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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

IMPACTS OF A NOMINAL NUCLEAR ELECTROMAGNETIC PULSE ON ELECTRIC POWER SYSTEMS

PHASE III FINAL REPORT

POWER SYSTEMS TECHNOLOGY PROGRAM

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
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Energy Division

IMPACTS OF A NOMINAL NUCLEAR ELECTROMAGNETIC PULSE ON ELECTRIC POWER SYSTEMS

Phase III

FINAL REPORT

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FOREWORD

The Office of Energy Management of the United States Department of Energy (DOE) has formulated a program for the research and development of technologies and systems for the assessment, operation, and control of electric power systems when subjected to electromagnetic pulse (EMP). The DOE EMP program plan is documented in a DOE report entitled Program Plan for Research and Development of Technologies and Systems for Electric Power Systems Under the Influence of Nuclear Electromagnetic Pulses, DOE/NBB-003, May 1983. The study documented in this report was conducted under program plan element E2, "EMP Assessment Methodology Development and Testing."

The EMP assessments discussed in this report have focused on elements of electric power systems that are closely coupled to conductors exposed to the incident EMP, such as transmission and distribution (T&D), substations, and generation. No attempt has been made to assess instrumentation and control (I&C) systems located deep within complex facilities. Furthermore, a conservative assessment approach has been used to determine the flashover vulnerability of transmission and distribution (T&D) lines by neglecting to account for the additional insulation value provided by wooden support structures. A goal of this study was to accomplish assessments that provide an "indication" of the effects of EMP on electric power systems. This was accomplished by the conservative assessment approach described above.

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ABSTRACT

A high-altitude nuclear detonation several hundred kilometers above the central United States will subject much of the nation to an electromagnetic pulse (EMP) consisting of intense steep-front short-duration transient electromagnetic fields followed by a geomagnetic disturbance with a duration of tens of seconds. Since 1983, the Department of Energy has been actively pursuing a research program to assess the potential impacts of one or more EMP events on the nation's electric energy supply. A nominal EMP environment suitable for assessing geographically large systems has been used to provide an indication of EMP impacts on electric power systems. It was found that a single high-altitude burst, which significantly disturbs the geomagnetic field, could cause significant load and generation loss, but permanent damage would be isolated. Multiple bursts would increase the disturbance. Nevertheless, based on the effects of a nominal EMP environment, a long-term blackout is not expected since major components such as power transformers are not likely to be damaged.

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1. INTRODUCTION

On July 8, 1962, at about 11:00 pm Hawaiian time, a nuclear detonation occurred 400 km (kilometers) above Johnston Atoll in the Pacific Ocean. This high-altitude nuclear test was conducted by the U.S. under the code name "Starfish." Approximately 800 miles from ground zero on the Hawaiian island of Oahu, 30 strings of street lights failed simultaneously at about the time of the Starfish shot [1]. The Hawaiian street light incident was examined by Vittitoe who concluded the failure was caused by the electromagnetic pulse (EMP) generated by the high-altitude burst [2]. The peak EMP electric field over Honolulu was estimated at about 5.6 kV/m (kilovolts per meter) [3]. Although the peak amplitude of the EMP was relatively small, the orientation of the street-light circuits with respect to the incident EMP angle allowed a coherent buildup of surges which resulted in blown fuses [2].

Modern weapons with higher gamma-ray yields coupled with higher geomagnetic fields over the central U.S. could produce EMPs with intense fields on the order of tens of kilovolts per meter. These higher fields, coupled with the introduction of modern solid-state and microprocessor-based control, instrumentation, and protection equipment in electric power systems, have caused concern in both government and civilian sectors. During the early 1980s, numerous newspaper and journal articles focused a significant amount of attention on the potential impacts of EMP on the nation's electric energy supply [4-12]. The concern was that one or more nuclear weapons, detonated in space above the continental United States, could disrupt electric power during a period of national crisis. A recent article discussing research into and development of new third-generation nuclear weapons that selectively produce gamma and electromagnetic radiation [13] implies that EMP effects may become even more important in the future.

In 1983, the Office of Energy Storage and Distribution of the U.S. Department of Energy (DOE) formulated a research program to assess the impact of EMP on electric power systems [14,15]. The primary goal of the program is to increase national security by assessing the impact of EMP on electric power systems and enhancing the reliability of electric power systems under the influence of EMP. A secondary goal is to improve the reliability of power systems under the influence of related disturbances, such as steep-front surges and geomagnetic storms.

The research conducted under the DOE EMP Program has been reviewed by a group of experts in the EMP and electric utility communities. This review assured that the studies were realistic for electric power systems and that solutions were in accordance with acceptable utility practice. The program depended on cooperation and coordination with related European, DOD, and Electric Power Research Institute (EPRI) research to minimize duplication of work. The program also worked closely with the North American Electric Reliability Council (NERC) in areas related to reliability and restoration.

The purpose of this report is to discuss the impact of EMP on civilian electric power systems. The report is an accumulation of research spanning several years. It addresses six major issues and offers recommendations for future research.

1. A Nominal EMP Environment. The use of a realistic unclassified electromagnetic environmental definition provides realistic, publishable results. A nominal environment consists of both E_1, the initial high-altitude electromagnetic pulse (HEMP), and E_3, the later-time magnetohydrodynamic electromagnetic pulse (MHD-EMP). Variations of EMP field intensity address the issue of system sensitivity to field magnitude. E_2, the intermediate-time high-altitude EMP, was considered in earlier assessments.

2. **Assessment Methodology**. Assessment of the impact of EMP on a power system is a complex process. For any power system it is possible to use traditional power system analysis techniques to evaluate the impact of EMP. However, as the size and complexity of a power system increases, the assessment grows increasingly complex.

3. **Effects of a High-Altitude EMP Event on Power Systems**. The impact of E_1 on a system consists of voltage stress and flashover effects. Load and generation loss and damage are possible. The impact of E_1 on control circuits in complex facilities was not assessed.

4. **Effects of Multiple High-Altitude Bursts on a Power System**. Due to the differing time nature of the two EMP effects, multiple bursts cause a hypergeometric impact on HEMP (E_1) effects (surviving load and generation may be reduced for each subsequent burst) and a superposition of MHD-EMP (E_3) effects.

5. **Restoration**. Given demonstrated power system vulnerability to EMP, restoration of the system is important.

6. **Mitigation**. Mitigation for HEMP involves designing equipment to accommodate the extremely rapid rates-of-rise of HEMP-induced surges, while mitigation for MHD-EMP is similar to that for geomagnetic storms.

The report describes a nominal EMP environment and presents the results of a probabilistic assessment of EMP impacts on electric power systems for a single burst. Restoration of electric power systems and mitigation of EMP effects are also discussed.

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2. A NOMINAL EMP ENVIRONMENT

A nuclear detonation in or above the earth's atmosphere produces an intense electromagnetic pulse [16,17]. A large portion of the EMP electromagnetic energy is within the radio-frequency spectrum. The EMP produced by a nuclear detonation is often referred to as nuclear EMP (NEMP). The electromagnetic fields radiated from the blast vary greatly with weapon characteristics, yield, and detonation height. A detonation at altitudes above 40 km produces an EMP called high-altitude EMP (HEMP* or E_1). HEMP is a steep-front short-duration transient, with a rise time on the order of a few nanoseconds, which decays to near zero in less than a microsecond. A single high-altitude burst can subject much of the continental United States to intense HEMP electric fields on the order of tens of kilovolts per meter. A HEMP event is followed by a very low amplitude EMP on the order of 10 V/km (volts per kilometer) which results from geomagnetic perturbations caused by a high-altitude nuclear detonation. This slow EMP is called magnetohydrodynamic EMP (MHD-EMP or E_3). MHD-EMP may affect power systems in a manner similar to that of geomagnetic storms [18].

To assess the effects of EMP on civilian electric power systems, it is necessary to have an electromagnetic environmental description as part of the specification for initial conditions. Much of the information on EMP cannot be discussed in the public domain due to security classification. Generalized waveforms do not represent actual EMP's but attempt instead to incorporate potentially damaging features of EMP such as a near maximum peak amplitude, a very fast rise time, and a very long fall time. Such bounding EMP definitions are suitable for conservative assessments of hardened military facilities and spatially local sites which may be subjected to the maximum threat. However, while this approach could be used in the assessment of the civilian electric power network, the significant geographic size of the power system and the

*Actually, HEMP consists of E_1, E_2, and E_3, but in this report HEMP refers only to the early time portion of the pulse, E_1, which has been common in earlier reports.

nature of the network properties evaluated under bounding EMP conditions would provide unrealistic estimates of system excitation and response.

To provide a nominal HEMP environment for power system assessments, the CHAP code, an environmental calculation code developed by DNA, was used [19]. The CHAP code is a self-consistent code which simultaneously solves both Maxwell's equations and the Compton-electron equation of motion, including the forces of the fields on the electrons and conservation of energy.

Figure 2.1 compares a measured HEMP pulse, the pulse as calculated by the CHAP code, and the calculated pulse when corrected for instrument response.

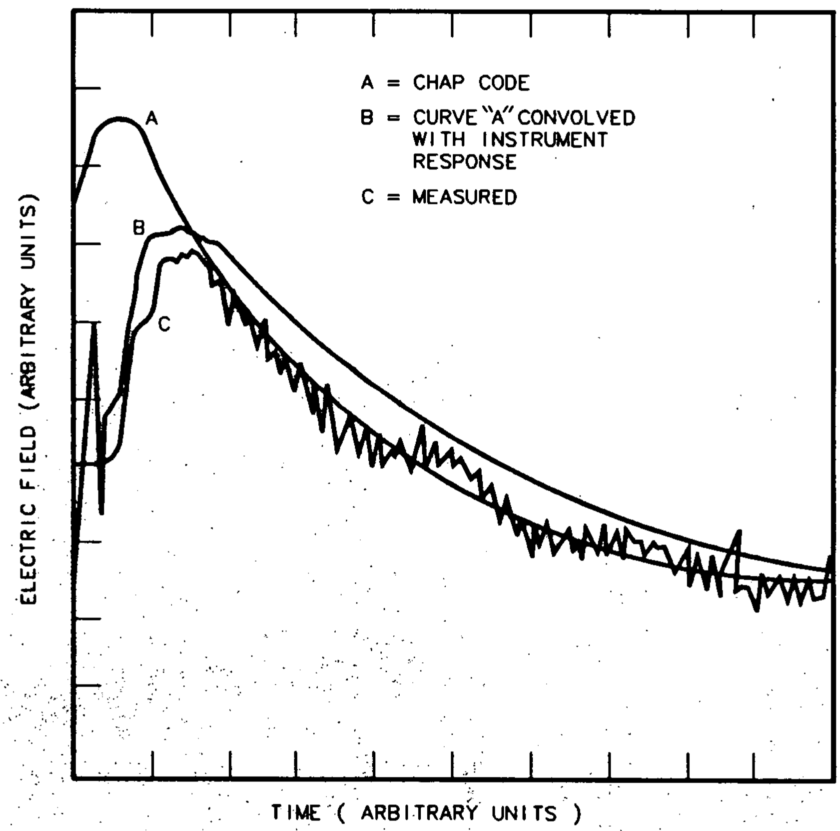

Figure 2.1. Comparison Between CHAP Code Results and Measured Data.

2.1 HEMP Description

The nominal HEMP (E_1) environment has fields near the maximum that can be produced by a high-altitude nuclear explosion. This environment is suitable for unclassified literature, having been calculated without using any values of weapon output parameters classified by the Atomic Energy Act of 1954. This nominal HEMP environment incorporates electric- and magnetic-field pulse characteristics and polarization that vary over the area of coverage, making it suitable for assessments of geographically large systems.

The nominal HEMP environment is based on an exponentially decaying gamma pulse with a decay constant on the order of 10 ns. The total energy of the gamma radiation is taken as 4.2 x 10^{13} joule. For a burst 400 km above the earth, the CHAP code calculated field peaks in the maximum field region to be near 40 kV/m. For a burst 200 km high, it calculated 50 kV/m. A contour plot of field magnitudes for the nominal HEMP environment, a burst 400 km above the earth, is shown in Figure 2.2.

