detonation will induce quasi-dc earth surface potential gradients which typically last for 100 seconds. The magnitude is in the range of 10 V/km. The voltage, established along extended transmission lines, can drive quasi-dc current pulses through multiple grounding points into the transmission system. The current magnitude can reach 1.5 kA.

Utilities have experienced similar phenomena at magnitudes up to 200 A from geomagnetically induced slow pulse currents. These are caused by solar flares. Measurements have shown that the solar induced slow pulse currents drive magnetic components (transformer cores) into saturation. The experience gained from solar induced currents is well applicable to the simulation of nuclear induced currents by the controlled injection of slow pulses into power systems. This report reviews the available experience on the effects of solar induced currents and ways to prevent them.

The slow quasi-dc pulse has the following effects on an ac power transmission system:

- Heating of conductors
- Transformer core half-cycle saturation causing:
 - increased ac excitation current
 - distorted ac excitation current (harmonics)
 - droop of line voltages
 - flux shift from transformer core into conductors and structural parts (eddy currents)

Half-cycle saturation in measuring transformers leads to reduced measuring accuracy, potential loss of signal, and wrong signal for protective relays. Through core remanence this effect can even remain after the quasi-dc pulse has ceased.

Equipment failures from overheating have not been reported. The effects of solar induced currents have been voltage droop (brown-out), increased losses, irregular power flow, circuit breaker misoperation, and loss of control. So far it has been possible to re-energize after disturbances caused by solar induced currents.

Limited testing with injected dc currents up to 100 A have been performed on components (transformers) and on power systems. Extending these tests to higher currents would provide the information needed for estimating the effect of nuclear induced quasi-dc currents on power systems.

Component testing is of limited value, because the major effects occur through interactions within the power system. The replication of exact MHD-EMP pulse shapes appears unimportant because the actual current pulse within a power system will be controlled by the L/R time constant. Simple ON-OFF control for the test pulser appears to be sufficient. The main interest lies in extending the test currents beyond 100 A.

Ways to mitigate the effects on power systems are also known. This can be achieved by placing over-voltage protected capacitor banks into the neutral-to-ground connection of selected power transformers.

The following utilities are candidates for cooperation because of previous involvement with solar induced EMP:

- Minnesota Power Co.
- Northern States Power
- Pennsylvania Power and Light
- Manitoba Hydro
- Bonneville Power

- Tennessee Valley Authority

Test agreements with utility companies will be needed. Possible test procedures in existing bulk transmission substations are described in Appendix A.

Multiple dc pulsers with a power level up to 3 MW will be required. Trailer mounting is highly desirable so that various utility substations can be reached.

The following technology options have been evaluated for pulser design:

- Capacitors (too bulky)
- Flywheel and Generator (expensive)
- Commercial Standby Generators (expensive)
- Variable Transformer-Rectifier with Utility Power Input
- Battery Bank

The dc pulser must be inserted into the transformer neutral-to-ground connection without breaking the ac current flow in that connection.

Any pulser with diode-rectifier output requires an ac bypass in the form of a protected capacitor bank. This increases the cost and weight of the standby generator and of the variable transformer option.

Testing of lead acid truck batteries showed an ability to pass high values of ac current for limited time periods (e.g. 30 kA_{rms} for 17 ms). The cell structure and electrolyte appeared fully stable under the action of high current magnitudes. The limits are set by heating of the lead conductors in the intercellular connections and terminal posts. (see Appendix B)

Designs for two pulser options are shown:

1. Variable Transformer-Rectifier Power Supply
2. Lead Acid Battery Bank Pulser

The battery bank option results in the least cost. The safety issue is addressed with selection and development of fast protective switchgear. The battery bank is segmented into 36 V units which are series connected to the desired test voltage for the duration of a test only. This reduces the likelihood of dangerous dc arcs. The battery bank pulser is trailer mounted. It is modular and can be designed for various voltage and current levels.

Single standard 8D truck batteries can be used for discharge currents up to 1 kA at 100 sec and possibly higher. The lead conductor crossections in the battery and the terminals must be specified with the manufacturer to limit overheating. An improved battery with copper terminals is available as an import from Australia.

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ABSTRACT

The work described in this report was sponsored by the Division of Electric Energy Systems (EES) of the U. S. Department of Energy (DOE) through a subcontract with the Power Systems Technology Program at the Oak Ridge National Laboratory (ORNL). The work deals with the effect of high altitude nuclear bursts on electric power systems. In addition to fast voltage transients, slow, quasi-dc currents are also induced into extended power systems with grounded neutral connections. Similar phenomena at lower magnitude are generated by solar induced electromagnetic pulses (EMP). These have caused power outages, related to solar storms, at northern latitudes. The applicable utility experience is reviewed in order to formulate an optimum approach to future testing. From a wide variety of options two pulser designs were selected as most practical, a transformer-rectifier power supply, and a lead acid battery pulser. Both can be mounted on a trailer as required for field testing on utility systems. The battery system results in the least cost.

Testing on power systems requires that the dc pulser pass high values of alternating current, resulting from neutral imbalance or from potential fault currents. Batteries have a high ability to pass alternating currents. Most other pulser options must be protected by an ac bypass in the form of an expensive capacitor bank. 8D truck batteries can meet the original specification of 1 kA test current. Improved batteries for higher discharge currents are available.

1.0 INTRODUCTION

Vulnerability of the electric power system to high altitude nuclear bursts is of strategic importance to national defense. The effect of slow electromagnetic pulses (EMP) is markedly different from fast EMP, which is basically a problem of fast high voltage surges.

Slow EMP is related to solar induced geomagnetic disturbances of power system operation which has been observed since the 40s. The effects stem from quasi-dc currents which can be induced into extended power systems, where they can saturate magnetic components.

The first aim of this project was a survey and evaluation of applicable utility experience in order to define an optimum approach to simulate the nuclear generated slow EMP. During the course of the project, several conclusions were reached which effected the specifications for test hardware.

Two consultants contributed their expertise to this project. John G. Kappenmann, Duluth, Minnesota, provided his experience from a recent series of tests on an operating power system where dc was injected in order to simulate slow geomagnetic disturbances. LeRoy Franklin, Escondido, California, contributed his knowledge of battery bank design. Al Ramrus, Henry Kent, George Schofield and Ken Whitham of Maxwell Laboratories clarified issues with valuable discussions.

The outcome of this project are recommendations for test arrangements and for the design of hardware, with the criteria: performance, safety, availability and cost. This report starts with a comprehensive survey of applicable knowledge collected by the utility industry.

A broad range of technical options is considered for the design of test pulsers. The two most promising options are considered in detail. The first one is a controlled dc power supply and the second one a battery bank pulser.

2.0 STATE-OF-THE-ART REVIEW

2.1 Effect Of Solar Induced Slow EMP On Power Systems

2.1.1 Geomagnetic Source for Slow Pulses

The earth's magnetic field is subject to large scale perturbations by high altitude nuclear detonations and also by solar flares. In either case, the geomagnetic field is changed by the motion of charged particles. This induces a measurable voltage gradient at the earth's surface. Information on the nuclear induced Electromagnetic Pulse (EMP) is very limited, although the effect of solar flare activity on extended power transmission systems is well documented. This experience is also applicable to the nuclear generated EMP because the underlying physics is similar.

The geomagnetic disturbances occur on a very slow time scale on the order of seconds to minutes, that is quasi-dc in relation to the 60 Hz power system frequency. The slow pulse is also called MHD-type EMP because it is generated by an interaction of a fluid of charged particles within the geomagnetic field.

Solar flares or sunspots occur with increased frequency every eleven years. A flare consists of high velocity ionized gas emitting radiation over a broad spectrum. The radiation reaches earth in about eight (8) minutes, while the gas arrives in 20-40 hours. Arrival of the solar storm effects radio transmissions all over the globe. Interaction with the polar magnetic field generates auroral currents which flow in a westerly direction in the northern hemisphere. These current sheets can reach a magnitude of 1 MA at an altitude of 80 to 400 km, leading to the well known celestial displays. Temporal variations of the auroral currents cause corresponding variations of the magnetic field at the earth's surface which induce easterly electric field gradients in the Northern Hemisphere. The quasi-dc, slow EMP enters extended power systems through ground connections. In other words, an extended transmission line forms a large, closed induction loop with the underlying conducting ground plane of the earth

if at least two ground connections are present. The depth of the conducting plane is a function of the earth's resistivity. The highest values of slow pulse EMP occur therefore in areas of low electrical conductivity (igneous rock). Calculated surface gradients for solar generated MHD-EMP range up to 10 V per mile (Ref. 1,2,3). Ref. 9 reports that high altitude nuclear bursts create geomagnetically induced earth surface gradients which are higher than those from solar flares. Values on the order of 10 V/km (16 V/mile) which last from tens to hundreds of seconds are predicted. A typical pulse includes polarity reversal. This may induce a peak MHD-EMP current on the order of 1000 A into an extended transmission system.

2.1.2 Quasi-dc Currents Enter 60 Hz Power Systems

Multiple ground connections are common in interconnected power systems. These are formed by the neutral ground of Y-connected power- and potential-transformers or reactors. Extended transmission lines between grounding points at widely separated positions act as slow pulse voltage sources. The quasi-dc currents can reach appreciable magnitude because of negligible reactance at the very low frequency. Fig.2.1 provides an illustration for the entry of geomagnetically induced currents into power systems. For the case of auto-transformers, it is possible that the quasi-dc currents flow between interconnected systems operating at different voltage levels. The effect of geomagnetic currents can therefore be felt over wide geographical areas, beyond the region of origin.

Fig. 2.1 Illustration of Very Slow Current Pulses Induced in Power Systems with Multiple Grounding Points.

The dc current magnitude is determined by the circuit resistance. The modern trend toward interconnections over large geographical areas and lower resistance in transformer windings and transmission lines, points to an increased importance of geomagnetic disturbances for extended power systems.