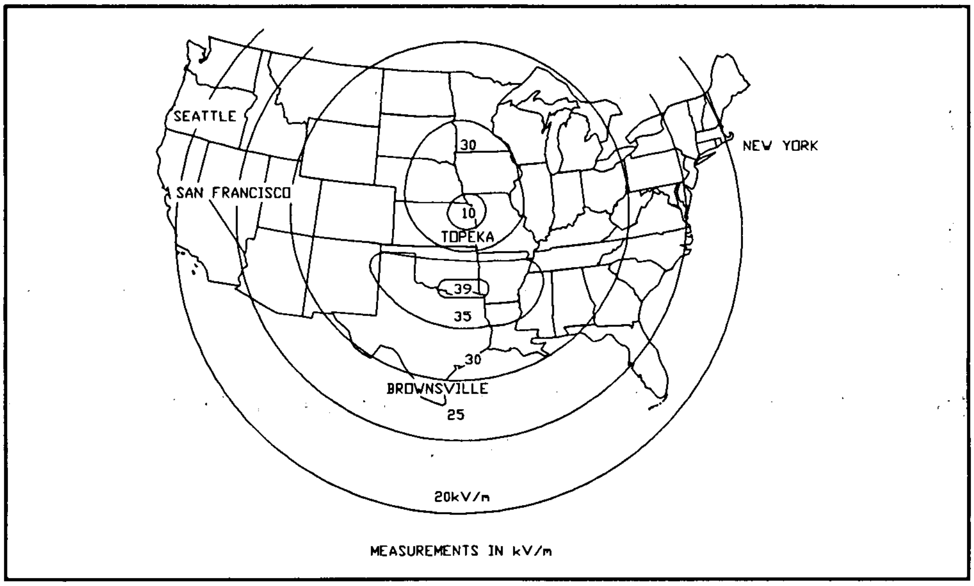

Figure 2.2. Contour Plot of Field Magnitude in kV/m for a Nominal HEMP Event.

2.2 MHD-EMP Description

The MHD-EMP (E_3) environment has been described in a previous paper [20]. This nominal MHD-EMP environment is based on measured data from the Starfish high-altitude nuclear detonation and MHD atmospheric calculations. The electric field in the maximum field region is about 24 V/km, and field duration is assumed to exceed the quasi-dc time-constants of the power system. An example of the MHD-EMP environment for a burst 400 km above Topeka, Kansas, is shown in Figure 2.3. The quasi-static electric field rises to a peak in the order of a second and has a duration of many tens of seconds. The frequency spectrum of MHD-EMP contains only low-frequency components of less than 1 Hz.

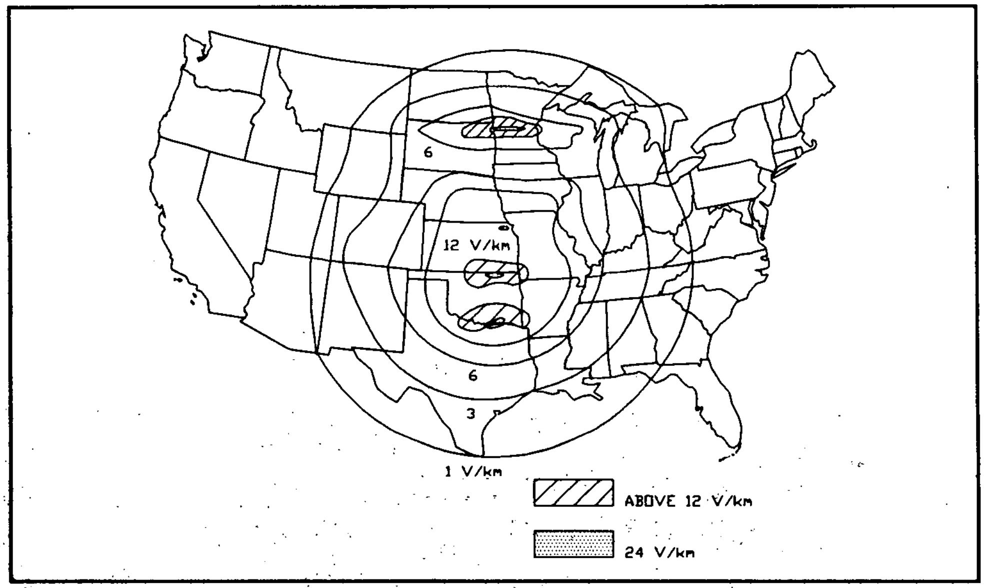

Figure 2.3. Contour Plot of Field Magnitude in V/km for a Nominal MHD-EMP Event.

3. ASSESSMENT METHODOLOGY

The interaction between EMP and electric power systems is a very complicated problem due to the wide frequency spectrum and global coverage of EMP. A comprehensive EMP assessment methodology for electric power systems has been developed by the Advanced Systems Technology division of ABB Power Systems, Inc., for the Oak Ridge National Laboratory [20-22]. This methodology addresses the impacts of HEMP and MHD-EMP on an electric power system.

The time sequence of events following a high-altitude nuclear detonation is shown in Figure 3.1.

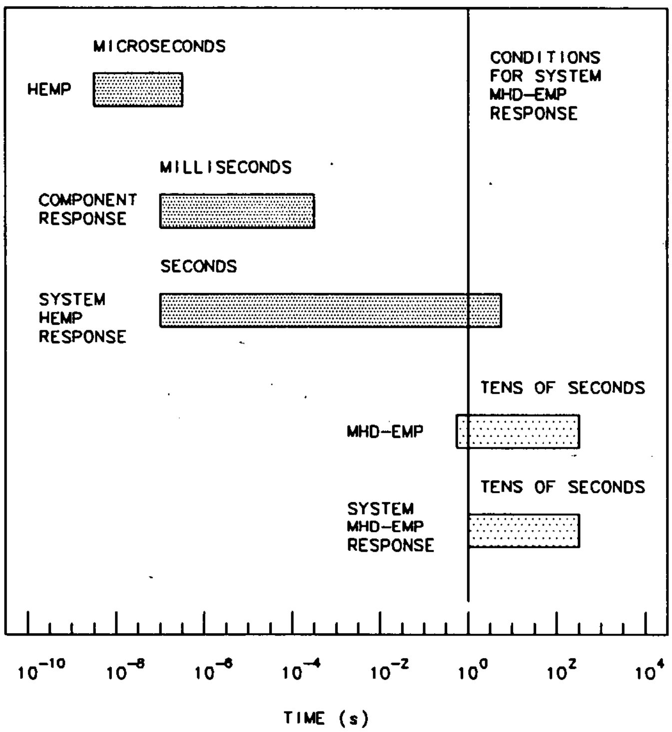

Figure 3.1. Time Sequence of a High-Altitude Event.

A simplified flow diagram of the assessment methodology is shown in Figure 3.2. The HEMP assessment methodology is based on the assumption that, for an initial period of time when HEMP interacts with the system, each subsystem (such as substations) and each functional group of circuits within subsystems can be assessed independently. The system states determined by the load flow and stability analysis of the system under the influence of HEMP at the time of the MHD-EMP event, T_0, are part of the initial conditions for the MHD-EMP assessment. The MHD-EMP assessment methodology has been adapted from power system analysis techniques developed to analyze the effects of geomagnetic storms on electric power systems.

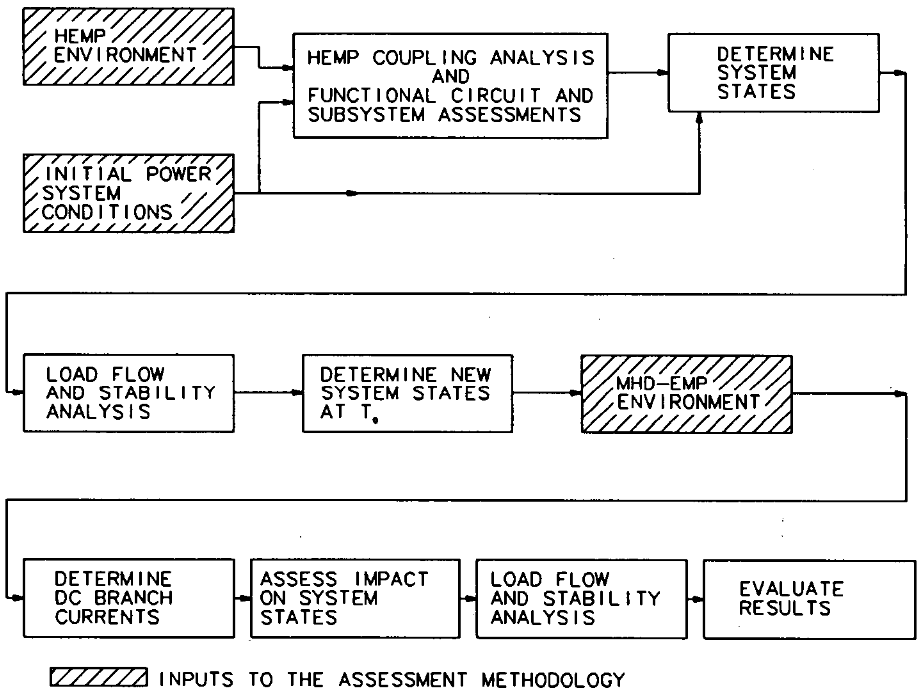

Figure 3.2. Methodology to Assess HEMP (E_1) and MHD-EMP (E_3) Impacts on an Electric Power System.

4. EFFECTS OF A HIGH-ALTITUDE EMP EVENT ON POWER SYSTEMS

As stated previously, two electromagnetic effects, HEMP and MHD-EMP, occur immediately after a high-altitude burst. The two effects have substantially different impacts on the electric power system. HEMP effects appear as flashovers and voltage-stress damage to both power delivery equipment and communications. MHD-EMP effects appear on power lines of great length as a quasi-dc current which flows through grounded transformers and shunt reactors. At extremely high levels, MHD-EMP can also impact communications used throughout the power system.

During a HEMP event, there is the possibility of load or generation loss or both. Either of these events could cause instability for the power grid. If the system remains intact or islands remain large, it experiences MHD-EMP; measurable MHD-EMP effects are a function of line length and field strength. During a nominal MHD-EMP event, quasi-dc currents flowing through the power transmission system can result in insupportable reactive power demand, breaking up the system because of unacceptably low voltages.

Since the two electromagnetic effects manifest themselves on the power system in such dissimilar ways, they must be evaluated separately. However, it must be realized that MHD-EMP may affect a system already modified by HEMP.

4.1 HEMP (E_1) Effects on Electric Power Systems

All HEMP impacts were evaluated on the premise of a nuclear burst of nominal characteristics. For sensitivity purposes, however, power system impacts at peak HEMP field levels other than nominal were also investigated. All probabilities of HEMP-induced flashover were calculated over the entire area of HEMP illumination for a 400-km-high burst, unless specified otherwise. This area is a circle of 2200-km radius.

Multiconductor frequency-domain coupling algorithms used in calculating flashover probabilities have been described in detail elsewhere [23].

For power delivery equipment, the greatest HEMP impact is flashover or insulation damage, with the ultimate result being loss of load or generation. The resulting imbalance could be such that the stability of the system cannot be maintained.

HEMP vulnerability data were assembled for equipment from numerous sources including

- testing at Maxwell Laboratories, which included transformers, voltage transformers, current transformers, and protective relays;
- testing at Westinghouse Relay-Instrument Division, which also included protective relays; and
- unclassified information on equipment such as motors, terminal boards, and low-voltage switchgear.

ORNL supplied transmission- and distribution-line insulation strength based on tests conducted at Maxwell Laboratories.

4.1.1 Transmission and Distribution

Unclassified research conducted during this program has not demonstrated that operating voltages above 69 kV are vulnerable to flashover during a HEMP event, and it has indicated that 69 kV is, at most, marginally vulnerable. Table 4.1 shows estimated flashover probabilities from that research for three different peak HEMP field values [24].

The analysis of vulnerability was conducted using specific, representative line configurations for four operating voltages, with HEMP insulation strength conservatively assumed to be 1.5 times the lightning CFO [25]. CFO, critical flashover, is the voltage magnitude of a defined surge for which flashover occurs fifty percent of the time.

Table 4.1. Flashover Probabilities of Several Operating Voltages.

OPERATING VOLTAGE kV	25 kV/m FIELD PERCENT		NOMINAL 39 kV/m FIELD PERCENT		50 kV/m FIELD PERCENT	
	Min.	Max.	Min.	Max.	Min.	Max.
500	0.0	0.0	0.0	0.0	0.0	0.0
230	0.0	0.0	0.0	0.0	0.0	0.0
69	0.0	0.0	0.0	0.0	0.0	1.7
12	0.2	1.0	3.1	6.0	9.0	15

Table 4.1 shows that distribution voltage levels are most prone to flashovers. In the U.S., distribution is classified into four voltage categories, 5, 15, 25, and 35 kV, with percentage of load served being 10.6, 77.5, 9.4, and 2.5, respectively [26]. For voltage classes other than 15 kV, flashover probabilities were determined by assuming a line configuration similar to that of the 12-kV line, with the HEMP insulation strength adjusted for each distribution voltage class. Only the maximum representative probability of flashover was calculated for operating voltages other than 15 kV. Table 4.2 shows the estimated vulnerability of the four distribution classes to HEMP-induced flashover for three strengths of peak HEMP field. Since the insulating value of wood supports has not been taken into account, the values shown are assumed to be conservative.

4.1.2 Loss of Load Due to HEMP

Flashovers themselves do not directly impact power system security. It is the resultant loss of load which ultimately affects the power system. Simply determining the level of flashovers in transmission and distribution is not sufficient to indicate expected loss of load. There are a number of factors affecting the expected load loss given a flashover on any line section.

Table 4.2. Distribution Class Flashover Probability for Various Peak HEMP Field Strengths.

VOLTAGE CLASS kV	NOMINAL 25 kV/m FIELD PERCENT Min.	Max.	39 kV/m FIELD PERCENT Min.	Max.	50 kV/m FIELD PERCENT Min.	Max.
5	-	2.8	-	14	-	22
15	0.2	1.0	3.1	6.0	9.0	15
25	-	0.0	-	0.8	-	2.0
35	-	0.0	-	0.0	-	0.8

Since no expected flashovers have been demonstrated for transmission and subtransmission for the unclassified environment, only load loss caused by distribution system flashover was considered. Expected load loss is determined by considering four major components of distribution systems: substation supply lines, primary feeders leaving the substation, primary feeders downstream of reclosers, and the sublaterals and interconnected network serving the customer.

A flashover within any of these components affects a different value of expected load loss depending on the component level. Figure 4.1 shows the relevant components of a power distribution system.

Two factors affect the amount of load lost due to a flashover at any component level:

- Hierarchy of the Component Levels
- Protection Philosophy of the Level

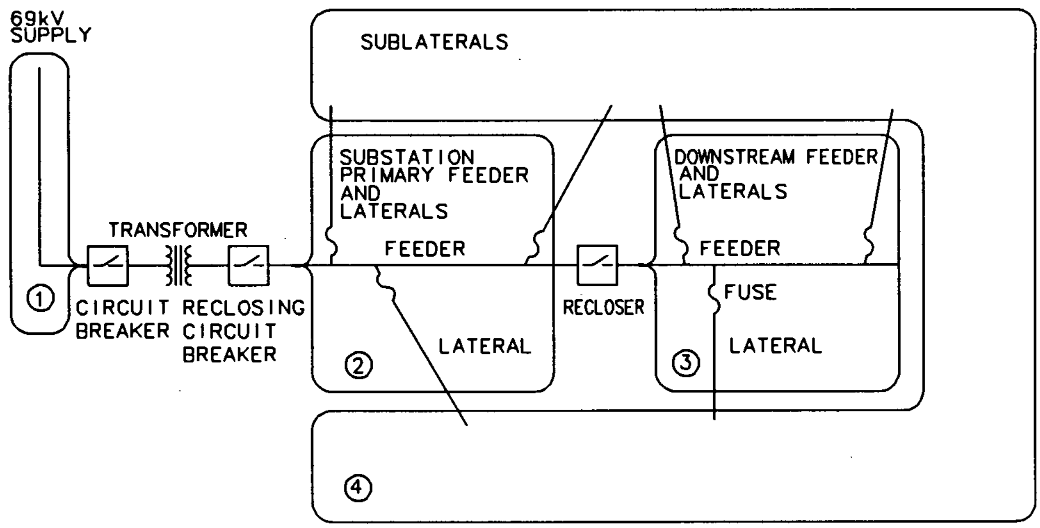

Figure 4.1. Component Levels of a Typical Distribution System.

The highest component level shown in Figure 4.1 is the 69-kV supply. The flashover of a 69-kV supply line will drop more load than the flashover of a sublateral serving a limited number of customers. The component level determines the amount of affected load, because for every component level there exists a statistical distribution of load for any one device of that component. That statistical distribution has an expected value which is the mean or average value of load supported by that component.

If the probability of load loss for every component level can be calculated, we can address the total system effect. Each component level depends on its upstream component. If an upstream component is out of service, downstream component-level flashovers will affect neither fuses nor total load loss.

The philosophy of protection for each component level must also be considered. A flashover on a sublateral will blow a fuse, disconnecting the sublateral from the rest of the circuit. The sublateral will remain out of service until fuse replacement. Similarly, for a flashover on a 69-kV supply line, a circuit breaker is expected to remove the line until intervention occurs.

However, the situation for feeders is somewhat different. Feeders leave substations through a reclosing circuit breaker; that is, the breaker can open under fault* and then close after a short delay. This prevents permanent outages for what is often a temporary fault. Note from Figure 4.1 that several laterals typically branch off primary feeders via fuses.

However, due to protection philosophy, a flashover on a lateral will trip the recloser (a circuit interrupting device which can be programmed for multiple reclosures) or the breaker on the feeder before blowing the fuse. This protection scheme is designed to minimize unnecessary fuse-blowing due to temporary faults.

What this means in terms of probability of load loss is that there are more opportunities for flashover than just one line section. There is an opportunity for flashover for every line orientation associated with each feeder and lateral assembly. A flashover on any lateral, or on the feeder itself, will cause the recloser to operate. Reclosers themselves are expected to be unaffected by HEMP [27].

Using the method which is described in more detail in Appendix A, the expected HEMP-induced loss of load on a system having two reclosing devices, three unique lateral orientations for each reclosing device, and 69-kV distribution-substation supply lines is shown in Table 4.3. The table also shows the surviving load due to nominal HEMP. The values

*A fault is a condition of direct or arcing electrical contact between one phase of the electric system and ground and/or another phase.

in Table 4.3 are lower boundaries for actual surviving load, since the insulating effects of wood structures have not been considered.

The table does not account for additional load loss possible from customer-service flashovers or from simultaneous flashover of adjacent lines. During simultaneous faults on lines within the same vicinity, fault current may be limited such that primary protective devices do not respond. Nevertheless, higher-level protective devices will activate. Being less selective, higher-level devices remove more than just the faulted lines from service, resulting in greater load loss.

4.1.3 Damage Due To HEMP

No distribution transformer with a directly mounted surge arrester is expected to be damaged, and most distribution transformers are so protected. However, in some regions of the country, lightning is so infrequent that surge arresters are not cost effective. For these unprotected distribution transformers there is some probability of damage, at least to 5-kV or 15-kV class transformers.

Table 4.3. Load Surviving HEMP Prior to Device Reclosure

VOLTAGE kV	LOAD SHARE PERCENT	SURVIVING LOAD PERCENT
5	10.6	3.9
15	77.5	51
25	9.4	8.9
35	2.5	2.5
TOTAL	100	66

However, for a burst of nominal characteristics, less than two percent of the unprotected transformers are expected to be damaged. For a burst yielding 50 kV/m peak HEMP field, less than four percent damage is expected [28].

4.1.4 Insulator Punctures

Besides the danger of flashover on distribution, there is the possibility of immediate insulator puncture as well as latent damage due to the rapid voltage rise of the larger HEMP waveforms. Distribution pin-type insulators, shown to be most vulnerable, are designed to survive 10 kV/nanosecond rise-times. However, tests have indicated a strength distribution of some variation, 2 to 20 kV/nanosecond [25]. At the distribution level, punctures may occur due to antiquated (predating 10 kV/ns designs) pin insulators, previously damaged insulators, or insulators on the tail of the puncture-withstand distribution.

4.1.5 Generation

For high-altitude events of nominal characteristics, research has not demonstrated vulnerability of generation to HEMP-induced surges coupled into the electric power transmission grid.

However, the vulnerability of generation to HEMP may exist in power plant electrical, control, and instrumentation systems. These systems include switchyard power, control, and instrumentation; low-voltage power lines; power-plant auxiliary systems; cooling-tower power, control, and instrumentation systems; combustion turbine generator packages; and control rooms.

Operation of the power plant is dependent upon proper functioning of all these subsystems and their major components. During analysis, these subsystems were represented to the major component level, such as motors, relays, and transducers.

4.1.5.1 Assumptions

All power, control, and instrumentation cables buried below the ground grid are assumed to be effectively shielded from HEMP. Therefore, the cable duct-bank network in main-plant areas is considered to be effectively shielded. It is assumed that the major threat in the main plant areas where an extensive ground grid is located is from transmitted surges. All mutual inductive and capacitive effects were neglected for conductors in duct banks, in trenches, and overhead. All cables were represented on a single-wire basis. These assumptions produce conservative results.

Duct banks outside the main power-plant area are considered unshielded since the ground grid in these areas is limited and the duct banks are shallow. These duct banks run to remote equipment such as gas turbines, fuel transfer pumps, well pumps, switchyards, and cooling towers.

The following equipment is generally assumed to be effectively shielded by metallic enclosures.

- Electrical conduit
- Indoor and outdoor metal enclosed switchgear
- Metal enclosed control and relay cabinets
- Indoor and outdoor motor control centers
- Battery rooms which are metal enclosed
- Control rooms which are metal enclosed

4.1.6 HEMP Vulnerabilities at Power Generating Plants

Remote 480-volt motors served by long unshielded runs of wire are at substantial risk. The level of vulnerability depends on orientation and location within the area of HEMP illumination. Any 480-volt motor operating at the time of a HEMP event and supplied over distances of 200 feet or greater with unshielded wires has some probability of risk. Possible systems at risk are water treatment facilities, demineralizing plants, fuel unloading pumps, fuel transfer pumps, and cooling water treatment plants.

Plant trip or forced shutdown of steam-generation power plants is possible due to loss of critical 480-volt equipment. This appears to be particularly true of cooling-tower fan motors. These fans are critical to plant operation. Their motors are remote from the motor control center by up to hundreds of feet and are vulnerable to large induced voltage surges if cabling is unshielded and shallowly buried. Control wiring flashovers can also be expected at cooling towers and in control rooms. Some instrument damage is possible.

Auxiliary power to power circuit breakers in switchyards may be lost due to panelboard failures or circuit breaker trips due to surges transferred to low voltage panelboards. If one of the auxiliary motors is operating at the instant of the surge, failure is possible. However, a limited number of power circuit breaker operations are still possible utilizing energy stored in the operating mechanism of the breakers.

Voltage transformers may experience low-side fuse blowing, causing false circuit breaker tripping by distance relay misoperation. In the control room, relay coils or relay rack terminal strips may flashover on both ac and dc circuits.

Generator unit transformers and auxiliary transformers are not expected to be vulnerable. The same is true of 4-kV switchgear and cables and 4160/480-volt transformers.

4.1.7 Loss of Generation Due to HEMP

It is important to evaluate the percentage of generation lost due to HEMP. The assessment showed particular vulnerability for 480-volt motors supplied by shallowly buried, unshielded 200-foot or longer cables [29]. Assuming that these 480-volt motors are the key factor, the probability of generation loss is similar to the probability of damage. Table 4.4 shows the probability of 480-volt motor damage when the motors are supplied by long, unshielded shallowly buried cables.

Table 4.4. Remote 480-Volt Motor Failure Probability When Motors Are Supplied by Unshielded Buried Cable.

(2200-km Radius Area of Illumination)

Field Strength	Average Burial Depth in Meters		
	0.5 m	0.79 m	1.0 m
kV/m	Percent	Percent	Percent
25	0	0	0
39	2.5	0	0
50	6.0	2.2	0

On this basis, HEMP would affect only large steam generation which relies on cooling towers. A conservative assumption would be that only nuclear and coal generation, 17.4 and 55.9 percent of the total, would be affected. Table 4.5 shows the breakdown of generation by energy source from the latest data available [30].

Table 4.5. Breakdown of 1987 Generation by North American Reliability Council (NERC) Region in Billions of kWh [30].

	Nuclear	Coal	Oil	Gas	Hydro	Pumped Storage	Other	Non-Utility	Total
ECAR	28.2	404.7	1.1	0.1	2.8	3.9	0.0	0.8	437.7
ERCOT	0.0	80.1	0.3	89.2	0.7	0.0	0.0	20.8	191.1
MAAC	60.9	100.6	13.7	7.8	4.1	2.0	1.1	1.0	189.2
MAIN	65.2	105.6	1.6	0.3	2.7	0.5	0.0	0.0	175.4
MAPP	25.2	80.0	0.4	0.4	11.8	0.0	0.1	0.1	118.0
NPCC	51.9	42.1	63.7	21.4	32.7	3.1	0.2	4.1	216.1
SERC	131.9	344.4	24.0	18.2	28.9	5.5	0.5	6.1	554.0
SPP	35.8	129.5	0.3	62.6	7.1	0.1	1.6	0.9	237.8
WSCC	53.3	165.7	2.4	66.6	161.1	2.4	12.8	18.9	480.8
TOTAL	452.4	1452.6	107.6	266.6	251.9	17.4	16.2	52.7	2600.0
PERCENT	17.4	55.9	4.14	10.3	9.69	0.66	0.62	2.03	100.0

There is also the possibility that nuclear generation will be vulnerable to tripping due to HEMP-induced problems in the extremely complex reactor control circuitry in control rooms [31]. This possibility must be addressed when determining lost generation percentages.