2.1.3 Measurements of Solar Induced Currents

The basic instruments for measuring the slow pulse solar induced currents in power systems are dc-ampere recorders placed in the neutral-ground connection of transformers. Numerous such recorders have been operated by utilities in the northern states and in Canada. A direct correlation with auroral currents and solar flares has been established. Over 30 utilities cooperated in a measuring program during the late sixties solar flare cycle peak. A total of 1860 readings gave the following distribution of current magnitude (Ref. 3).

% of readings	100	50	30	20	10	5	2
magnitude of solar induced current	>4A	>6A	>9A	>12A	>17A	>26A	>50A

The highest severity occurs in northern latitudes over igneous rock formations (New Foundland and Labrador Power) with 38.7 disturbances per month.

Also, the Philadelphia Electric Co. measured solar induced currents of 30 A, lasting for more than 8 minutes. Later publications report solar induced currents of 200 A magnitude and 20 minutes duration. (Ref. 5).

2.1.4 Calculation of Direct Current Flow

Ref. 6 reports a numerical method to predict the direction and magnitude of geomagnetically induced current in a complex and highly interconnected power system spanning a large geographic area. Earlier analysis had considered only relatively uncomplicated radial transmission systems extending over a limited geographic area. Modern power systems have a higher density of transmission lines and a larger

number of ground points. The analysis is further complicated by the common usage of autotransformer connections in the bulk transmission system. These transformer connections allow the flow of direct current from one voltage level to another, which greatly expands the number of possible circuit paths for dc flow. The magnitude and flow direction of the dc is not obvious for these systems.

The numerical method developed in Ref. 6 computes the expected direct current flow in each ground connection. The input data specifies the circuit configuration and geographic topology, the circuit equivalent dc impedance, and the assumed earth surface potential. The algorithms of Ref. 6 could be used to calculate direct current flow in any particular power system generated by an EMP induced earth surface potential. The computer simulation could supplement field tests by determining the location of the test system dc sources which will most accurately reproduce the actual disturbances.

2.1.5 Equipment Problems Effecting Power System Operations

DC currents flowing through transformer windings can cause a multitude of problems. The dc current will generate a magnetizing bias in the iron core. This can deeply saturate the iron core on alternate half-cycles because the dc current can exceed the normal transformer magnetizing current magnitude by a large factor. Transformer design changes can reduce the problem, but unfortunately, only by leading to uneconomic solutions.

Simultaneous application of ac and dc excitation to a transformer generates increased magnitude and gross distortion of the normal ac excitation current. Power transformers and reactors will then generate excessive harmonics and voltage fluctuations which can cause overheating and power flow changes. Deep saturation on alternate half-cycles changes the flux distribution within a transformer. Magnetic flux will tend to spill over the laminated core and link with conductors or structural parts. These may then experience heating due

to induced eddy currents. Excessive consumption of reactive power by transformers can lead to system wide voltage regulation problems.

The effect of dc bias currents on measuring transformers can be inaccuracy, leading to loss of signal or inappropriate activation of protective relaying. Remnant magnetization can even effect the accuracy of measuring transformers after the dc bias has been removed.

Ref. 4 reports that better current transformer (CT) performance can be achieved if higher CT ratios and low burdens are used; although, accurate CT response can still result in lack of security and lack of dependability in the application of transformer differential protection when quasi-dc is present.

Utilities have reported many instances of automatic circuit breaker operation, caused by geomagnetically induced quasi-dc currents.

Generally it has been possible to re-energize after a short time delay. Related transformer failures have not been reported. The severity of transformer heating is the subject of recent investigations.

2.2 Previous Testing

2.2.1 Testing of Power Systems

Only magnetic components in a power system are directly effected by the geomagnetically induced currents. Observations of power systems under the influence of solar generated slow pulse disturbances have provided most of the information to date. The critical components, such as power transformers, voltage and current transformers, can be analyzed separately at relatively little expense; although, this provides only a limited prediction of the power system action under the influence of geomagnetic disturbances, be they solar or nuclear generated. Both the components and the systems aspect have been analyzed under two EPRI projects for a newly commissioned 500 kV transmission line of 750 km length in an area that is susceptible to geomagnetic disturbances. (Ref. 6, 7). This power line provides an

interconnection between the systems of three different utility companies. Ref. 6 recorded the geomagnetic fluctuations over a 3 year period, together with the earth surface potential and geomagnetically induced currents. Computer analysis determined the distribution of the induced quasi-dc currents throughout the system, together with the increase in transformer reactive power requirements, due to half-cycle saturation and the effect on load flow. Assuming a maximum earth surface gradient of 6.2 V/km (10 V/mile), a voltage droop of 20% was calculated for certain locations of the system. The total system VAR generation increased by 45% to 90% with many of the generating units reaching their VAR limits.

An analysis of harmonic generation and switching transients revealed the following problem areas:

1. Energizing a long line in the presence of geomagnetically induced currents can result in sustained overvoltages, higher than the continuous overvoltage rating of line-end equipment.

2. Secondary arc currents during single-pole switching have higher harmonic content and up to 10 times the magnitude, thus reducing the probability of a successful line reclosure in the presence of induced quasi-dc currents.

3. Circuit breaker recovery voltages can be higher.

Further analysis of Ref. 6 concerns the effect of quasi-dc currents on current transformers and related relay operations. It is predicted that differential relay mis-operations can result from high levels of geomagnetic disturbances. It is also shown that harmonics generated by power transformer saturation may cause overloading of filters in high voltage converter/inverter equipment of dc transmission lines.

Field testing on three different power transformers in the Minnesota power systems is described in Ref. 7. DC currents were injected into transformers while under 60 Hz operating voltage. No damage to these transformers could be tolerated. The dc current

injections were therefore limited to one or two minutes duration. The dc current was increased in steps up to 100 A. Thermal effects on the transformers were not a part of this study. Gas analysis was used to assure that no thermal degradation occurred within the transformers during the limited test periods.

The tests were carefully instrumented to provide data for comparison with computer models predicting transformer and system response to geomagnetically induced currents. Current and voltage waveforms were recorded together with measurements of temperatures, vibration and acoustic noise.

The primary purpose of these tests was to measure the effect of direct current upon the generation of harmonics and the reactive power requirements of large transformers.

24 or 36 V lead acid batteries, controlled by a rheostat served as dc current source which was inserted into the transformer ground connection. Polarizing cells were used for shunting potential single phase fault currents away from the dc power source.

The measurements were made on an unloaded but energized 3-phase bank of single phase transformers and on two loaded 3-phase transformers of identical rating but different core design.

The following observations were made:

- The injected direct current rose in about 15 sec to the steady state value, due to the large L/R time constant of the transformer circuit.
- It was confirmed that the current injected into the neutral of a 3-phase transformer split equally between the three phases.

- Half-cycle saturation was observed to occur in each of the tests. Noticeable saturation effects were not significant until 25 amp dc (8.3 amps dc/phase) was reached. Saturation effects increased in magnitude with increased direct current.

In all cases, the transformer consumed more reactive power and produced increased transformer audible noise with an increase of direct current. The half-cycle saturation produced both even and odd harmonic currents. These currents, combined with the system impedance, produce increased voltage distortion. The increased reactive power consumption of the transformers also reduced the fundamental component of the system voltage.

Fig. 2.2 Unloaded Single Phase Transformer Magnetizing Current with 75 amp dc Injection (Ref. 7).

Fig. 2.3 Harmonic Currents on the 500 kV Side of Unloaded Single Phase Transformer with dc Injection (Ref. 7).

Fig. 2.4 Reconstituted Hysteresis Curve with 75 amp dc Injection for Unloaded Transformer (Ref. 7).

Fig. 2.5 500 kV Line Current with 75 amp dc Injection into Unloaded Transformer (Ref. 7).

Fig. 2.6 115 kV Line Current with 100 amp dc Injection into Loaded 3 Phase Transformer (Ref. 7).

Fig. 2.7 Harmonic Current on the 230 kV Side of Transformer with dc Injection (Ref. 7).

Injection of direct current into an unloaded bank of single phase 500/230 kV, 360/600 MVA transformers produced the clearest demonstration of core saturation, because it is not masked by load current. The transformer was of shell type design. The excitation current was provided from the 500 kV side. An example of distorted excitation current, shown in Fig. 2.2, is caused by half-cycle saturation of the core.

A harmonic analysis was performed on the measured voltages and currents. Fig. 2.3 shows the harmonic currents present in the transformer exciting current for normal conditions and with various levels of direct current. As shown, the exciting current has both increased even and odd harmonics as the level of dc excitation increases. The ac neutral current of the transformer also increased substantially in magnitude and harmonics with increased dc excitation. The neutral current increased from 2.6 amps rms with no dc excitation

to 66.4 amps rms with 75 amps of dc excitation. Correspondingly the rms exciting current increased from 5.1 A to 52.2 A accompanied by much louder acoustic emission. The transformer hysteresis curve under half-cycle saturation can be calculated from a plotting of the 500 kV-side voltage versus the transformer exciting current. The hysteresis curve for the 75 amp dc excitation test is shown in Fig. 2.4. The largest portion of the area contained by the hysteresis curve is located in the first quadrant. The total area of the hysteresis curve representing transformer core losses is also greatly increased due to the half-cycle saturation.

The harmonics generated by the half-cycle saturation increased the distortion of the line current of the adjacent 500 kV transmission lines. The lines (due to their high capacitive charging) act as a sink for the harmonics produced in the transformer. Fig. 2.5 is a recording of the current in one of the 500 kV lines. The current principally consists of 53 amps of 60 Hz, 40 amps of third harmonic, and 35 amps of fifth harmonic.

A similar test series was performed on a loaded 3-phase 230/115 kV autotransformer, rated 200/333 MVA with a three-legged core and winding design. The injected direct current was forced to flow through the series winding as well as the common winding. A loaded transformer does not allow a direct measurement of the excitation current; although, this condition does present a more realistic duplication of the effects originating from geomagnetically induced currents.