4.1.8 Loss Percentages

Ignoring loss of generation due to control-room circuitry disturbance, the initial estimate of probability of generation loss can be determined from the probabilities of Table 4.4. Since cooling-pump fan motors are the vulnerable component, generation loss is a function of large steam-generation. The combined percentage of nuclear and coal generation was assumed to be the vulnerable quantity of generation and is reflected in Table 4.6.

Table 4.6. Probabilities of Generation Loss Based on 480-Volt Motor Damage.

(2200-km Radius Area of Illumination)
(Motors Supplied by Unshielded Buried Cable)

Field Strength	Average Burial Depth		
	0.5 m	0.79 m	1.0 m
kV/m	Percent	Percent	Percent
25	0	0	0
39	1.8	0	0
50	4.4	1.6	0

4.1.9 Anomalous Damage

Damage occurrence at generating plants is expected to be random and scattered, with the exception of remote 480-volt motors. The extent of damaged equipment will be neither severe nor extensive, but will cause some difficulty and will be a factor in continued operation of the system. No damage is expected in 4-kV equipment.

4.1.10 HEMP Impacts on Communications and Controls

Detailed analysis of all communication, instrumentation, and control systems is inconsistent with the current state of unclassified electromagnetic analysis. Comprehensive evaluation of all circuitry within a control room, taking into account all metal structures and surfaces as well as circuit interaction, is not feasible in this study.

Although this unclassified study has not determined explicit generation loss due to instrumentation and control system upset, it does address the greater susceptibility of nuclear power plants to control system upset due to the increased complexity and redundancy of their control systems. The impact on generation, given loss of all nuclear plants, is discussed.

Loss of communication is not expected to result in immediate loss of generation; explicit levels of expected communication loss were not determined as part of this study.

4.2 MHD-EMP Effects on Power Systems

During an MHD-EMP event, quasi-dc currents are induced in the electric power system. These currents can reach levels exceeding the exciting currents of transmission and sub-transmission transformers. These quasi-dc currents cause severe half-cycle saturation, causing harmonics and increased VAR demand. In addition, the quasi-dc currents disturb internal transformer flux paths, causing conductor and tank heating.

Due to the inherently short interval of MHD-EMP, 400 seconds maximum, it is unlikely that the transformer will suffer immediate, noticeable damage. However, the increased VAR demand will adversely affect a power system by most likely exceeding the system capability and resulting in severe voltage drop throughout the system.

Grounded shunt capacitor banks have experienced neutral overcurrent trips during geomagnetic storms and are therefore subject to MHD-EMP impact [32].

There are several types of relaying problems which can occur. Delta-wye power transformers can be affected by the differential effects of current through one side of the transformer and not the other. Because of this, differential relaying schemes are vulnerable to misoperation. During past geomagnetic storm events, several occurrences of transformer-differential tripping have occurred, though only on relays without harmonic restraint.

Overcurrent ground relays are also subject to false tripping due to increased zero sequence current.

Geomagnetic storms sometimes cause some difficulty in radio communications, and while MHD-EMP effects are of shorter duration, the electromagnetic distortion can be expected to be more intense.

MHD-EMP could also cause problems during switching [33]. System reconfiguration may be inhibited during an MHD-EMP event.

High-voltage dc transmission is also at risk during an MHD-EMP event because of the possibility of overcurrent trips in harmonic filters. MHD-EMP-induced current flows are known to generate high magnitudes of low-order harmonics, but it has also been shown that higher harmonics can be of a magnitude sufficient to cause overcurrent trips in higher-order filters [33].

There is also a possibility of commutation failure of inverter terminals due to severe voltage distortion caused by harmonics. Commutation failure is a definite possibility with voltage distortion of 30 percent or higher [33]. Converter transformers are subject to voltage distortion due to the quasi-dc current.

Static VAR compensators appear vulnerable to MHD-EMP due to demonstrated vulnerability to geomagnetic storm effects [34].

Turbine generators are vulnerable to induced harmonics in the stator windings, in particular, second harmonic or negative sequence which could arise from an unequal excitation of a transformer bank. No occurrence of tripping during geomagnetic storms has been documented to date, but instances of alarm have occurred. Tripping might occur if the level of MHD-EMP were high enough.

Previous work shows electric power systems to be at some risk from MHD-EMP [35]. In a simulation of a nominal MHD-EMP event on the Arizona Public Service (APS) system, the surrounding Western States Coordinating Council (WSCC) system was included in the analysis but not stressed with any MHD-EMP effects. The percentage of APS system buses below various per unit voltage levels is shown in Table 4.7. System breakup is possible during a nominal MHD-EMP event.

Table 4.7. Results of APS MHD-EMP Analysis.

Voltage Level Per Unit	Buses Below Voltage Level Percent
0.9	54
0.8	41
0.7	18
0.6	2
0.5	Approx. 2

4.3 Expected Electric Power System Response to HEMP and MHD-EMP

Extensive plans and protective systems are in effect throughout the power system grid for load shedding in steps triggered by underfrequency relaying. There are also overfrequency (overspeed) and underfrequency protection schemes applied to trip turbine-generator units. These off-normal frequency schemes are designed to protect the turbine from operating continuously at speeds which are a resonant frequency for the various rows of blades. These schemes are coordinated with the load-shedding schemes. Most overfrequency or overspeed relaying schemes are applied to prevent excessive acceleration due to opening of the generator breaker. Figure 4.2 shows manufacturer-recommended underfrequency restrictions for steam turbines; overfrequency restrictions are a mirror image.

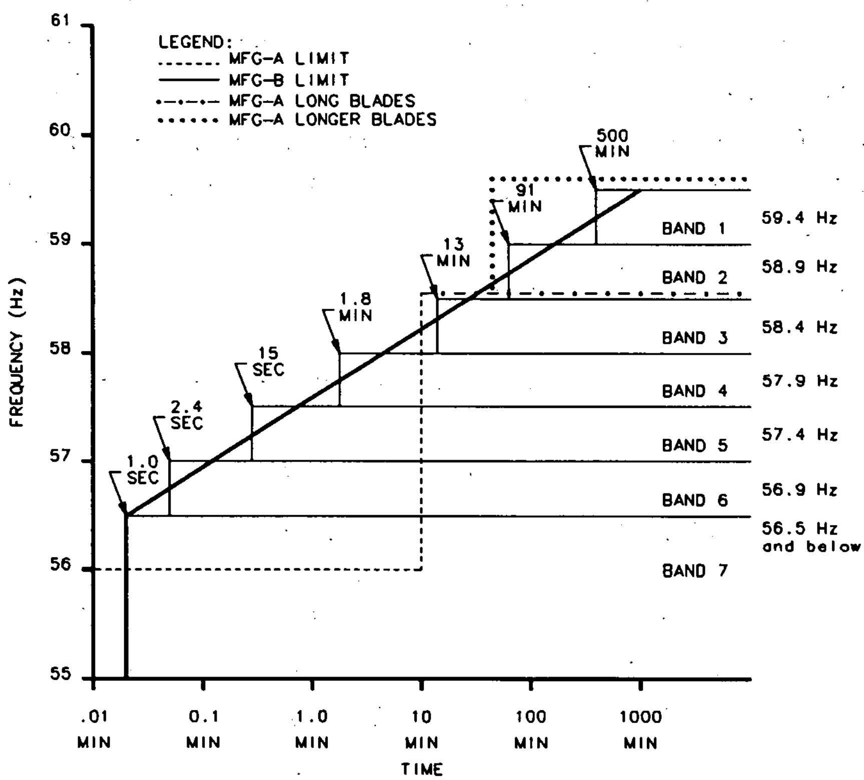

Figure 4.2. Recommended Underfrequency Restrictions for Steam Turbines.

The actual effect of excessive load loss or generation loss is dependent on the system configuration and load. Several aspects affect the response of a system to an event which causes frequency deviation:

- Power factor of the system load

- Level of capacity of the online generation
- Distribution of the load loss
- Distribution of the generation, in particular, spinning reserve

Table 4.8 shows the total generation impact of a single HEMP event.

Table 4.8. Sensitivity of HEMP Effects on Generation.

HEMP	GENERATION[1]	
Field kV/m	Loss of Gen.[2] Percent	Loss of Gen.[3] Percent
25	0.0	17.4
39	0.0	17.4
50	1.6	18.6

Loss of generation is shown with and without inclusion of total loss of nuclear generation due to control-room circuitry disturbances.

HEMP will cause a severe disturbance to electric power systems. For a burst of nominal characteristics, 39 kV/m peak HEMP field, stability is questionable.

If the electric power system breaks apart, longer lines – those most susceptible to MHD-EMP – may be isolated from the system. If the power system breaks apart due to HEMP, little effect is expected from MHD-EMP unless the electromagnetic fields are an order of magnitude greater than nominal (Starfish). Given high enough field intensity, even distribution networks could be affected.

[1] Depth of cable burial assumed to be 0.79 meters.
[2] Assumes no loss of nuclear generation due to control-circuitry disturbance.
[3] Assumes total loss of nuclear generation due to control-circuitry disturbance.

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5. EFFECTS OF MULTIPLE BURSTS ON POWER SYSTEMS

Complete evaluation of high-altitude burst effects on power systems requires consideration of multiple bursts. For multiple bursts, the assumption is that their occurrence is sequential, occurring at least one second apart. Because of the staggered occurrence, the two effects, HEMP and MHD-EMP, affect power systems differently due to the differing time periods of each effect. HEMP effects span microseconds; MHD-EMP effects span tens or hundreds of seconds.

The effects of multiple HEMP events appear as sequential events. Each event is ended before the next event occurs. The impact on load and generation is cumulative. There is geographic overlap of HEMP illumination, but no time overlap.

The effects of MHD-EMP are superimposed. The events effectively occur simultaneously; thus, the effects of MHD-EMP are additive. Only for the special case of multiple bursts at the same location is field intensity not entirely additive, but effect duration would be extended. For other than the special case, severity of the impact increases with spatial overlap since MHD-EMP events overlap in both time and geography. Figure 5.1 shows a possible scenario of ten high-altitude events occurring over the continental U.S. The bold circle depicts the area of illumination of a nominal HEMP event occurring at a 400-km height of burst (HOB).

5.1 Multiple HEMP Effects on Load

The cumulative effect of HEMP is less than additive. For example, once a fuse is blown, it cannot be blown again. For every subsequent illumination, the quantity of additional load loss is reduced since it is a function of ever smaller amounts of surviving load. The effect is similar for generation loss.

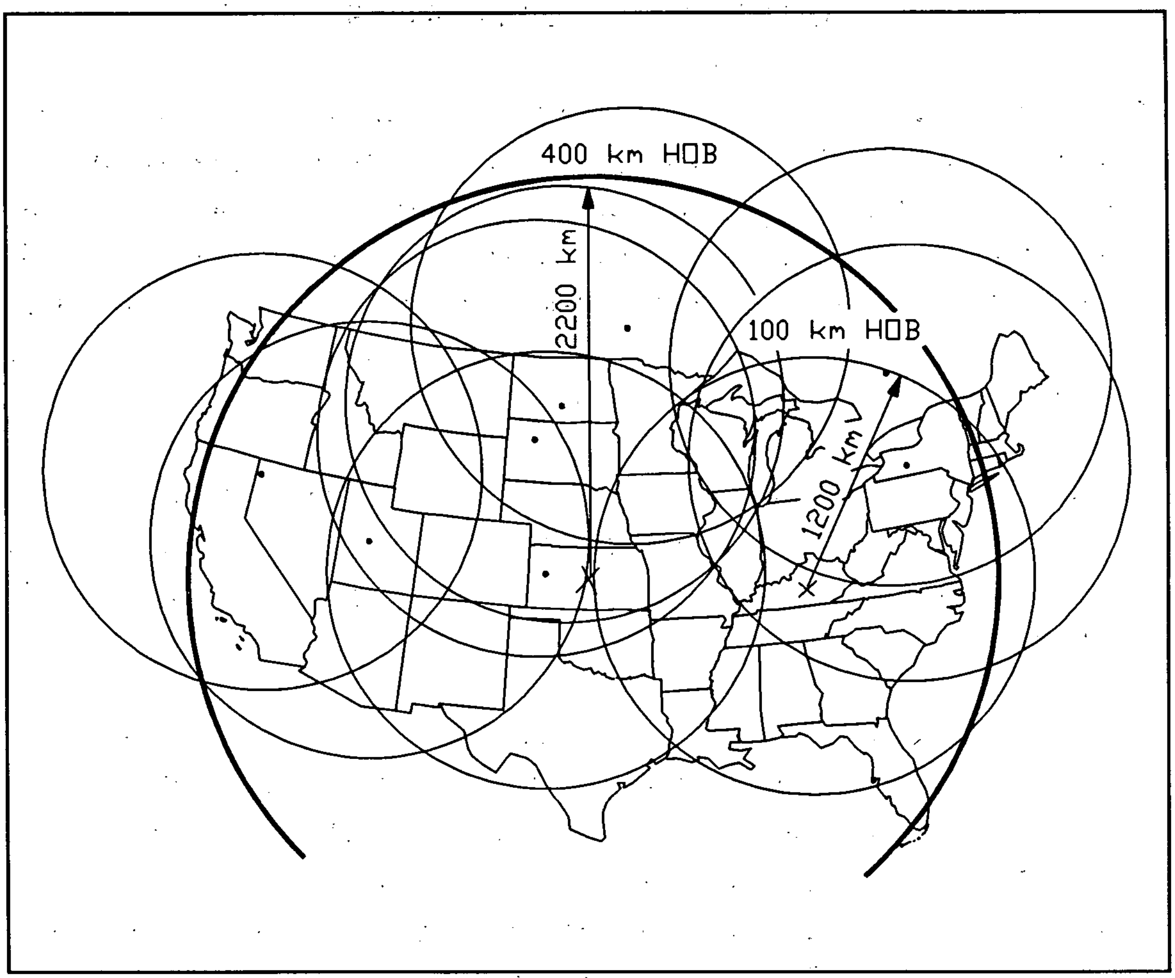

Figure 5.1. Multiple Burst Scenario.