Again, injecting direct currents up to 100 A caused half-cycle saturation. The current distortions are less pronounced because the effect is superposed on the load current, (see Fig. 2.6). A comparison of the harmonics produced at the various dc test levels is shown in Fig. 2.7. Because of the load current, the fundamental component has been deleted. The transformer produces both even and odd harmonics which generally increase with increasing dc excitation. The neutral current increased from 6.3 A_{rms} to 168.9 A_{rms} due to the injection of 100 A direct current.

In a third test series, described in Ref. 7, direct current was injected into a loaded 3-phase shell type auto transformer rated 230/115 KV, 200/333 MVA. The difference in core design produced slight differences in the test results, which are mainly noticeable in the harmonic content of the neutral current. Significant test results are summarized in Table 2-1.

Table 2.1.

SUMMARY OF TEST RESULTS ON LOADED
SHELL TYPE TRANSFORMER (Ref. 7)

<u>Measured Values</u>	<u>Injected dc Magnitude</u>				
	<u>None</u>	<u>25A</u>	<u>50A</u>	<u>75A</u>	<u>100A</u>
Transformer Neutral					
Current (amps-rms)	6.3	11.4	15.6	21.4	24.2
230 kV Voltage Drop (kV)	-	.2	.66	1.07	1.52
230 kV Voltage					
Distortion (1/1)	1.89	2.51	3.71	5.35	6.0
Transformer					
Audible Noise (dBA)	80.6	83.4	80.3	83.7	85.3

Voltage distortion is defined as

$$\frac{\text{Sum of rms Harmonic Voltages}}{\text{rms Fundamental Voltage}} \times 100\%$$

The audible noise was measured at 14 ft. distance.

The testing, described above, was terminated before thermal effects could become appreciable in the power transformers of the Minnesota system. Obviously, one did not want to take chances with expensive equipment in service.

2.2.2 Testing of Components

Considerable disagreement exists as to whether or not power transformers are in serious danger of thermal failure due to

geomagnetic effects. Ref. 8 predicts that one minute of exposure to quasi-dc induced currents of double the excitation current magnitude would lead to excessive internal localized heating.

Ref. 5 describes component testing on 3 KVA shell form model transformers. These transformers are exposed to simultaneous ac and dc excitation. Currents, temperatures, and stray magnetic fields were measured. The following conclusions were reached in Ref. 5:

1. The magnitude of the ac component of the stray field near a transformer core is dependent on the degree of saturation of the core, and is independent of the load current.

2. Although geomagnetically induced currents cause core saturation to occur, the major effect is that of high exciting current, not high stray flux.

3. Hence overheating in the windings due to I^2R loss would be the dominant effect, not overheating of metallic structural parts.

4. The standard overtemperature sensors (110°C alarm, 140°C) trip would therefore be adequate to detect overheating due to geothermal disturbances.

In perspective, it must be said that these tests were performed only on small model transformers of one type of design with up to 13 A of direct current injected.

The prediction of localized heating in transformers is a complex topic. Further analysis, compiling of field experience, and testing would be indicated, in particular for the higher current magnitudes expected from nuclear generated MHD-EMP.

2.3 Mitigation

The effect of geomagnetic disturbances can be eliminated if the induced quasi-direct currents are prevented from flowing through the power system's ground connections. Reasons of safety dictate that low

reactance ground connections exist for 60 Hz power system currents. Ref. 7 investigates means for selective blocking of the quasi-dc. Nonlinear resistors, polarizing cells, and capacitors were considered, together with an active scheme of injecting counter-balancing currents.

Capacitors were chosen as the most practical solution. A prototype device was developed for installation in the transformer neutral to ground connection. Overvoltage protection for the blocking capacitor and the neutral point is provided by a fast closing gap, shorting the capacitor if system faults occur which otherwise would create destructive overvoltages. These devices, installed in the ground connections of selected transformers, could effectively protect utility power systems from the effect of MHD-EMP.

3.0 SELECTION OF TECHNICAL APPROACH

3.1 Review Of Requirements and Objectives

The previous section summarized the applicable experience gained by the Electric Power Industry, which is mainly derived from observations of electric power transmission systems under the influence of solar flare generated geomagnetic disturbances. These observations are by necessity sporadic. Only two controlled experiments with injected quasi-dc currents at low magnitude are known. One was performed on model transformers; the other was performed on an operating transmission system.

The present study will define an optimum approach to further measurements of the effect of MHD type EMP on power systems.

Design concepts will be generated for test equipment able to inject very slow MHD-EMP pulses into transformers or operating power transmission systems. The original specifications were extended during the course of this project. The main parameters are listed in Table 3.1.

Table 3.1.

SPECIFICATIONS FOR SLOW EMP PULSER

Parameter	Original Specification	Revised Dec. 19/'85
Current rise time	0.5 to 5 s	determined by L/R of the power circuit
Magnitude peak current	1 kA into 1 ohm load	1.5 kA
Current hold time	not specified	100 s
Open circuit voltage	not specified	2 kV
Mounting	not specified	mobile on trailer
Power requirement	1 MW	3 MW
Storage capacity	15 A hr	42 A hr
Polarity	not specified	positive and negative with respect to ground

As additional requirements the ac current must be specified which may be superposed with the quasi-dc slow pulse. The normal transformer imbalance current ranges from 0 to about 50 A. The ac imbalance current increases strongly during dc injection. Extrapolation of test data from Ref. 7 indicates that the magnitude may exceed 1,000 A_{rms} including a high content of harmonics.

Also ground faults on the transmission system would cause high values of ac current to flow in the transformer neutral connection. For planning purposes Minnesota Power Co. uses a value of 10 kA for 10 cycles (0.166 sec) in the transmission system described in Ref. 7. This value is typical for extended transmission systems, which are vulnerable to MHD-EMP. High density power systems near metropolitan areas would have higher fault currents. But these systems are not likely candidates for testing with injected dc currents.

For the purpose of this study 25 kA and 10 cycles are chosen as parameters for ground fault currents.

Simulation of the MHD-EMP shape does not seem important. The current pulse rise time will largely be controlled by the L/R time constant of the power system. The dc current magnitude is of primary importance because it controls magnetic saturation and thermal heating. The pulse duration also effects heating. Near square wave current test pulses appear most practical.

The test facility should be suitable for the laboratory testing of various size transformers and also for testing on operating power systems. This translates into a requirement for trailer mounting. System testing would require multiple pulsers. It is likely that smaller pulsers would be chosen initially.

The criteria of evaluation are:

- Technical function for specified parameters
- Safety to personnel and connected equipment
- Flexibility to meet changing requirements

- Cost
- Service and maintenance requirements

3.2 Pulse Source Coupling To Power Systems

We are concerned with testing either components (transformers) or power transmission systems under operating conditions. This requires the superposition of quasi-dc slow pulses on 60 Hz ac currents and its harmonics. The standard voltage for transmission systems ranges from 69 kV to 1100 kV.

Fortunately it is not necessary to inject the quasi-dc current into any of the high voltage conductors of the power system.

Individual transformers can be tested by injecting the slow pulse into a tertiary winding while it is 60 Hz energized through a primary or secondary. The required dc source power will be rather modest in this case because the resistance of the tertiary winding will be low. See Fig. 3.1.

For testing extended power systems it will be desirable to inject quasi-dc currents from multiple pulsers at different locations. The dc is injected into the transformer neutral-to-ground connection. This not only duplicates the natural phenomenon, but also simplifies the requirements for the test equipment used to produce the direct current. See Fig. 3.2.

The transformer ground connection must maintain a low value of ac impedance for reasons of safety. Otherwise dangerous voltages would be created if a ground fault occurred on a connected transmission line.

3 Phase transmission systems with a grounded neutral Y connection of transformers are common. Here only a small system - imbalance current up to 50 A may flow under normal operating conditions. The direct current will cause the transformer to half-cycle saturate. This produces even and odd harmonics. The triplen harmonics will flow in the neutral and through the test equipment to ground. At high direct current test levels, the rms magnitude of ac neutral current will be many times higher than 50 A. These high ac currents will persist for the duration of the direct current test cycle. Field tests produced the following neutral currents for a 100 amp dc injection into a 230/115 kV transformer:

TABLE 3.2

HARMONIC CONTENT OF AC NEUTRAL CURRENT AT 100 A DC (Ref. 6)

60 Hz -	4.4 A
2nd -	2.2 A
3rd -	147.8 A
4th -	2.2 A
5th -	1.5 A
6th -	80.0 A
9th -	17.4 A
12th -	8.5 A

Total Effective Current - 169.3 A

The magnitude of the neutral current, as shown above, consists mainly of the triplen (i.e., zero sequence) harmonics. A neutral current oscillogram is reproduced in Fig. 3.3. The magnitude of the ac neutral current depends on the size and design of the transformer. A steady increase of the transformer neutral ac current with injected dc current up to 100 A is observed in Ref. 6. The following data is reported:

TABLE 3.3

AC NEUTRAL CURRENT VS. DC INJECTION CURRENT

<u>dc Injection Current</u>	<u>ac Neutral Current (A-rms)</u>
28 A	18.5 A
50 A	69. A
75 A	125. A
100 A	169. A

The relationship at higher dc currents is not known. We can expect ac neutral currents on the order of magnitude of the injected dc current.

Fig. 3.1 Testing of Individual Transformer.
Slow Pulse Injection through Tertiary Winding.

Fig. 3.2 Testing of Power System.
Slow Pulse Injection into Transformer
Ground Connection.

Fig. 3.3 Neutral Current with 100 amp dc Injection in 230/115 kV Transformer.

A ground fault, on the other hand, would create current magnitudes on the order of 10^4 A for the duration of a fraction of a second as determined by the clearing time of associated circuit breakers.

Fault current protection is required for:

1. Protecting the transformer neutral from excessive voltage surges. Most large power, high voltage transformers have a neutral insulation graded to the 110-150 kV Basic Insulation Level (i.e. 15 kV class).
2. Protecting the dc pulse source from high magnitudes of 60 Hz current. Various dc current sources will differ in their requirement for protection.

A ground fault is a rare occurrence, but it may occur during testing on operational power systems. Similarly, a nearby switching event could produce a sizable transient neutral current.