Multiple bursts have the same HEMP considerations as a single burst with the addition of overlap level, which is the number of times an area is illuminated by HEMP. For multiple HEMP events, the considerations are:

- Component-Level Hierarchy
- Protection Philosophy of Each Component Level
- HEMP-Overlap Level

Protection philosophy and overlap level add considerable complexity to multiple burst evaluation. A probabilistic assessment is tediously complex.

It is important to realize that for "N" bursts, there are "N" possible levels of overlap; those regions which see the effect of only one HEMP illumination have an overlap level of one. A probabilistic evaluation of load loss is necessary for each level of overlap. Since regions of overlap will not be consistent in size, load loss at each level of overlap must be proportioned according to the area involved. The weighted values of load loss can be summed to indicate total expected load loss from a multiple burst scenario.

Protection schemes complicate HEMP overlap even more than they do single bursts. It is typical in distribution for reclosers to delay tripping after the first reclose cycle. Reclosers remain closed after the first cycle because the fault is probably not temporary, under ordinary conditions, if the first recloser cycle did not clear the fault. The idea is to allow the "permanent" fault to blow the closest fuse, minimizing load loss under normal conditions.

For distribution systems where reclosers have tripped and reclosing devices are assumed to reclose after one second and hold throughout subsequent HEMP events, probability evaluation is possible. Laterals now become an additional component level because reclosing devices on feeders no longer trip due to faults on laterals. Faults on laterals will blow fuses, permanently removing load from the system. The factors for the feeder component levels are no longer raised to a power. Each distribution voltage class must be addressed separately for each level of HEMP-illumination overlap and weighted before summation. (See Appendix A.)

5.2 Multiple HEMP Effects on Arresters

Application standards for surge arresters used in distribution systems do not address multiple operations, but both gapped silicon-carbide and metal-oxide arresters undergo multiple tests during duty-cycle testing. By test standards, duty-cycle tests consist of at least twenty arrester operations staggered fifty or sixty seconds apart. Each operation passes an eight-by-twenty-microsecond discharge current with a magnitude of 5,000 amperes for normal-duty and 10,000 for heavy-duty. On this basis, multiple bursts are not expected to affect arrester performance for nominal HEMP events.

5.3 Multiple HEMP Effects on Generation

A similar effect occurs with generation, but without complications such as those caused by reclosing devices on distribution. Surviving generation for each level of overlap is merely the survival percentage for a single burst raised to a power equal to the level of overlap. For example, if the level of overlap were two, the surviving-generation percentage would be squared. The values of surviving load for each level of overlap must be weighted based on the proportion of area of overlap, and the results summed to get total surviving generation and its complement, total generation lost.

5.4 MHD-EMP

MHD-EMP effects are superimposed. MHD-EMP effects easily span tens of seconds and can last up to several hundred seconds. It is assumed that multiple bursts will cause a slightly staggered superposition of effect and will raise the effective quasi-dc volts/km over the area of MHD-EMP illumination. The resultant volts/km will be the superposition of the field effect of each individual burst. The effect of multiple bursts can be modeled as being an MHD-EMP event of higher field intensity.

5.5 Expected Electric Power System Response to Multiple HEMP and MHD-EMP Events

The effects of multiple bursts is scenario- (target-pattern) specific, but some general conclusions are possible.

- Multiple bursts will increase protective-device activity, which the power system must accommodate to avoid breakup.
- Multiple bursts may increase the number of blown fuses at the lateral and sublateral level.
- Multiple bursts increase the likelihood of system breakup.

Multiple bursts increase protective device activity; any area of overlap will be subject to multiple HEMP events. If the bursts have differing ground-zero locations, lines of different orientation will experience flashover. Multiple bursts, assumed to occur one second apart, will prolong the period of protective-device activity.

Multiple bursts may also increase the number of blown fuses; after one second, many reclosers will reclose and hold. Most reclosing devices are designed to remain closed after the initial reclose. Any of the laterals experiencing faults after the initial reclosure will be removed from the system by fuse operation. In terms of the sublaterals, bursts of differing ground-zero locations will fault different line orientations, increasing the number of blown fuses.

Multiple bursts increase the likelihood of system breakup; more load and generation can be lost, protective-device activity can increase in frequency and duration, and effective electromagnetic field intensity of both HEMP (up to a point) and MHD-EMP can be increased or prolonged.

Multiple bursts can only aggravate the impacts of a single HEMP or MHD-EMP event.

6. POST-HEMP RESTORATION OF ELECTRIC POWER SYSTEMS

Previous assessment of electric power systems under the impact of a high-altitude nuclear burst indicates that some possibility of system breakup exists for either the initial, rapid transient electromagnetic pulse (HEMP) or the subsequent, quasi-dc magnetohydrodynamic electromagnetic pulse (MHD-EMP). For a high-altitude event, no other effect of a nuclear detonation is observed on the earth's surface. For a burst of nominal characteristics (39 kV/m peak HEMP field), system breakup could occur due to either HEMP or MHD-EMP effects. For a burst of nominal characteristics, HEMP is likely to cause a major disturbance. It is plausible that system breakup might occur due to sudden loss of load or generation. Nevertheless, should either MHD-EMP or HEMP cause the power system to break up, the system must be restored. Since HEMP is unlike most power system disturbances, it is important to investigate the issue of system restoration after a high-altitude nuclear burst.

The need to evaluate post-EMP power system restoration was recognized when realistic analysis verified that power systems might be vulnerable to HEMP. As methods of power system assessment were refined, plans were implemented to interview experienced power system operators responsible for power system restoration. Such an approach was deemed more appropriate than pure research alone.

The organization that serves as a forum for power system restoration activity in the U.S. is the North American Electric Reliability Council (NERC). NERC consists of nine Regional Reliability Councils which include virtually all of the electric power systems in the U.S. and Canada as shown in Figure 6.1. NERC was formed in 1968 by the electric utility industry to promote reliable and adequate bulk power supplies in the electric utility system of North America. NERC's primary concerns are the security of the interconnected transmission network, the avoidance of cascading tripouts that might cause widespread power

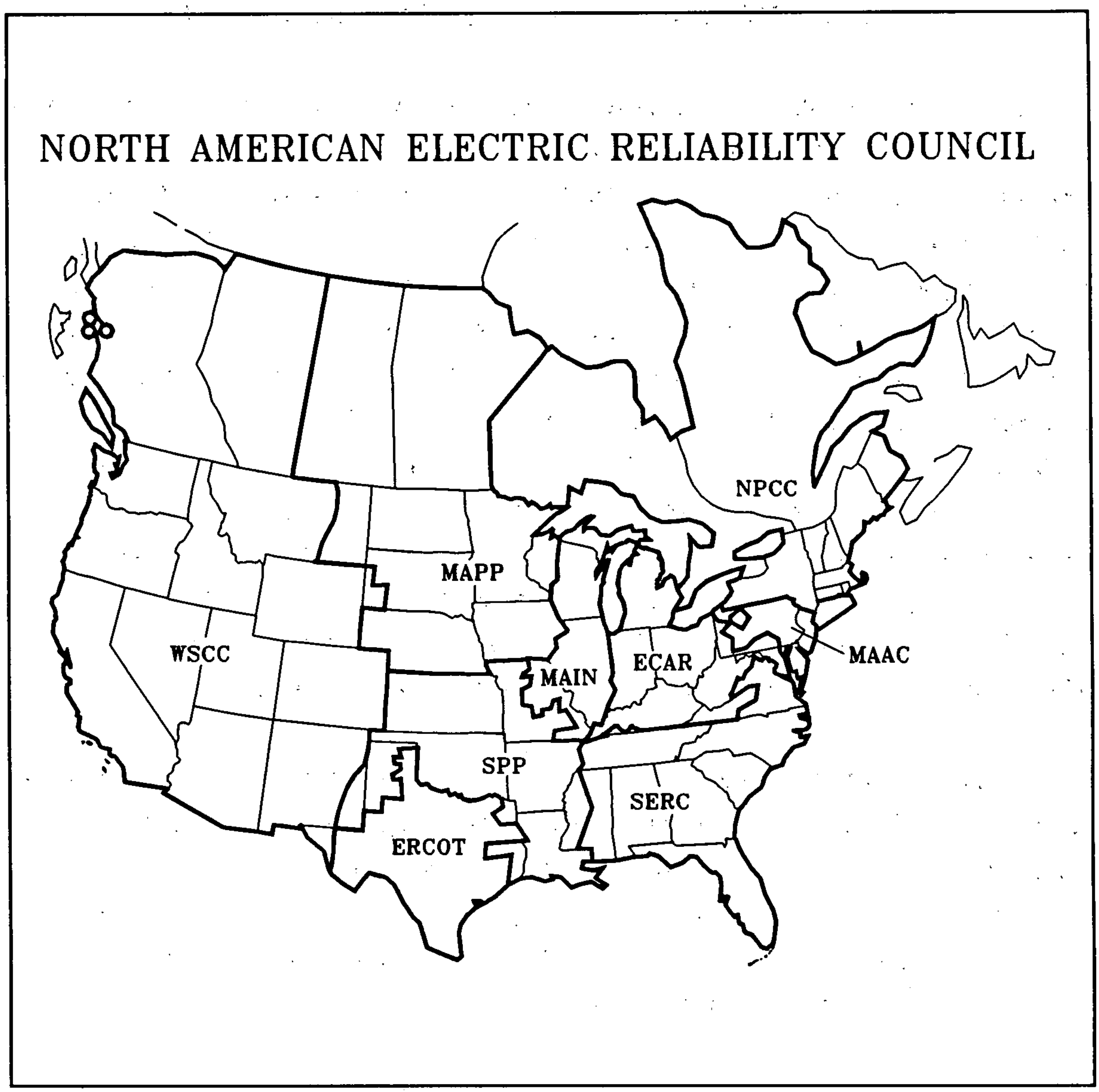

Figure 6.1. The North American Electric Reliability Council.

outage, and the adequacy of generating capability required to meet the electric demand of all its customers.

NERC generously assisted the project at hand by arranging several interviews with experienced power system operators. The discussion which follows is a summary of the information gleaned from those interviews as well as from additional research.

Since HEMP is the unique aspect of a high-altitude burst, restoration after a high-altitude event is referred to as post-HEMP restoration, even though an electric power system might be broken up due to either HEMP or MHD-EMP effects.

Restoration plans exist in many utilities, with a majority holding periodic drills using those plans. Several utilities have actual experience in restoring power systems after major outages.

Although restoration plans are based on collective experience from system disturbances, a high-altitude nuclear burst has never occurred over the continental U.S., and post-HEMP restoration is not part of utility experience.

Since high-altitude nuclear burst effects are unique to utility-restoration experience , it is imperative to look at restoration plans in light of an actual high-altitude detonation. It is important to look at post-HEMP restoration in terms of similarities to and differences from prior utility experience.

There are three major aspects to power system restoration:

- Communications
- Manual and Time-Limited Systems
- Restoration Plans

Each of these aspects is a factor in post-HEMP restoration, and some discussion of them is necessary.

6.1 Communications

Communications are important for system restoration and include utility-owned or leased microwave systems; utility-owned or leased telephone lines; HF, VHF, or UHF radio systems, including base, mobile, and repeater stations; fiberoptic systems; and power-line carrier.

Communications for electric power systems exist for voice or data transmission. While all of the previously mentioned communication systems can be used for either, the primary use of radio systems is for voice communications. However, a small number of utilities use radio for transmission of both voice and control signals.

Communication systems other than radio are used primarily for data and Supervisory Control And Data Acquisition (SCADA) systems. (SCADA is a generic term for systems which enable a central location to provide monitoring and control of remote power system devices or equipment, such as power system circuit breakers.) Power-line carrier is still used, while fiberoptics is just making its appearance. In some cases, the microwave and telephone systems are integrated into a unified network.

Control centers are the base for power system generation, transmission, and distribution control. A control center consists of computers for display of information as well as for remote control, with control center computers linked to remote facilities by communication systems. Automatic Generation Control (AGC) and Energy Management Systems (EMS) are typically based in control centers. (EMS is an extremely sophisticated form of SCADA and may include AGC capability as well as economic dispatch of generation. AGC is a system of generation control which automatically adjusts generation to regulate tie-line flows, frequency, and for some systems, time errors.) Control centers are deemed critical to restoration, and it is felt that complete failure of the critical control center equipment or control center power supply would seriously retard system restoration. However, control centers for both utilities and power pools normally have all critical equipment (dispatch and control) operating on uninterruptible power supplies (UPSs) which would mitigate surges coming in on the power line. It is also important to note that EMS and SCADA generally have redundant computers for operation. In addition, backup diesel generators are present. The UPS battery is typically sized to supply load for approximately 30 minutes, which is more than sufficient to start backup diesel generators. There is usually sufficient fuel on site for most control centers to operate for several days.

The types of failures expected in control centers range from upset of EMS computers and SCADA equipment to complete failure of the system. In the former case, the equipment will need to be rebooted. In the latter, repairs will be needed if redundancy does not exist. The effect in the former case is retarded restoration. In the latter, substantial delay may occur since all system monitoring and control would be accomplished manually.

It is extremely important for system operators to understand the system configuration prior to and during any restoration. System status identification is a software function in EMS systems whereby the interconnected power system boundaries, including those of islands when present, are identified. (Islands are electrically isolated regions over which generation and load balance closely enough to allow generation to continue providing electric power.) This identification facilitates quick and successful restoration of a collapsed system. This ability, whether automated or manual, is required to establish the extent of a system collapse by identifying the status of all transmission lines, generators, and substations. Any impairment of this capability would seriously delay system restoration. For example, a transmission line would not likely be energized without an operator knowing what loads or equipment are connected to it and what system capacity is behind it. The resulting voltage levels at the sending and receiving ends would also require monitoring to maintain permissible limits.

If system-status identification capability is lost, then manual techniques must be used. System status is determined by the use of geographically distributed manpower with some combination of telephone or radio. The amount of manpower required is a function of the degree of failure that has occurred in the EMS system, the degree of failure of local SCADA and remote units, the availability of microwave and telephone communications, and the availability of EMS computers. Such failures would delay system restoration, with more failures causing greater delays. Complete EMS/SCADA failure could add several days to restoration time because of the personnel-intensive system-status identification process.

6.2 Personnel- or Time-Limited Systems

After a system breakup, several subsystems, in particular protective systems, may require some human intervention, while other systems have inherent time restrictions. For example, during an MHD-EMP event, differential transformer relays without harmonic restraint may operate. Typical utility practice requires transformer inspection before re-energization. The capital expenditure and lead times involved make any other course of action unacceptable. In addition, HEMP-induced flashovers of station batteries may blow the fuses in their dc circuits. Examples of sub-systems having time restrictions include backup batteries, diesel generators, and UPS devices.

For situations involving transformer relay trips, which might well be expected due to MHD-EMP, the inspection of equipment requires both time and manpower. This can be expected to increase restoration times. However, the extent to which this has an effect on overall restoration is a function of the number of trips which occur. Human intervention would also be required to replace fuses blown by HEMP-induced flashovers on distribution circuits.

Batteries and backup diesel generators in control centers and in substations are generally perceived as very reliable, and diesel generators are tested frequently, as often as once a week. However, reliable as they may be, generators are time-limited based on available fuel. Typically, several days of fuel are on hand at most sites. This is also true of microwave remote sites which have backup diesel generators.

Most substations do not have backup diesel generators for station service power. Station service power is normally provided by an independent distribution feeder. In a HEMP event, however, power to these feeders may be lost for several hours or days. The batteries at power plants, substations, and microwave sites may last only 2 to 8 hours. If auxiliary power is not restored by then, control and protection functions may be lost. This poses a potentially serious problem at major substations, since a post-HEMP outage could last several days. In order to re-energize and operate these substations, it would be necessary to first re-establish station auxiliary power, either from a portable diesel generator or from the normal, separately fed station service supply (if present). These problems would also be expected to delay system restoration.

6.3 Restoration Plans

During a major system collapse, support from other utilities or areas cannot be relied upon during the early stages of system restoration. Since all adjacent areas might be in similar predicaments, each utility or area could be on its own until substantial portions of the system have been restored.

6.3.1 Power Plant Blackstart

All utilities and power pools interviewed have blackstart plans; this is standard practice. These plans generally include designation of certain units as blackstart units, i.e., units that can be started without any off-site or grid-supplied power. These may be hydro units, diesel generators, or combustion turbine generators. These units are then used to re-energize portions of the transmission system to provide start-up power for other generation units. Load is added as necessary to control system voltage and generator minimum loading requirements. The grid is then reassembled sequentially through established procedures.

Many utilities test their blackstart power plants annually or biannually, while others simply train their operators through regular blackstart drills. Most have experience in blackstarting power plants. The degree of sophistication present in blackstart plans depends on the amount of system disruption experienced in the past, but all blackstart plans are extensive and address multiple contingencies.

6.3.2 Restoration

Because system breakup might be caused by several vastly differing circumstances, most utilities and power pools cannot always predict how or into what configuration the system will break. System restoration might require blackstart and reconnection of all the islands and utilities in and between major importing and exporting areas. In addition, a major collapse of the power system may result in equipment damage, the extent of which would need to be established prior to attempted restoration. Because of this, restoration planning addresses multiple contingencies and often prevention of breakup as well.

As with blackstart, all interviewed utilities and power pools had some form of system restoration plan, though not all were of the same level of sophistication or completeness. Completeness ranges from having restoration voltage and frequency control studies still in progress to having completed plans and annual operating drills on restoration. The need for frequent updating of plans and operator drills is well recognized throughout the industry.

Typically, these restoration plans are coordinated with neighbor utilities' plans. As with blackstart, the degree of sophistication present in these plans and the amount of operator training appear to correspond to previous need for restoration.

Restoration plans also include the optimum use of personnel, with many individuals scheduled to work around the clock at specific sites. Arrangements for food and sleep accommodations are included in restoration plans.

6.4 Summary of Restoration

The results of the investigation of post-HEMP restoration are encouraging, but there are specific considerations. All of the planning previously accomplished for restoration will aid in post-HEMP restoration, but if not already included, communication-loss contingencies must be addressed.

The conclusions which can be reached from this investigation of restoration are several.

1. System damage will not be substantially different from a system breakup caused by other means. HEMP and MHD-EMP are unlikely to cause major damage; most damage, if any, will result from system breakup. However, instrumentation and control circuits deep within complex facilities such as power plants were not assessed in this study, and damage to such circuitry is possible.

2. The key to rapid system restoration is the ability to identify the configuration of the system after breakup. This ability depends on communications and computer systems typically located in utility control centers.

Should several simultaneous failures of microwave, telephone, and radio systems occur, both verbal and data communications would most likely be disrupted to a greater extent than previously experienced by most utilities. While computer-based SCADA and EMS are typically powered through UPS systems, they must interface with some communication system and may be vulnerable. Should the SCADA system or EMS system be seriously upset or damaged, system control and system-status identification may be inhibited. Difficulty would be expected in establishing both the boundaries of various system islands and the configuration of the total system. The upset may only require rebooting the computer, in which case the system may simply be unavailable for a short period; or the computer may be irreparably impaired, requiring manual system-status identification. It is also possible that erroneous data may be received, requiring the operator to determine what is valid. Should control-center power fail, the system could be maintained by diesels and UPS systems.

Loss of AGC is neither a cause for system breakup nor a delaying factor in restoration.

3. Exacerbating circumstances that may delay restoration are manual resetting of certain relays, re-fusing of protective systems, and use of time-limited backup batteries.

   It is possible that protection systems may not all operate properly, particularly under the effects of MHD-EMP. Some protective devices, such as impedance relays and transformer differential relays without harmonic restraint, may operate improperly and trip. In addition, some fuses in dc-powered control circuits may blow. Some fuses are expected to require replacement on distribution circuits. Human intervention will be required to get these systems on line. The availability of qualified, experienced personnel is a factor in post-HEMP restoration.

4. Current plans with communication-failure contingencies are probably satisfactory for post-HEMP restoration, but, as is current practice, should undergo periodic evaluation.

   It is felt that, given major communication and system-status identification-capability loss, approximately five days would be required to restore the system following an EMP event. This compares with approximately one day for restoration due to causes unrelated to HEMP which do not include communication failure.

Last, it must be remembered that utilities have an economic responsibility to their customers and shareholders and must factor this into all decisions concerning reliability. Revenue and cost structures are regulated, and economic reality impacts all aspects of power system operation.

6.5 Future Restoration Efforts

The utility industry continually evaluates restoration plans as well as threats to power system reliability. The industry is quite active in investigating threats to system security and compiles power system disturbance and restoration activity on a yearly basis.

There are a few avenues of EMP research which would be especially useful in restoration planning. In particular, an evaluation of expected communication loss for various types of communication systems would aid in contingency planning. Another useful area of research would be an investigation into the vulnerability of telephone interfaces and handsets. Some evidence, albeit scant, exists that a few telephone interfaces in high-voltage switchyards have demonstrated vulnerability to electromagnetic transients from switching activity.

7. MITIGATION

Over the years, the electric utility industry has developed procedures and protective measures to cope with transient overvoltages, overcurrents, and EMC (electromagnetic compatibility) difficulties. These problems occur in power plants and substations as a result of switching surges, lightning, and corona. For example, the initial installations of solid-state and microprocessor-based relay systems experienced severe EMC or EMI (electromagnetic interference) problems in substation environments. Upsets were due to component failures and inadequate filtering of transient noise in power supplies for both computer and data-acquisition equipment [36].

The entire power system incorporates numerous protective measures to prevent lightning and fault transients from causing a significant number of failures or upsets. While many of these measures are applicable to the mitigation of EMP, typical power system transients approach neither the magnitudes nor the rates-of-rise of HEMP-induced transients.

Evidence exists that lightning may be somewhat comparable in effect to HEMP, but the effect is more localized. To date, neither analysis nor experiment has demonstrated that present designs can withstand HEMP-induced transients. Nevertheless, Vance [37] has suggested that utilities can make a crude assessment of the HEMP vulnerability of power system equipment and circuitry by observing the types of equipment that fail or misoperate during severe disturbances. Those components that malfunction or fail during lightning storms or severe faults are at greatest risk from HEMP-induced transients. Since HEMP is global, equipment failures and system upsets which occur during lightning storms, or faults, may be symptomatic of a potentially broader problem for a HEMP event.

7.1 Present State of Mitigation Measures in the Power System

Few standards exist that require tests for relaying and other electronic power-system components, which would ensure these components' surviving the steep-front surges characteristic of EMP. A limited number of standards are currently being drafted, but no domestic standards exist which address the requirements for EMP-type tests of either surge-protective or voltage-limiting devices.

7.1.1 Industry Practice

While standards are few, current industry practice may mitigate EMP effects. These procedures address adding capacitance, grounding, cable layout, shielding, and dc-current blocking.

7.1.1.1 Adding Capacitance

Present utility practice for protection against transient overvoltages in relaying and control circuits consists of installing small surge-protecting capacitors at appropriate terminals. These capacitors are installed with short leads at either the relay terminal strips in the relay cabinet or at the panel between the incoming ac phase leads and the common point of cabinet ground. This practice has proven effective against transient voltages normally occurring in the operation of a power system. Nevertheless, the addition of the surge-protection capacitors may not be as effective in protecting against the higher frequencies associated with a HEMP event since some capacitors demonstrate inherent inductance at higher frequencies.

7.1.1.2 Grounding

Current grounding practice dictates that substation and power-plant grounding systems be composed of numerous buried "electrodes" in the form of metal structures bonded together. This practice provides a reference potential for relaying and other equipment, and serves to protect equipment and personnel from power-frequency disturbances. In practice, these grounding systems are not specifically designed to mitigate EMP effects other than voltage rise.