Protection is in principle provided by a device that will block low level dc voltages and shunt 60 Hz ac voltage with harmonics or dc voltage above a threshold value. Candidate devices are:

- Capacitor - Bypass
- L-C Filter
- Polarization Cell
- Non-linear Resistor
- Triggered Closing Gap
- Choice of a dc source with very low internal ac impedance

Capacitor Bypass

Ref. 7 proposes capacitors in the transformer neutral-ground connections for blocking the flow of geomagnetically induced currents in power systems. A fast acting closing switch is arranged in parallel for protection against damaging voltage surges due to ground fault currents. The capacitor bank has a typical value of 11 micro Farad rated at 12.5 kV_{rms}. This translates to a 60 Hz reactance of 241 Ohms. The expected 50 A of neutral imbalance current will generate about 12 kV across these capacitors. This concept, with some modification, can also be used as low impedance capacitive bypass for the high ac neutral current expected during direct current injection. The capacitors also block the direct current which forces it to flow through the transformer.

Extrapolation of earlier results predicts that the ac neutral current could exceed 1000 A_{rms} for a 1000 A direct current injection. The neutral capacitors should be sized for an appropriate current rating. The impedance of the capacitors (at the triplen harmonic frequencies) should be kept to low values to keep the voltage rise at the transformer neutral within equipment limits.

As an example, a capacitive bypass could be designed based upon the use of common power capacitors rated 200 kVA, 12.5 kV. Each unit has a 16 amp rating at 60 Hz, likely this current rating would also apply at the lower order triplen harmonics. Therefore, a 1000 amp rating would require approximately 63 units connected in parallel. This gives a total capacitance of 214 micro Farad which has an impedance of 12.5 Ohm at 60 Hz, or 4.5 Ohm at 180 Hz.

As mentioned previously, a fast acting ground switch is necessary to prevent fault overvoltage. It is possible that capacitors in the neutral connection may excite overvoltages by ferro-resonance. The fast acting switch could also provide protection against this occurrence.

L-C Filters

L-C filters have also been considered. They are difficult to apply because of the high harmonic content in the transformer neutral under dc excitation.

Polarizing Cells

Polarizing Cells are common as safety devices in cathodic corrosion protection systems, where they block small applied dc potentials, but short out higher magnitudes of ac currents. They are built like storage batteries with two identical stainless steel electrodes. Essentially they act like nonlinear resistors with a breakover-voltage of about 2 V per cell. The action depends on the formation of thin gas films covering the electrodes in an aqueous solution.

Commercially available cells are rated to pass from 5 kA to 50 kA for 1/2 second depending on size. The internal resistance of the largest cell is about 0.3 milliohm at 50 kA of 60 Hz current. The price of polarization cells ranges from 109 to 650 dollars depending upon size. (Ref. 10). This is prohibitive for protecting dc sources with voltages as high as 1 kV. Also polarizing cells are open to the atmosphere. They are not well suited for trailer transport.

Nonlinear Resistors

Highly nonlinear resistors of the zinc oxide type have become commercially available in recent years. The main application is for surge voltage protection. Use of ZnO resistors for fault protection in transformer neutrals was investigated in Ref. 7. It was concluded that the required energy dissipation calls for a resistor volume which is prohibitively expensive.

Spark Gap

A spark gap with gaseous dielectric can be used for overvoltage protection for short time periods. The occurrence of a fault current would damage the electrode surface. The spark gap would have to be replaced after the occurrence of a high current fault.

Triggered Closing Gap

A low impedance ground connection has to be established if a ground fault should occur during testing. This is best achieved with a metallic contact closure which must be fast acting.

A fast microsecond response is needed for protecting capacitors. Instantaneous protection can be provided by zinc oxide nonlinear resistors. But these devices are energy limited.

A triggered closing gap must therefore be placed in parallel. An explosively activated closing gap is described in Ref. 7. A detonating charge is used for bending copper fingers in order to close a gap in a fraction of a millisecond. The trigger signal for a hot wire detonator is derived from a zinc oxide varistor. See Fig. 3.4.

As an alternative a vacuum interrupter could be used as closing gap. The required contact spacing is only a few mm in vacuum.

Magnetic repulsion of the moveable contact from a pulse coil can be used for rapid acceleration and contact closure within about one millisecond. See Fig. 3.5. This appears sufficiently short for protecting the zinc oxide varistor, the capacitor and the dc source from the effects of a grounded fault on the power system.

Fig. 3.4 Surge Voltage Protection for ac - Bypass Capacitor Bank.

Fig. 3.5 Fast Acting - Vacuum Interrupter with Magnetic Repulsion Coil Actuator and Pneumatic Holding Force.

The dc source must of course be able to operate into a short circuit until that condition is removed. The vacuum interrupter option would require development and testing. The challenge would be to prevent contact bounce and welding when closing in on a high magnitude fault current. A combination of magnetic repulsion and pneumatic pressure could provide fast acceleration and high holding force.

The need for an expensive and rather sensitive capacitor bank can be eliminated if suitable lead acid batteries are chosen as the dc pulse source. Lead acid batteries have internal impedances in the low milliohm range. One may expect that they will be able to pass high values of ac current. For test results on automotive starter batteries see Appendix B.

3.3 Pulse Sources

The peak power requirement extends up to 3 MW. Distribution circuits can easily provide this power level to a laboratory set-up. This would unfortunately allow only the testing of components, which could provide only limited information on the effects of core saturation in transformers. The more important effects on the power system cannot be tested in the laboratory. A test agreement would have to be reached with utility companies. Pulsers would be trailer mounted and energy storage would be desirable because a suitable power source may not be found at every substation test location. Slow EMP testing in a typical bulk transmission substation is reviewed in Appendix A. It is concluded that direct current injection within one particular substation can be attained by fairly simple pulsers requiring no more than 200 Volts because the current returns within the substation grounding mat. Achieving a detailed simulation of MHD-EMP with direct current flow along extended power lines within a utility grid will require detailed analysis and multiple pulsers acting in synchronism. These pulsers would require a range of open circuit voltages. It is not necessary to design all pulsers for the maximum amount of 2 kV.

3.3.1 Variable Transformer-Rectifier Pulser Source

A pulse source without energy storage can be in the form of a conventional dc power supply consisting of transformers, rectification, control, metering and protection. Any of the standard 3 phase distribution voltage levels could be chosen for the input. Voltage control can be provided either by phase control with SCR's or by variable ratio transformers. A variable transformer is preferred because of ruggedness, insensitivity to voltage surges and the absence of harmonics generation. Air insulation is better suited to the transformer than oil insulation because the voltage level does not exceed 25 kV.

Fig. 3.6 shows the power supply components and Fig. 3.7 the diagram.

Fig. 3.6 Components of the Variable Transformer - Power Supply.

Fig. 3.7 Diagram of the Variable Transformer - Power Supply.

Electro Engineering Works (EEW) quoted to the following:

Power Supply Specifications:

Output: 0 to 1200 Vdc
0 to 1200 amp dc
On 110 seconds, off 30 minutes
12 phase rectification. 2% nominal rms ripple, 720 Hz, into resistive load. Ripple will be higher for inductive load and lower for capacitive load.
Output can be floated at 20 kVrms, 60 Hz of ground.

Test Voltage: Test Voltage: 41 kVrms, 60 Hz for 60 seconds, output voltage is set with variable transformer driven by dc motor. Output voltage may be set at any value within its range and may be raised or lowered at any time provided duty cycle is not exceeded. Time to go from zero to full voltage and from full voltage to zero will be adjustable from 5 to 100 seconds.

Input: 2400 V
3 phase
60 Hertz

Control Power: 240 V
3 phase
60 Hertz

Control: 10 Volt - power supply on
0 Volt - power supply off
0 to + 10 Volt - power supply output voltage to increase, rate of increase to depend on amplitude of control voltage.
0 to -10 Volt - power supply output voltage to decrease, rate of decrease to depend on amplitude of control voltage.

Control: 2400 Volt connected and disconnected from power supply by EEW supplied vacuum contactor.

Power Supply Specifications (cont'd.):

Environment:	Indoor 30°C maximum
Metering:	Voltage: 2% accuracy, isolated from power supply output. Current: 2% accuracy, isolated from power supply output.
Transient Protection:	Provided by EEW
Output Insulation:	Will meet ANSI C57.12.01-1979 tests for 18000 Volts nominal system voltage, 95 kV BIL.

The size of the power supply is 7'x 10'x 7' high. The weight is 15,000 lbs.

An uprated power supply (1.5 kA, 2 kV) would have the following dimensions 8'x 13'x 9' high and a weight of 24,000 lbs.

Also it is possible to provide the input transformer with taps for the following standard voltages. 4.2 kV, 7.2 kV and 13.8 kV in order to be more flexible in adapting to various sources of power as they may be available in various substations. 34.5 kV is more difficult to achieve.

On-off control for power flow to the isolation transformer is provided by a 3 phase vacuum contactor. The contactor receives commands either from the control console or from a protective over-current detector.

The variable transformer provides continuously variable voltage adjustment to the load by varying the position of a set of brushes on a commutator, or exposed winding surface. Brush position is controlled by a reversible dc motor. 12-phase rectification provides a low ripple content for the dc output. Current and voltage signals are brought through isolation stages to a console indication and to the programmable controller. Specified voltage or current pulses can be generated by the controller.

3.3.2 Pulser with Energy Storage

Energy storage can be achieved in various forms. A useful figure of merit is the basic energy density which is listed below.

TABLE 3.4
ENERGY STORAGE OPTIONS

Energy Storage	Energy Density (J/kg)	Output
Chemical, Combustion Fuel	$2 \cdot 10^7$	thermal
Lead Acid Battery	$1.6 \cdot 10^5$	electrical
Mechanical (Cu-Be Flywheel)	$6.5 \cdot 10^4$	mechanical
Capacitors	370	electrical

The choice of pulser options must be based upon the commercial availability of suitable technology.

Capacitors must be ruled out because of low energy density.