At least one utility has initiated single-point grounding of the equipment signal for specific instrumentation [38] in order to reduce noise problems. Reference [38] states that "the signal ground conductors should be insulated not only to isolate the signal ground from the incidental ground connections, which could introduce circulating currents, but also to protect it from corrosion." Nevertheless, single-point grounding may be problematic where frequencies exceed 300 kHz. At these frequencies, the signal-ground lead length may approach the signal wavelength, and the apparent ground impedance could be significant.

Published grounding practices exist for specific kinds of equipment, such as for instrument transformers. Reference [39] provides guidance for the grounding of instrument-transformer secondary circuits, instrument-transformer cases, and power-transformer secondary circuits when used for relaying and instrumentation. The recommended point of grounding for the secondary circuits is at "one end of the secondary winding of each instrument transformer and physically at the first point of application (switchboard or relay panel) of the instrument transformer secondary circuit." For high-voltage current transformers (CTs), the leads from the secondary should be connected to the shield and run along the physical ground of the CT to the ground mat. From that point to the relay house, the leads should run as closely as possible to the ground mat. These suggestions ensure personnel safety and proper performance of relays at power-line frequencies, but may also aid in EMP mitigation.

At all utilities, grounding of high-voltage capacitor banks receives careful attention, especially where back-to-back switching occurs. Back-to-back switching can generate high-magnitude, high-frequency currents and voltages, and measures taken to reduce these transients should be adequate for EMP.

Many references and standards pertaining to measurement cables recommend that shielded cables be used in substations, particularly in EHV (extra-high voltage) substations, but little agreement exists on the best method of grounding the shield. For EMP, all grounding is important, since trouble can occur with the existence of either insufficient grounding or grounding of interconnected (cooperating) electronic equipment to different points in the grounding system.

7.1.1.3 **Cable Layout**

In general, it is recommended practice at utilities that secondary-wiring cables from transformer, control, and signaling devices be laid in the earth, or in cable trenches, at the same depth as the grounding system. This practice improves coupling between the cables and the grounding system. Other techniques are also used. Grounding-wire fabric which is tied to the station ground mat may be part of the bottom of the trench, and a ground conductor may be run close to the top of the trench along one side. The ground conductors at the top are usually attached to the ground mat at numerous points. Similarly, all cables are run close to, and parallel with, ground-system leads. All circuits typically follow the same path to and from ground-system leads. Dc and ac secondary circuits and ac service-power cables seldom coexist in the same duct or trench. It is recommended practice that dissimilar cable circuits, run in the same trough for any distance, should be separated as far as possible or should have some grounded metallic shield inserted between them.

Since coupling-capacitor voltage dividers (CCVTs) conduct large high-frequency transient currents to ground, standards recommend that shielded cable be run as closely as possible to the physical power grounds with the shield grounded at the base of the CCVT [40]. The decision on whether to ground the shield at the receiving end depends on the application. It has been suggested that a tubular ground connection be used in place of a ground conductor, and that the secondary wiring be run through the tube [40].

Cable layout practices such as these, if properly accomplished, may provide substantial mitigation of EMP effects.

7.1.1.4 **Shielding**

Utilities have some awareness of the impact of EMI. The proximity of control centers to substations has led to power industry investigations of the effects of EMI on computers. These investigations have resulted in realization of an increased need for shielding. Results of various investigations conclude that the magnitudes of high-frequency electromagnetic transient disturbances occurring in substations can exceed the immunity specifications of electronic relay and control equipment, at least when the equipment is housed in conventional buildings. One reference discussed the method used by one utility to reduce the transient field magnitudes to acceptable levels [41]. These techniques, used at the time of building construction, included increased shielding with sheet metal; bonding of door and window frames, pipes, plumbing, and steel conduits; and insertion of radio-frequency suppression filters in all penetrating power, communication, and interior fluorescent-lighting circuits. Cable shields were grounded at one end only, either inside or outside of the computer room.

The authors of the previous reference concluded that "the inherent structural shielding would be adequate at a distance of 100 meters from arcing disconnects or less if the building were laterally displaced from the overhead lines."

Several types of buildings are used for control and relaying houses in switchyards. A common form is concrete construction with little or no shielding properties except for metal reinforcing bars. Calculations and measurements of the penetration of EMP fields are documented for such structures [42], and theoretical calculations of magnetic field penetration through protective metal screens for shapes other than that of a building also exist [43]. The mitigating effect of most structures currently in use is generally not adequate for EMP. In addition, many metallic shields, such as cable shields, are brought into structures such as relay control houses before grounding. Although rooms with elaborate shielding providing 100 dB of attenuation are commercially available [44], only limited attention is given to shielding critical facilities.

There are published suggestions on equipment isolation and separation to control typical EMI. Reference [45] suggests that all circuits in the instrumentation and control system be isolated by the use of transformers and/or optical isolators, with this isolation system powered by its own source. The reference also suggests that permissible radiated interference fields can be attained either by separation (160 feet) or by shielding of the control house. Unfortunately, separation of equipment has little impact on HEMP.

While the inherent shielding effect of a building is beneficial, it is unlikely to be sufficient to mitigate EMP.

7.1.1.5 Dc-Current Blocking

There is also an MHD-EMP component of EMP, but current industry practice has little mitigative effect. Dc current in power systems normally occurs only during geomagnetic storm conditions, which are rare, and occurs mostly in the northern regions or in regions having large subsurface igneous layers which limit earth conductivity. No large-scale measures of quasi-dc current mitigation are currently in practice.

Though series capacitors do inhibit dc current, the limited number installed would have little mitigative impact nationwide.

7.2 Circuits Requiring HEMP Mitigation

HEMP assessment studies have shown that power-system circuits most likely to be at risk from HEMP are those operating below 69 kV without adequate surge protection, grounding, or shielding.

Elements at risk include low-voltage, control, and motor circuits in generation plants; distribution circuits and equipment; control, monitoring, and protection devices in substations; and similar circuits and digital equipment in utility energy management systems, dispatch centers, and communication facilities.

We can categorize these elements into four groups:

- Distribution System Components
- Low-Voltage Motors
- Protection and Control Equipment
- Electric Utility Communications

Equipment, other than power circuitry, having the greatest sensitivity to EMP include the following [46]:

1. Active (switched "ON") electronic devices including transistors and integrated circuits.

2. Passive (switched "OFF") electrical and electronic components which have low-power or low-voltage ratings, such as microwave diodes.

3. Semiconductor diodes and silicon rectifiers, especially those connected to long cable runs.

4. Low-power or high-speed digital processing systems and digital memory cores (sensitive to operational upset).

This suggests that the circuits in power systems most likely to be damaged by HEMP may include microwave and radio communication systems, digital power-system-relaying circuits, and electronic control circuits [46].

7.2.1 Distribution System Components

References [24] and [28] have shown that some probability exists that distribution lines can experience voltages high enough to flash over or fail components. References [47], [48], and [49] have indicated that distribution components, such as transformers and insulators, are at some risk to these HEMP-induced voltages. Reference [27] has shown that certain electronic or microprocessor-based control equipment used on distribution systems may experience some disruptive failures or upsets. However, this reference implies that with proper grounding and appropriate use of metal enclosures such failures will be few.

As far as distribution transformers are concerned, tests performed on specific designs show that distribution surge arresters mounted close to the transformer can provide adequate surge protection [47]. Analysis suggests that transformers not protected by directly mounted arresters may be at risk.

At distribution-class voltage levels, line insulators are at risk from flashover or puncture, especially those with many years of service.

7.2.2 Low-Voltage Motors

HEMP assessment studies of power plants have indicated that 480-volt motors at the end of long (200-foot or greater), shallowly buried, unshielded cables can be at risk.

7.2.3 Protection and Control Equipment

Protection and control equipment is a necessary part of power system operation. Protection and control equipment is typically powered by 120-volt ac and uses 48-, 125-, or 250-volt dc for control. However, there are apparatus rated at 240-volt or 480-volt ac that incorporate direct-acting solid-state protection and control devices. Examples include low-voltage air circuit breakers which have direct-acting series trip, shunt trip, or solid-state current and voltage sensing devices. This equipment falls into the 600-kV class and is expected to be at some risk from EMP.

The risk to protective systems from a HEMP event results from a high-voltage surge that can be either coupled directly onto the leads of relays or circuits or transferred from other devices. Surges can be transferred through current or voltage transformers (especially coupling-capacitor voltage transformers) via connecting leads. In general, the entire protection and control system, consisting of sensors, leads, protective relays, auxiliary devices, and control components including battery and circuit-breaker trip coils, is at risk.

Dc circuits in protective relay systems are also at risk, albeit low risk. Loss of battery power could render the protective systems inoperative. If HEMP-induced flashovers occur simultaneously on the main positive and negative busses, dc fuses will blow, interrupting dc power to the protective system.

At present there is no experimental evidence showing a HEMP-induced insulation breakdown of ac-energized protection and control circuitry to be self-clearing. Therefore, ac protection and control systems must be considered at risk until data is obtained to indicate that the insulation used throughout these systems is self-restoring.

7.2.4 Electric Utility Communications

The continued operation and control of a modern power system is highly dependent upon the proper operation of its communication system. The availability of communication is critical to rapid restoration of a system following an outage of service [50]. The communication system is a complex arrangement of microwave, VHF/UHF, hard-wire cable, fiberoptics, and leased telephone circuits, and some level of communication failure is expected as a result of a HEMP event.

7.3 HEMP Mitigation Methods

"A facility is designated as HEMP-protected when its operations are not degraded to an unacceptable level by HEMP-induced electrical stress [51]." It is imperative to determine critical facility components and their level of acceptable operation, and then provide some acceptable means of prevention.

Controlling interference in buildings for sensitive electronic equipment requires suppression of conducted interference as well as radiated electromagnetic interference [44]. Reference [52] states, "It is the violations caused by penetrating cables and antennas that will inject most of the damaging energy into equipment," that is, into a shielded enclosure. "All penetrations of cables, pipes, waveguides, etc. into an EMP-protected facility should enter at one location, if possible, at a point-of-entry panel. EMP protection techniques for penetrating conductors are as follows:

1. Bonding of all external grounds, pipes, waveguides, conduits and cable shields to the facility shield at a single entry point.

2. Protection of insulated signal conductors by means of a shielded EMP vault.

3. Isolation of external and internal grounds.

4. Water, sewage, and fuel pipes should be decoupled from a facility by using at least 5 meters of plastic pipe where entering the building."

There are additional considerations in hardening a facility against HEMP stress. An important factor is the effective use of shielding or electromagnetic barriers to surround the components which are susceptible to HEMP stress and critical to the acceptable operation of the facility. Depending upon the assumed rise time for the HEMP pulse, the frequency spectrum may extend above 1000 MHz, though most of the energy exists in the range of 10 kHz to 10 MHz [51].

Heretofore, basic protection methods have been described in terms of shielding surfaces of the equipment and penetration zones of the facility [37]. These protective techniques and devices include the following [51]:

1. Improving the shielding of the surface or zone including those components, such as wiring, cables, and pipes, which must pass through the surface or enter the zone.

2. Adequately applying and properly placing bonding, e.g., elimination of HEMP entries of water pipes, etc., by electrically bonding the pipe to the exterior surface of a shield.

3. Increasing the allowable transient level through the surface or zone but reducing the magnitude of the HEMP-induced transient in the critical zone or at the critical component or functional group by the use of surge protection, filtering, or suppression.

4. Attending to ground paths in order to remove loops of HEMP ground currents which might otherwise produce spurious magnetic fields and voltage differences within the component or functional group. Grounding systems should be designed such that no transient current flows through the grounding system, particularly in control rooms. Looping of internal grounding conductors should be minimized by use of single-point grounding where possible, such as with "crow's-foot," "fishbone," or "Christmas tree" techniques. Inner-conducting cabling, such as coaxial cables, should follow grounding-wire routes.

5. Improving the inherent ability of equipment, components, and functional groups to withstand damage or upset.

The measures needed to effectively harden a facility against EMP can be expensive if retrofitted, however. Reference [52] states, "British military experience over a dozen years or more indicates that, on newly purchased or designed electronic equipment and its housing, EMP protection adds about 5% to its installed cost. However, EMP retrofitting on existing equipment may cost in excess of 25% of the equipment costs."

7.3.1 Distribution System Components

Surge-protective devices have been shown to protect distribution system equipment from HEMP. Although there may be a voltage turn-up of the arrester protective level (sparkover) when tested alone, the capacitance of the transformer appears to reduce the rate-of-rise of the surge such that properly rated, gapped silicon-carbide arresters provide adequate protection. Metal-oxide arresters, when properly rated, could also provide improved protection. A similar conclusion might be drawn about direct-mounted surge arresters protecting other distribution equipment, such as cable potheads, although the capacitance may be less.