Mechanical energy storage in flywheels is feasible in connection with a coupled dc generator. Voltage control can be arranged by varying the field excitation current. The low insulation level of a dc generator and the reaction torque during discharge are two factors that merit attention. This option was not pursued further because of high cost.

Commercial standby generators can be used which store energy in the form of combustion fuel. These units can be transported on a truck and mounted on an insulated platform if that should become necessary. The standby generator consists of the combustion engine and an alternator. The output voltage can be controlled by varying the field excitation current. A diode bridge must be added for rectifying the generator output. Either a diesel motor or gas turbine can be chosen for driving the alternator. The type of drive motor effects the price and weight of the pulser. A 900 kW rating would be sufficient to deliver 1 MW for the duration of 100 seconds. A turbine drive costs more than a diesel drive. The advantages of the turbine driven systems

are: less weight, compactness, reduced vibration, and maintenance requirements.

Standby generator systems with turbine and diesel drives are compared in the following:

TABLE 3.5
COMPARISON OF STANDBY GENERATORS

	Turbine		Diesel	
Standby Rating (kW)	900	3,000	900	1,500
Basic System Cost (K\$)	300	1,100	150	180
Weight (kg)	5,500	20,000	12,000	14,000
Width (m)	1.4	2.1	2.2	2.5
Length (m)	4.1	7.9	5.6	6.8
Height (m)	1.7	2.4	2.6	2.6

The standby generators can be truck mounted for mobility. Controls switching and rectification would have to be added. The required ac bypass in the form of a capacitor bank would be identical to that for the variable transformer power supply.

3.3.3 Storage Battery Bank

Secondary storage batteries have the advantage of high energy density, and commercial availability at a low cost. The main contenders are nickel-cadmium and lead acid batteries. Nickel-cadmium batteries excel in performance at freezing temperatures. High cost and low cell voltage are the disadvantages.

Lead acid batteries are chosen for the EMP pulser because of performance features in relation to price. Lead acid batteries are manufactured in many specialized forms. The requirements of the EMP pulsers are best met by batteries which are designed for starting combustion engines. Such batteries are manufactured for aviation and automotive use. The applicable test parameter is the cranking current which designates the current that a battery can deliver at 0°F for 30 seconds while the battery cell voltage is allowed to drop from 2. Volt

to 1.2 Volt. Lead acid batteries can deliver higher currents at room temperature. Automotive batteries are designed for low internal resistance and high current output. The A·hr capacity is more than adequate so that deep discharging is not required. This lengthens the battery life. The search concentrates on finding an automotive battery with the highest cranking current and suitable terminals.

"Pulsar" Battery of Dunlop Batteries, Australia

A novel design of automotive battery has been developed in Australia. The output voltage is 12V for a maintenance free design. The batteries have reduced internal resistance and increased cranking current when compared with standard batteries of equal A·hr capacity. The output terminals are flat copper strips. This allows for better connections than the standard lead terminal posts on conventional batteries. The Pulsar battery promises a weight reduction to less than one half for equal cranking current when compared with standard automotive batteries. Production of the Pulsar battery has started in Australia. Small quantities are imported into the USA for use in racing cars. The price is about 10% higher than for standard batteries. The Pulsar battery promises performance advantages, but presently limited availability directs the selection to standard automotive batteries.

Standard Automotive Lead-Acid Battery

The highest cranking current is available from the 8D truck battery. This is a standard size and rating available from various US manufacturers with the following characteristics:

Designation	8D Truck Battery
Voltage	12 V
Cranking Current	900 to 1300 A at - 17.8°C
Length m (inch)	0.527 (20.75)
Width m (inch)	0.273 (10.75)
Height m (inch)	0.244 (9.63)
Wet Weight kg (lb)	64 (141)
Electrolyte Volume l (quarts)	12.6 (13.3)

Capacity	208 A·hr
Price	about 135 dollars each

The cell interconnections and terminal posts are the weak points in regard to high current discharge ability. Dimensions and materials for these items should be specified separately. It is known that a lead acid battery at room temperature can deliver substantially more current than the rated cranking current at -17.8°C . 1.5 kA of current is feasible. The attainable pulse duration would have to be determined experimentally. 1.5 kA for 100 sec corresponds to 42 A·hr. This is within the capacity rating of the 8D battery. It is expected that the pulse duration at maximum current will be limited by heating in the cell connections and terminals. See Appendix B for test results.

From a comparison with polarization cells it is inferred that lead acid batteries have the capability to pass high magnitudes of ac current for short time periods. This is a very desirable feature because it reduces or eliminates the need for an ac bypass capacitor bank. The lead acid battery has a very high capacitance which is due to an electrode polarization layer. The value is about 0.2 Farad per cell and A·hr at 60 Hz (Ref. 11). This amounts to 3.5 Farad for one 8D truck battery. The resonance of this capacitance with the circuit inductance may fall into the range of the power system frequency and its harmonics. The impedance would go to a minimum for the resonance frequency which is a desirable effect. Other factors may arise from the possible excitation of ferro-resonance with the transformers under test.

4.0 PULSER DESIGN

A trailer mounted lead acid battery is the primary pulser option because of the ability to pass alternating current. Automotive batteries are available at relatively low prices. The battery pulser stores energy which makes it independent of the power available in a particular substation. The pulser design considers the following features:

- Performance
- Safety
- Cost
- Trailer Mobility
- Diagnostics
- Integration with Power System

4.1 Performance And Safety Of Battery Pulser

The revised specification requires an open circuit voltage of 2 kV. A fully charged battery has a terminal voltage of 15.2 V (Ref. 12). Correspondingly 132 batteries would be required which can be arranged in 44 groups of three. (The analysis of Appendix A shows that several pulsers with various open circuit voltages up to 2 kV will be required). It is likely that one would start by building pulsers with a smaller number of batteries in series. 132 batteries discharged to a cell voltage of 1.7 V would provide a pulser terminal voltage of 1,350 V. Discharge currents of 2 kA have been drawn from 8D truck batteries. The permissible pulse length at the required 1.5 kA must be determined experimentally. This will depend on the specifications for the cell interconnections and the terminal posts. A pulse time of 100 sec appears feasible.

Fig. 4.1 Diagram of Battery Pulser.

The generation of arbitrary wave shapes will not be required for MHD-EMP simulation. A constant current square wave of variable magnitude and duration will be ideal. Voltage selection can therefore be attained by no-load switching before pulser operation. On-off switching is attained by a dc load break switch or contactor.

Three batteries are connected in series, limiting the unit voltage to a safe level of 36 V. A charger is connected across each set of three batteries to keep them at full charge. Safety is a major concern with a large battery bank, as a high voltage arc would meander and cause damage. The bank is normally, for this reason, segmented into 36 V units. The appropriate number of units, for a given injection voltage, is series connected shortly before the pulser is used. This function is achieved by sets of contactors S_1 and S_2 . In Fig. 4.1 battery units 1,2,3 and 4 are connected in series to deliver a terminal voltage $4 \times 36 \text{ V} = 144 \text{ V}$. Contactor S_1 and S_2 are ganged so that S_1 is open when S_2 is closed and vice versa. For safety reasons S_1 and S_2 are operated pneumatically. This eliminates the possibility of establishing short circuits through control wires.

The battery pulser can be grounded at either terminal so that the polarity can be chosen freely. A regulating resistor can balance current droop during extended discharges. A graphite pile regulator is well suited for this purpose. The resistance of a stack of graphite disks is varied continuously by pneumatic pressure (Ref. 13). Absorbing 30 MJ of energy in the regulating resistor would require about 75 kg. of graphite.

Graphite pile resistors are designed with up to 1/2 Volt per disk and a resistance ratio up to 30 to 1. Standard disks have an outer diameter of 0.75" and 0.04" thickness. The disks are assembled in ceramic tubes. Control pressure is in the range of 1 to 10 lb. which can be generated pneumatically in order to attain electrical isolation. The graphite pile resistance can be chosen within the milliohm to ohm range. The regulating resistor can be bypassed by switch S_3 to allow operation at maximum available current.

On-off control is obtained with the dc load switch. A single unit to meet the voltage requirements could not be located. It appears that two units of the BBC dc load switch, type 406902, connected in series would be suitable. This switch is used in rail road traction systems.

Ratings of the dc Load Switch, Type BBC 406902

Max. Service Voltage	900 V
Max. Arc Voltage	1800 V
Continuous Current	3000 A
Withstand Current	50 kA
1 Sec Current	25 kA
Switching Time	2.5 sec
Impulse Withstand Across Contacts	16 kV
Impulse Withstand to Ground	16 kV
Voltage Drop at 3 kA	39 mV
Service Life	10,000 operations

As an alternative, 600 V dc contactors are available from Westinghouse. More than two of these units would have to be placed in series. The insulation to ground would suffer with this choice.

Fig. 4.2 Truck Mounted Battery Pulser. Side View.

Fig. 4.3 Truck Mounted Battery Pulser.
Rear View

4.2 Trailer Mobility

A side view of the truck mounted battery pulser is shown in Fig. 4.2. Each battery is mounted on a sliding shelf for easy maintenance and removal. Electrical connections are made with screw terminals which also hold the sliding shelf in place. The three lower shelves contain batteries. Fig. 4.2 shows a bank with 120 batteries. This concept can be extended to incorporate more batteries on a longer trailer. The fourth shelf houses the battery charger. The switching contactors S_1 and S_2 are installed on the 5th shelf.

Switch gear, regulators, controls and supplies are housed in separate compartments at the front and rear of the trailer. A rear view is shown in Fig. 4.3. A fold-out walkway and canopy runs the length of the trailer, allowing access to each battery compartment. Each battery shelf is accessible by an overhead crane. The total battery weight will be $136 \times 141 \text{ lb} = 8,700 \text{ kg}$ (19,000 lb). Trailers are available with a load carrying capacity of 36,300 kg (80,000 lb). A trailer width of 2.44 m (8 ft) is standard, Fig. 4.2 shows a trailer length of 10 m (32 ft). Trailer length of 12.2 m (40 ft), 12.8 m (42 ft), and 13.7 m (45 ft) are standard. The standard height is 4.3 m (14 ft).

4.3 Diagnostics

For pulser diagnostics, a measurement of current and voltage with 1% accuracy is required. Fiberoptic transmission is chosen for reasons of safety. The battery status can be monitored with a portable instrument because the terminals of all batteries are available at the front of the battery shelf. Current injection into a power system will be controlled from a remote location because any pulser must be considered as hazardous, allowing for the effect of possible power system fault currents. Operator control and pulser metering occur through pneumatic and fiber-optic lines.

For applicable power system diagnostics see Ref. 7.

4.4 Connection To Power System

The normal operating state for the Y-connected power transformer requires a solidly grounded neutral connection. For the purpose of injecting direct current, we have to open this connection in order to insert the battery circuit while maintaining alternating current flow. The solid grounding must be re-established quickly if fault generated overvoltages occur. The circuit is shown in Fig. 4.4.

The battery bank has a limited ability to pass high values of ac current for short time periods. Test data on this topic are needed for a final choice of protection levels and switch gear characteristics. Testing of standard 8D automotive batteries is described in Appendix B.

The basic operating sequence is:

1. Connect the pulser to the transformer neutral without opening the circuit (S_4 -open, S_5 -closed, S_6 -open).
2. Set the desired battery voltage with S_1 and S_2 (Fig. 4.1).
3. Set the regulating resistor for the desired current value.
4. Close S_4 . DC will flow in a loop through S_5 .
5. Open S_5 . The dc load switch interrupts the dc and the superposed ac current. A spark gap provides overvoltage protection. The direct current will be commutated into the power system and grow according to the L/R time constant.
6. The occurrence of a single line fault would cause high ac currents to flow in the transformer neutral connection. This is detected by dI/dt , I sensors which give a signal to the fast closing switch S_6 . Closing of S_6 re-establishes the solid grounding connection for the transformer neutral. Open S_4 to disconnect the battery bank.

For end of test, S_5 is closed before S_4 is opened.

The same dc load switch can be chosen for S₅ as for S₄.

Normally open vacuum interrupters for S₆ are available from Ref. 14. (Vacuum interrupters could not be used for S₅ because they cannot interrupt without a current zero crossing). Closing in on high fault currents requires a mechanism which provides a high contact force to prevent contact bounce and welding. For this reason the commercially available vacuum interrupter has a closing time of 8 to 10 ms. The advantage of a vacuum interrupter is commercial availability and proven reliability, which is critical for application as a safety feature. The slow closing time can be overcome by the parallel connection of an explosively operated closing switch which can attain a 1 ms closing time. (See Ref. 7). This combination of vacuum interrupter and explosive closing switch appears as an optimum combination to provide function and safety at minimum cost. Currents over about 4 kA will be kept out of the battery circuit. This will ease the design requirements on contactors S₁ and S₂.

Fig. 4.4 Connection of Battery Pulser to Transformer Neutral for Injecting dc into 60 Hz Power System.

5.0 COST

Price estimates are collected for the purpose of comparing pulser options.

5.1 Flywheel And dc Generator

A 1 kA pulser consisting of a flywheel and dc generator to be charged with an induction motor, was quoted \$327,000 by Westinghouse, Round Rock, Texas. (Ref. Preston White 512-255-4141 ext. 320). Controls and an ac current bypass must be added. This option was not considered any further.

5.2 Commercial Standby Generators

Quotes on Solar Electric Turbine-Generators and Caterpillar Diesel-Generators were obtained from Hawthorne Machinery Co., San Diego (619-279-4230).

Rating (KW)	Turbine		Diesel	
	900	3,000	900	2 x 1,500
Cost Generator (K\$)	300	1,100	150	2 x 180
Rectifier (K\$)	3	10	3	10
Controls (K\$)	19	19	19	19
Switching (K\$)	53	53	53	53
AC Bypass (K\$)	70	70	70	70
Trailer (K\$)	<u>45</u>	<u>50</u>	<u>45</u>	<u>55</u>
Total Materials (K\$)	490	1,302	340	567

Labor & Burden

Engineering	52
Drafting	27
Assembly	46
Test	<u>14</u>
Total	(K\$) 140

5.3 Variable Transformer-Rectifier Pulse Source

The variable transformer - rectifier pulse source was quoted by Electro Engineering Works, San Leandro, CA. (415-569-3326). The specifications are given in Section 3.3.1.

Open Circuit Voltage	1.2 kV dc	2.0 kV dc
Output Current	1.0 kV dc	1.5 kA dc
Input Voltage	2.4 kV	2.4 kV, 4.2 kV 7.2 kV, 13.8 kV
Power Supply Cost (K\$)	129	265
Controls (K\$)	19	19
AC Bypass	65	65
65 Power Capacitors		
200 kVA, 12.5 kV (K\$)		
Zinc-oxide Surge Protectors	5	5
DC Load Break Switches (4) (K\$)	18	18
Fast Closing Switch Dev	35	35
Trailer	<u>45</u>	<u>50</u>
Total Materials	K\$ 316	K\$ 457

Labor & Burden

Engineering	52
Drafting	27
Assembly	46
Test	<u>14</u>
Total	K\$ 140

5.4 Lead Acid Battery Pulser

The price estimate covers a pulser with open circuit voltage of 2 kV. The output current of 1.5 kA should be verified experimentally.

	<u>Units</u>	<u>\$ each</u>	<u>Total \$</u>
8D Truck Batteries	132	135	17,820
Battery Chargers	44	200	8,800
Contactors S ₁ , S ₂	88	250	22,000
Pneumatic Actuator	44	100	4,400
Pneumatic Control	1	3,000	3,000
Drawer and Slides	220	50	11,000
Drawer Plates PVC	220	25	5,500
Rack Framework	44	150	6,600
Copper Bus Work	2,000 lb	2.5	5,000
Insulation	500 lb	5.0	2,500
DC Load Switch	4	4,500	18,000
Fast Closing Switch Dev.			35,000
Vacuum Closing Switch			8,000
Control Resistor Dev.	1	25,000	25,000
Control, Interlocks		5,000	5,000
Exhaust Fan, Lights		3,000	3,000
Trailer, 40,000 lb, 45 ft.	1	45,000	<u>45,000</u>
Total Materials:		(K\$)	225.62

Labor & Burden

Engineering	62.4
Drafting	27.2
Assembly	62.4
Test	<u>14.1</u>
(K\$)	166.1

The cost for four options rated at 2KA, 1.5KA is summarized below:

TABLE 5.1

PULSER COST COMPARISON					
		Lead Acid	Variable	Standby	Standby
		Batteries	Transformer	Generator	Generator
				Diesel	Turbine
Materials	(K\$)	226	457	567	1,302
Labor and Burden	(K\$)	166	140	140	140
TOTAL	(K\$)	392	597	707	1,442

6.0 CONCLUSIONS

The utility industry has collected experience on the effect of solar-induced EMP in power systems which is generally applicable to nuclear generated MHD-EMP even though it covers only about 10% of the expected current range.

System disruption and possible destruction of equipment must be expected over a wide area.

Preventive measures could be employed in the form of protected capacitor banks installed in the system neutral to ground connections.

Laboratory testing on transformers, measuring and relaying equipment can be performed with dc pulsers of limited voltage capability (about 150V, 1,500A).

Isolated effects, such as heating or harmonic generation can be obtained in the laboratory. The system interaction must be tested with a cooperating utility. Previous testing has been limited to direct current of 100A. Extension of current magnitude is of major interest.

On-off control for the pulser is sufficient because the slow pulse shape is largely controlled by the L/R time constant of the connected power equipment.

Trailer mounting and energy storage in the pulser are important features for system testing in the field. Multiple pulsers will be required for extended system testing.

The dc pulser must either be able to carry high values of alternating current (neutral imbalance and fault currents), or it must be provided with a protected capacitor bank as ac by-pass.

Two options are suggested for laboratory and field testing.

1. Variable Transformer-Rectifier Power Supply.
2. Battery Bank Pulser.

A lead acid battery bank results in the least cost. Safety issues are incorporated into the design. The module voltage is only 36 V to prevent dangerous arc. The desired test voltage is erected just prior to testing with remote switching by pneumatic control. Off-the-shelf components can be used. A battery pulser does not require a separate ac bypass in the form of an expensive protected capacitor bank. Testing of 8D truck batteries has shown that they can conduct 60 Hz current at 30 kA_{rms} for 17 ms without damage. Fault currents of longer duration will be shorted out by a fast closing switch. The batteries are expected to carry the ac neutral imbalance current within the limit of their thermal capacity. A modular battery bank design covers a wide range of voltage and current.

Standard 8D truck batteries can be used for discharge currents up to 1 kA at 100 sec and possibly higher. The lead conductor crossections in the battery and the terminals must be specified with the manufacturer to limit overheating. An improved battery with copper terminals is available as an import from Australia.

7.0 RECOMMENDATIONS

1. Survey the U.S. electric power system's damage potential from MHD-EMP, depending upon system characteristics, interconnections and expected surface voltage gradient.
2. Define cooperative test plans with interested utilities.
3. Establish a laboratory facility to test components.
4. Evaluate advanced lead acid batteries, such as the PULSAR.
5. Develop fast switches for protection of pulsers or capacitor banks in the ground to neutral connection of power systems.
6. Proceed with the design of small battery pulsers initially used for laboratory testing of components.
7. Define measures to prevent disruption and damage from MHD-EMP.

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Campbell, CA. (408-377-4621).

APPENDIX A

Slow EMP Testing by
Injection of DC Currents into
Power Systems

Consideration of Transmission Substation Practices

by John G. Kappenman

Minnesota Power Co.
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The requirements for the dc pulser and associated test systems are dependent upon the power system in which the tests are conducted. A pulser test system can easily be set up to inject direct currents that would primarily flow within a substation. A pulser test system that forces direct currents to flow outside a substation, over long transmission lines to other substations, would have to be much more sophisticated.

Examples of field tests can more clearly demonstrate these differences. For the field tests, done on the Minnesota Power system as described in reference 7, the direct current was constrained to flow within the substation. Most major substations will be terminated with several high voltage transmission lines of several voltage levels. A major substation is also likely to have two or more large power transformers between the voltage steps. On a bulk transmission substation (for example 500/230 kV), the transformers will typically be of an auto-transformer type configuration. Fig. A is a one-line diagram of a typical bulk transmission substation. Three transmission voltage levels are present: 115 kV, 230 kV, and 500 kV.

Four large power transformers are located in the substation. Two are 500/230 kV transformers. All of them are auto-transformers and all are connected to the substation ground mat at different locations within the substation. Five 115 kV transmission lines, three 230 kV transmission lines, and two 500 kV transmission lines enter the substation. The direct current injected into the transformer neutral will see a resistance equivalent to the phase quantities divided by three since the three phases are in parallel.

The equivalent resistances of each of the lines are given in the diagram of Fig. A. The equivalent resistances of the transformers are given as well, except that the resistance is divided according to the resistance in the common and series winding of the auto-transformers. Note that the equivalent resistances of the transformers are at least an order of magnitude smaller than the equivalent resistances of each of the transmission lines.

With the equivalent resistance data, the direct current flow in a power system can be estimated for the test conditions. For example, if a direct current pulser were installed in the neutral of transformer #3, the majority of the direct current injected would flow in a loop within the substation as shown in Fig. B. The loop starts at the neutral of transformer #3 through its common winding, then to the 115 kV bus which connects back to the common winding of transformer #2. At this point, the direct current will return to the substation ground mat through the common winding of transformer #2. Since the transformer resistances are much smaller than the transmission line resistances, essentially none of the direct current will flow into the rest of the system. Because of the auto-transformer connections, the direct current flows only partially through transformer #3. By opening breaker A (which directly connects the 115 kV sides of transformers 2 & 3), the direct current injected is now forced to flow through both the series and common winding of transformer #3 before the direct current returns to ground in the substation ground mat as shown in Fig. C. The pulser voltage source required for these tests is very small (i.e. 24 Volts), because the direct current loop is confined to the substation and therefore has a very low resistance.

In these examples and in the Minnesota Power test, the direct current flowed principally within the substation due to the higher resistances of the transmission lines. Extraordinary procedures would be required to force the direct current to flow into the system beyond the substation.

Two methods could be applied to force the flow of direct current into the transmission system beyond the immediate substation. The first method would require reconfiguring the substation by temporary switching so that a dc pulser would only interact with a single transformer with transmission lines. The alternate method would be to use multiple dc pulser sources operated in synchronism to inject dc into the bulk system. Examples of both methods will more clearly demonstrate the requirements necessary for each of these tests.

The substation and system shown in Fig. A, and the tests conducted by Minnesota Power, clearly indicate that direct current (injected in a substation with more than one transformer) will flow within a loop confined to that particular substation. To more realistically duplicate the expected direct current flow (either produced by a geomagnetic disturbances or MHD-EMP), a method has to be devised to force the direct current to flow into the transmission lines connected to a substation. The easiest means to accomplish this would be to install a dc pulser in the neutral of a transformer at a substation which has only one transformer. Under these conditions, a low resistance loop back to the substation ground mat, would not exist and the injected direct current would have to flow into the transmission lines connected to the substation. Substations of this type (with only one transformer) are more common at the subtransmission levels and therefore are likely not suitable for tests of this type. The vast majority of substations at the UHV and EHV transmission levels have more than one transformer located at the substation. For these more common occurrences, temporary switching in the substation would be necessary to remove the multiple transformers from the network. For example, the system in Fig. A could be reduced by switching to allow direct current injection into the two 500 kV lines. By proper switching, the system in Fig. A could be reduced to the system in Fig. D. The dc pulser would be located in the neutral of transformer 7T. The direct current would flow through the series and common winding of the transformer and then flow into the 500 kV lines. The system resistance applicable to the pulser current flow, consists of the transformer resistance plus the parallel equivalent resistance of the two 500 kV lines. This circuit would have a resistance of approximately 1.1 Ohms as measured from the neutral of transformer 7T. Therefore, a pulser for injecting 1000 Amp of direct current would have to produce a dc voltage of at least 1100 Volts. For a similar set of tests (except that the direct current flow is desired on the 115 kV transmission lines), the system in Fig. A could be reduced by switching to the test system given in Fig. E. The dc pulser would be located in the neutral of transformer 3T. The direct current would flow through

the common winding only of the transformer and then into the five 115 kV lines. For this test configuration, the equivalent resistance of the circuit as measured from the neutral of transformer 3T would be approximately 0.24 Ohms. In this case, a 1000 Amp direct current injection would only require a 240 Volt dc source.

This test method, however, has a major disadvantage. The switching required to obtain the test configurations results in a contrived power system configuration that is far from normal. Utility companies may find it very difficult to provide for such test configurations without compromising reliability or shedding load. Also, since major elements of the power systems are isolated, the configuration would not be truly representative of the same network, subjected to a real EMP disturbance.

The second test method would be able to inject direct currents into the transmission system without the switching reconfigurations required in the first method. As earlier shown in Fig. B and C, the direct current injected into a transformer will return to ground through the closest available transformer within the substation. In a real EMP disturbance, the potential of the entire substation ground mat rises. However, in a test such as this, a dc potential can only be applied to one transformer neutral rather than the entire substation ground. If all the transformers within the substation could have dc pulsers connected to their neutral points, then the neutrals of all the transformers within the substation would experience a dc potential rise similar to an EMP disturbance. The direct current injected would be forced to flow into the transmission lines exiting the substation.

For the system as originally shown in Fig. A, four dc pulsers would be required for this test method. The parallel equivalent resistance of all the transmission lines exiting the substation is approximately 0.119 Ohms. Therefore, in order to inject a total direct current of 1000 Amps, the pulsers would be required to develop a dc potential of 119 Volts each. Since the 115 kV lines have the lowest

parallel resistance, most of the direct current injected will flow into these lines. Of the 1000 Amps of current injected, approximately 600 Amps will flow on the 115 kV lines, 285 Amps on the 230 kV lines and only 116 Amps on the 500 kV lines. In a real EMP disturbance, the largest direct current flows would be expected on the 500 kV lines. These test conditions still differ from a real EMP disturbance with respect to the earth surface potential. The 115 kV lines in this example are relatively short and the 500 kV lines are relatively long, which accounts for the larger 500 kV line resistances. In an EMP disturbance, an earth surface potential gradient is created. Therefore, a 500 kV line which spans a longer distance than a 115 kV line will have a greater potential difference and a resulting higher direct current flow than a 115 kV line (Ref. 6). In order to preserve this characteristic for test conditions, dc pulsers could be installed at the remote ends of the 500 kV lines. These pulsers should have a polarity opposite to the pulsers in the Fig. A substation. This will create conditions in which the potential difference across the 500 kV lines are greater than for the shorter lines.

Fig. A One-Line Diagram of a Typical Bulk Transmission Substation.

Fig. B. Main dc Current Flow with Pulser Inserted at Transformer 3T.

Fig. C. Main dc Current Flow with Pulser Inserted at Transformer 3T and Breaker A Opened.

Fig. D. Switching Arrangement for Fig. A to direct dc Current into 500 kV Transmission Lines.

Fig. E. Switching Arrangement of Fig. A to direct dc Current into 115 kV Transmission Lines.

APPENDIX B

HIGH POWER TESTING OF 8D AUTOMOTIVE BATTERIES

Introduction

Lead-acid batteries represent a high energy density source of pulse power. The application at hand will expose the battery to alternating current flow in addition to the dc discharge currents. The dc discharge capability is obtained from the battery manufacturers.

The capability of lead acid batteries to conduct high values of alternating current is not known. AC testing is therefore conducted. We are concerned with the effect of heating, electrodynamic forces and chemical action by the alternating current.

Test batteries were selected from commercially available types. The highest discharge currents are provided by the 8D automotive battery which is manufactured for starting large diesel engines. The overall dimensions are standardized by the Battery Council International (BCI).

BCI Specifications for 8D Battery

Max. Length	0.527 m
Max. Width	0.283 m
Max. Height	0.276 m

Typical Parameters of 8D Battery

Wet Weight	64 kg (141 lb)
Dry Weight	48 kg (106 lb)
Electrolyte	12.6 l (13.3 Quarts)
Cold Cranking Capacity	725 to 1300 A
Reserve Capacity	390 min.

The reserve capacity is defined as the number of minutes a fully charged battery can maintain a current of 25 A to 1.75 Volt per cell at 25°C.

The cold crank test rating is the current that a fully charged battery can deliver at -17.8°C for 30 sec to a voltage of 1.2 Volt per cell. This is the most applicable standard parameter of automotive batteries to characterize the ability to deliver high discharge currents. As a rule of thumb, a battery at room temperature is able to deliver about 1.5 times the cold crank rating amperes under otherwise identical test conditions.

The cold crank rating is determined by the internal construction, such as total plate area, quality of the separators and the crosssection of the lead connections.

We are not only concerned with the ability of a battery to deliver high currents, but also to conduct the high values of applied alternating current without excessive heating.

In a search of the industry three manufacturers were located who produce 8D batteries with high cold crank rating, and also use large diameter terminal posts:

1. Deka Battery
East Penn Mfg. Company
Deka Rd.
Lion Station, PA 19536
Mr. Jim Lupold (215) 682-6361
2. ESTEE Battery Company
2700 Carrier Ave.
Commerce, CA 90091
Mr. Franklin McKanin (213) 724-5080
3. Voltmaster Company
POB 388
Corydon, Iowa 50060
Mr. Roger Winslow (515) 872-2660

Each manufacturer supplied 2 batteries for test.

Test Facility

A commercial 60 Hz high power test laboratory was used. This laboratory has a 500 MVA test generator and all facilities for controlling and measuring test currents in the desired range. Safety is provided by an outdoor concrete test cell and a protected observation area.

Address: Reinhard Paulus
 Mgr. High Current Laboratory
 Allen Bradley Company
 1201 South 2nd Street
 Milwaukee, Wis. 53204
 Tel: (414) 671-2000

Testing was conducted by Rolf Dethlefsen of Maxwell Labs and Tom Hudson of the Department of Energy.

Test Batteries

Two (2) test batteries were delivered in wet-charge condition by each of the 3 manufacturers. A check of the electrolyte specific gravity confirmed that all batteries were in a state of full charge before and after testing. Relevant battery parameters are listed below:

Manufacturer	Deka Battery East Penn Mfg. Co.	ESTEE	Voltmaster
Model No.	8D-908 DMF	8D-225	8D-808
Cold Crank	1,300 A	1,050 A	1,170 A
Current Rating			
Reserve Capacity	410 min.	450 min.	430 min.
Terminal Post	3.16 cm ²	2.34 cm ²	2.5 cm ²
X-Section			
Inner Cell Post	2.26 cm ²	2.06 cm ²	2.18 cm ²
X-Section			
Supplied	automotive	automotive	automotive
Terminals	on side terminal	on post	post with side terminal

Side Terminal	2.14 cm ²	N/A	2.02 cm ²
X-Section			

The dimensions of the automotive terminals are shown in Fig. A. Heavy copper clamps with matching taper had been prepared for connection to cable.

Diagnostics

Calibrated current, voltage and time measurements were provided by the High Power Laboratory oscillograms.

Specific gravity of the electrolyte was measured with a portable tester as used for automotive service. The electrolyte temperature was measured with laboratory thermometers, and the temperature of the battery terminals with a portable thermocouple instrument.

Test Procedure

Test power was delivered through a transformer from the 500 MVA test generator. Initially all six test batteries were connected in series. The batteries were connected with negative terminals to negative terminals and positive to positive so that the resultant dc voltage across the string of batteries was zero. This prevented dc current flow into the transformer.

Starting at 1 kA, increasing magnitude of current was passed through the batteries. The duration of current flow was guided by a constant value of $I^2 \cdot t$. Modifications were made, based upon visual observations of the batteries during a test. The vent caps were left in place on the batteries during testing in order to simulate the condition of use.

The two Deka batteries were returned to the manufacturer after the test. The other four batteries were shipped to the attention of Tom Hudson at DOE for further test and observation.

Test Results

A total of 16 high current test shots was obtained. Three of them served for the purpose of calibration. The initial tests at 1089 A through a string of 6 batteries showed that the side terminals, as supplied on the ESTEE and Voltmaster batteries, represented a weak link because of small lead conductor crosssection. The battery temperature was 16°C at the start of testing. After test No. 3A the electrolyte temperature reached 19°C, the automotive terminal with heavy copper clamp reached 17°C and the side terminals 50°C.

After test 4B (2kA for 20 sec), the side terminals melted on one Voltmaster battery. The second Voltmaster battery showed incipient melting. At this time only 2 ESTEE batteries were connected in series to the test circuit. After passing 2238A for 23.5 sec., an intercell lead connection melted. The cell vent cover popped off the faulted cell and a spray of acid was ejected. The electrolyte temperature in the faulted cell was 44°C. The remaining cells ranged from 29°C to 31°C.

Test No.	Batteries	Current kA _{rms}	Duration	Voltage (across batteries) V _{rms}	Internal Resistance per battery mOhm	I ² · t kA ² · sec	
1A	all 6 in series	1.089	58.3 ms				
2A	"	"	33 s	17.9	274	39.1	side terminals heated to 50°C
3A	"	"	31 s	18.3	2.8	36.8	"
4B	"	2.0	20 s	-	-	80.0	side terminal melted on Voltmaster
5B	ESTEE 2 in series	1.120	53.3 ms	-	-		
6B	"	2.238	23.5 s	12.8	2.86	117.7	internal connection melted on ESTEE
7B	Voltmaster 2 in series	2.156	15.5 s	15.4	3.57	72.0	
8B	"	2.985	9.5 s	22.4	3.75	84.6	internal connection melted on Voltmaster
9B	Deka 2 in series	3.025	5.05 s	15.0	2.48	46.2	
10C	"	4.910	1.02 s	20.2	2.06	24.6	
11C	"	4.170	75 ms	17.0	2.04	1.3	
12C	"	7.8	75 ms	33.7	2.16	4.6	
13D	"	16	66.7 ms	72.1	2.25	19.2	
14D	"	20.9	50 ms	94.6	2.26	21.8	sparking at automotive lead terminal
15E	"	24.7	41.7 ms	-	-	25.4	
16E	"	30.4	16.7 ms	152	2.50	15.4	arcing at automotive lead terminal

Table of Test Results

Two Voltmaster batteries were then connected to the circuit using the automotive terminals with heavy copper clamps. After conducting 2156 A for 15.5 sec., the terminal temperature ranged from 19°C TO 21°C, the electrolyte temperature ranged from 24°C to 26°C. At the end of test No. 8B (2985 A for 9.5 sec) a cell interconnection melted with a similar display as before. The terminal temperature ranged from 21°C to 33°C, and the electrolyte temperature from 27°C to 29°C.

Two Deka batteries were connected in series to the test circuit using the automotive terminals with heavy copper clamps. Test currents were raised to 16000 A for shortened time intervals without any display or undue temperature rise. For test No. 14D (20900 A for 50 ms) sparking occurred between the copper clamp and one automotive terminal. This was fixed by inserting copper slivers and increasing the contact pressure. In test No. 15 E, 24700 A were passed for 41.7 ms without problems.

Under test No. 16 E (30400 A for 16.7 ms), arcing melted one automotive terminal and part of the copper clamp. It was observed that the lead terminal softens under the action of high current magnitude. The metal flows, and frequent re-tightening becomes necessary. Other problems were not observed. The electrolyte did not show any excessive heating or gas evolution. The specific gravity of the electrolyte before and after the test was 1.3 g/cc indicating a state of full charge.

DC Discharge Testing

The three manufacturers performed high current discharge tests in their facilities. The current magnitude was limited by the available test equipment. The results are given below:

Deka Battery: Discharge 1500 A for 100 sec.

Automotive terminals showed a temperature
rise of about 15°C above room temperature.

ESTEE: Two batteries at room temperature were discharged at 1300 A until the terminal voltage fell to 7.2 Volt. This occurred at 69 sec. and 77.4 sec. respectively.

Voltmaster:	Time	Current	Terminal Voltage	Electrolyte Temp
	sec.	A	V	°C
Battery 1	0	0	12.83	26
	5	1100	8.7	
	30	1100	8.57	
	70	1100	8.32	31

Voltmaster: (cont)	Time	Current	Terminal Voltage	Electrolyte Temp
	sec.	A	V	°C
Battery 2	0	0	13.5	27
	5	1100	8.8	
	30	1100	8.7	
	65	1100	8.4	29

The manufacturers report that the 8D battery, as a quality assurance test, is discharged at 3000 A for 2 sec.

The ac testing indicated values of internal resistance for the 8D battery ranging from 2.1 mOhm to 3.7 mOhm.

Deka batteries showed the lowest internal resistance and Voltmaster the highest.

At 3 mOhm one would expect a short circuit current of 4 kA.

Discussion

The batteries from 3 manufacturers differ in the lead conductor crosssections employed. This correlates with the measured value of internal resistance.

The Deka battery reportedly uses the heaviest lead crossections of the three types tested. This correlates with the lowest value of internal resistance and the highest cold crank rating.

Voltmaster and ESTEE showed comparable values.

Adiabatic melting of a conductor is related to the square of current density times the time duration of current flow. (Action Integral, $j^2 \cdot t$). The following values are reported by Tucker and Toth. *

	Melting Temp (°C)	Resistivity at 20°C (micro Ohm - cm)	$j^2 \cdot t$ for melt begin ($A^2 \cdot s \cdot mm^{-4}$)
Lead	327	22	1283
Copper	1083	1.77	80492

* Tucker and Toth, A Computer Code for the Prediction of the Behavior of Electrical Circuits Containing Exploding Wire Elements.
SANDIA Report SAND - 75-0041.

Adiabatic heating will hold true only for current flow durations in the millisecond range. For longer time periods, heat can flow away from the hot spot occurring at the location of narrowest conductor cross-section. Melting of the lead conductor was observed at the end of 3 test shots. These are correlated in the following table:

Test No.	Current (kA _{rms})	Duration (sec)	$I^2 \cdot t$ (kA ² ·s)	Min.	$j^2 \cdot t$ $\frac{\text{kA}^2 \cdot \text{s}}{\text{cm}^4}$	Melt Location
				Lead X-Section (cm ²)		
4B	2.	20.0	80.	2.02	19.6	Voltmaster side terminal
6B	2.238	23.5	117.7	2.06	27.7	ESTEE inter-cell
8B	2.985	9.5	84.6	2.18	17.8	Voltmaster inter-cell
Adiabatic Heating					12.8	

The action integral $j^2 \cdot t$ is largest for long periods of current flow and for the intercell connections where more effective cooling by the electrolyte can be assumed. Heating within the battery lead conductors is well predictable for currents in the kA range.

At 20.9 kA the first sparking was observed in Test No. 14D between the tapered automotive lead terminals and a heavy copper clamp with matching taper. Frequent re-tightening was necessary because the soft lead tended to flow. The standard terminals on automotive batteries appear unreliable for passing high values of current over 10 kA. Improvements could be made with specially designed clamps. (Serrated copper surface and Belville washers). Copper terminals may be cast into the lead conductor. On the other hand, one should remember that the batteries of the MHD-EMP pulser can be protected by fast closing switches from the effect of high fault currents.

The electrolyte appeared fully stable under the action of 60 Hz currents up to 30.4 kA_{rms} without any evidence of overheating or pressure rise due to gas generation. This is encouraging news together with the low measured values of internal impedance.

Negative Post

Positive Post

Vertical Dimensions $\pm .020''$ Others $\pm .005''$

Fig. A. Heavy Duty Automotive Battery Terminals.

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