Surge protection across every distribution insulator might lessen flashovers and damage, but it is not cost-effective. Fortunately, the increased use of higher distribution voltages, such as 34.5 kV with its associated higher insulation levels, will assist in reducing the probability of HEMP-induced failures on distribution circuits. Continuance of this trend will aid in mitigating EMP.

7.3.2 Low-Voltage Motors

It is difficult to justify the installation of extensive surge protection for HEMP on existing 480-volt motors, but where appropriate for switching considerations, it would be prudent to include surge protection or shielded cables for future plants. Unfortunately, space for surge arresters or "surge packs" could be a problem in some motor control centers.

7.3.3 Protection and Control Equipment

Several actions may mitigate HEMP impact on protective systems:

- Surge-protection capacitors can be mounted close to the relay being protected by connecting an appropriate capacitor between the incoming relay-lead terminals and the relay case, or, for rack-mounted equipment, by mounting the capacitor between the PC-board ground and the incoming leads. This practice would reduce the possibility of resonance within these circuits when they are hit by the incoming HEMP pulse.

- Extensive use of shielded control cable would significantly reduce the induced differential and common-mode voltages in the leads and increase the attenuation of the transferred surge.

This would be expensive, however, and grounding of the shield would require careful consideration.

- Low-voltage surge arresters with sufficiently low protective characteristics could be installed on terminal strips at the relay panel or cabinet. If unshielded conductors are used, the arresters could be located where the conductors enter the relay control house, but there must be a sufficiently low-impedance ground available at that location. Similarly, installing arresters on sensor lead terminals in the control cabinet of power transformers or on secondary terminal-strip connections on voltage and current transformers could offer protection.

- Arresters suitable for dc voltages could be installed at the operating coils of circuit breakers or at other suitable locations in the dc control circuits.

- Commercial surge-protective packages that are designed for use with power supplies for sensitive electronic gear or computers could be installed, but caution is warranted. The extensive use of surge capacitors associated with long cable runs may result in misoperation of relay equipment due to redistribution of charge on this capacitance. One utility has attributed a false tripping event to an unequal charging of the cable capacitance of the positive and negative leads in a dc circuit. Following a surge which apparently caused unequal charging of the lead capacitances, capacitive current was sufficient to trip a relay. No apparent breakdown of insulation occurred. This experience implies a risk of relay misoperation when using surge capacitors for mitigation.

Differences in utility practice when routing and installing fuses on dc cables will affect the level of risk during HEMP events. Routing of cables should be carefully considered with EMP in mind. Radial circuits with both supply and return conductors contained within the same cable have been suggested. This routing precludes loops and their correspondingly induced electromotive force, thus having a mitigative effect on EMP.

7.3.4 Electric Utility Communications

Current mitigation methods may be adequate for protection against EMP for much of the communication system. However, with the exception of telephone plant facilities, little attention has been paid to the effects of HEMP on the equipment interface into the communication system.

The addition of low-cost, low-voltage surge-protective devices may be warranted, and such devices would provide more protection for other EMI sources, such as lightning and switching.

Further investigations of the impact of replacing hard wire and unshielded cable with fiberoptic systems are necessary. As the cost of such systems decreases and their installation becomes easier, using them for replacement in critical circuits may be justified. Such installations would also improve reliability in severe lightning and switching surge environments.

Since low-voltage solid-state circuits are at greatest risk, improvements in HEMP protection for currently installed communication and computer systems might include [52]:

1. Maximizing shielding provided by existing cabinets and housings by paying attention to penetration details and by adding simple shielding structures such as wire mesh.

2. Installing low-voltage varistors with proper protective characteristics on conductors penetrating these shields.

3. Installing low-pass filters on conductors penetrating the shielding [53].

4. Identifying and, if possible, modifying those computer and logic circuits that tend to misoperate and lock out, or improving the inherent ability of the equipment or components to withstand damage or upset.

Waveguides, shielded cables, and ground leads should be grounded at the point of entry on the outside surface of the enclosure [54].

A communication system may also be vulnerable at its power source. Power line filters are commercially available which, in combination with metal-oxide surge arresters and back-to-back-diode voltage suppressors, could provide attenuation of HEMP surges on power lines penetrating a facility. While there are numerous suppliers of surge suppressors who promote their products as being adequate for protection against HEMP surges, the adequacy actually depends on the specifics of application. A test on a typical power-line filter in combination with a distribution transformer using impulses having rise times of 20 to 50 nanoseconds found that the filter provided only 38 to 53 dB of attenuation [53]. Nevertheless, when adequately applied, surge suppression is an effective means of EMP mitigation.

7.4 MHD-EMP Mitigation

Circuits directly affected by MHD-EMP are transmission and sub-transmission lines of significant length. While it is the lines of transmission and sub-transmission systems which experience high levels of quasi-dc current, it is the quasi-dc flow through the transmission and sub-transmission transformers which causes the transformer saturation, harmonics, and increased VAR demand which create the secondary and detrimental effects of MHD-EMP.

MHD-EMP events pose no direct threat to protective relays. The major problem is the relay's failure to correctly perform its protective function. While relays may respond incorrectly due to distorted signals, they are neither damaged nor directly affected by the MHD-EMP event. There is little or no risk of physical damage to any of the components of the protective system.

In effect, it is the entire power system which is at risk from the secondary effects of MHD-EMP, but the secondary effects are not the target of mitigation; the target of mitigation is the quasi-dc current, which must be prevented.

7.5 Mitigation Methods for MHD-EMP

Since the quasi-dc current of MHD-EMP depends on ground paths, it has been suggested that capacitors be placed in the neutrals of all grounded high-voltage transformers and reactors. This practice would mitigate not only MHD-EMP-induced currents but also geomagnetically induced currents from geomagnetic storms. However, it creates unacceptable problems for utilities; it would affect protective system operation, and few if any applications exist.

Instrument transformers also experience quasi-dc current. Most problems stem from the saturation of the magnetic circuits of voltage and instrument transformers. The use of transformers or transducers which are not susceptible to saturation would eliminate this effect of MHD-EMP. Such devices do exist. Air-core current and voltage transformers or other non-magnetic-circuit current or voltage sensors are immune to saturation, and non-magnetic-circuit transducers are presently being developed using fiberoptic technologies. Also immune are linear couplers typically used for high fault-current applications.

However, elimination of saturation effects from the instrument transformers or transducers does not entirely eliminate the risk of relay misoperation. Saturation of the power-transformer magnetic core would still cause protection problems. No matter how well the primary current is signalled to the protective relays, the effects of the wave distortion can affect relay performance. The best solution to the protection system difficulty (as well as the accompanying problems of MHD-EMP) is to effectively block the quasi-dc current flowing in the primary circuits of the power system.

The most practical method of mitigating MHD-EMP is to install series capacitors. Series capacitors not only block quasi-dc currents, but also improve power transmission. Unfortunately, the cost is prohibitive unless power system operating conditions favor the installation.

8. CONCLUSIONS

A high-altitude nuclear event with nominal characteristics can have a significant impact on an electric power system. HEMP-caused system effects are loss of load, loss of generation, and limited equipment damage. Damage may be either immediately catastrophic or latent. MHD-EMP effects are similar to those of geomagnetic storms, but have shorter duration and higher intensity. Voltage problems due to insupportable VAR demand can be severe.

8.1 HEMP (E_1)

While the extent of distribution flashovers is not overwhelming for a high-altitude event of nominal characteristics, recloser protection of distribution feeder laterals against temporary faults exacerbates the system impact to a significant level. Recloser tripping on lateral faults will cause a drastic loss of load immediately after a HEMP event. Subsequent reclosure will return some of the lost load, but no earlier than one second. For an event of nominal characteristics, expected initial load loss over a circular area of HEMP illumination of 2200-km radius could be a significant fraction of total load.

Generation loss due to auxiliary system flashover is minor, but generation loss due to upset of control circuitry is more difficult to evaluate. This is especially true of nuclear generation: the appropriately cautious tendency to trip the reactor for most disturbances makes nuclear generation more susceptible to tripping. A reasonable estimate of generation loss is the loss due to auxiliary flashover plus all nuclear generation.

For an event of nominal characteristics, damage will consist of a scattering of punctured insulators with some insulators damaged but still functional, a few distribution transformers, some 480-volt motors serving generation plants, and scattered random control-equipment damage. The greatest likelihood of major equipment damage is from system breakup, should system breakup occur. For a burst of nominal characteristics, some islanding of the power system may occur, and system breakup is possible.

8.2 MHD-EMP (E_3)

For a burst of nominal characteristics, MHD-EMP will affect the power system by causing quasi-dc currents to flow throughout the transmission system. These quasi-dc currents will cause severe half-cycle saturation in transformers, generating harmonics and increased reactive power demand. The impact will be quite similar to geomagnetic storm effects, but of shorter duration and higher intensity. Severe voltage drop is expected due to insupportable VAR demand.

Little physical damage is expected from a nominal MHD-EMP event due to its short duration. For an MHD-EMP event of nominal duration but an order of magnitude (10 times) greater intensity, however, damage is conceivable. Nevertheless, even for a nominal MHD-EMP event, some islanding of the power system may occur.

8.3 Multiple Events

The impact of multiple events on load and generation is more difficult to quantify, but greater coverage at higher electromagnetic field intensities is likely for both prompt HEMP and MHD-EMP. Overlapping areas of HEMP illumination are subjected to sequential disturbances with cumulative impact on surviving load and generation. Multiple bursts increase the likelihood of system breakup and may also increase the number of insulator punctures due to repeated stress.

8.4 Restoration

An evaluation of post-EMP power system restoration was important, given the demonstrated vulnerability of the electric power system. The evaluation consisted of extensive research and multiple interviews with individuals responsible for power system restoration. NERC, which serves as a forum for power-system restoration in the U.S., generously arranged several interviews with power system operators.

There are three major aspects to post-EMP power system restoration: communications, personnel- or time-limited systems, and restoration plans.

8.4.1 Communications

Communications for voice and data are important for system restoration and include utility-owned or leased microwave systems; utility-owned or leased telephone lines; HF, VHF, or UHF radio systems; fiberoptic systems; and power-line carrier. Some communication loss due to EMP is likely; a limited attempt has been made to quantify this loss [50].

Communication systems other than radio are used primarily for supervisory control and data acquisition (SCADA) systems. SCADA is a generic term for systems which enable a control center to provide monitoring and control of remote power system devices or equipment. For restoration, the most important function of SCADA is identification of the power system configuration. If this capability is lost, manual techniques using manpower and mapboards are required. Complete SCADA failure could add several days to restoration because of manpower-intensive system-status identification.

8.4.2 Personnel- or Time-Limited Systems

After a system breakup, several sub-systems, in particular protective systems, may require some human intervention. For example, during an MHD-EMP event, differential transformer relays without harmonic restraint may operate. Typical utility practice requires transformer inspection before re-energization. Similarly, replacement of fuses in dc control circuits or distribution networks requires personnel. These activities could seriously tax available manpower.

Other systems have inherent time limitations. Batteries and backup diesel generators in control centers and substations are reliable; generators are often tested weekly. However, generators are time-limited based on available fuel, and batteries at power plants, substations, and microwave sites are usually designed to last only a few hours. If a post-HEMP outage lasted several days, these limitations would further delay system restoration.

8.4.3 Restoration Plans

Most utilities and power pools have blackstart plans, and many test their blackstart power plants annually or biannually, while others simply train their operators through periodic blackstart drills.

Because system breakup might be caused by several vastly differing circumstances, most utilities and power pools address multiple contingencies. The need for frequent updating of plans, optimum use of personnel, and operator drills is well recognized.

8.5 Mitigation

Utilities have done much to protect power systems from transients and related EMC effects, but transients from lightning and switching seldom reach the rapid rates-of-rise common to HEMP, though there is evidence that local effects of lightning are somewhat comparable.

British military experience indicates that retrofitting EMP hardening can cost in excess of twenty-five percent of original installed cost, but designing EMP hardening into new equipment costs only five percent of original installed cost [52]. Standards are in place and being drafted for EMP testing of relaying and some electronic components, but additional EMP-related standards for voltage-limiting devices are needed.

Auxiliary and control circuits should incorporate metal conduit for remote 480-volt motors or include surge packs on the motors themselves. New designs for telephone interfaces and radio systems should include EMP hardening. Recommended mitigation of mobile radio overvoltage is by means of inexpensive overvoltage devices on the antennae. Shielding of existing metal cabinets should be maximized by reducing apertures or by adding shielding structures such as wire mesh. Any conductors penetrating cabinets should include low-voltage varistors or low-pass filters [53].

Capacitive devices in transformer and reactor neutrals have not met with much enthusiasm for mitigating GICs and are unlikely to be added for MHD-EMP prevention. A more effective technique for mitigating MHD-EMP is series capacitor installation.

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9. RECOMMENDATIONS FOR FUTURE RESEARCH

Future EMP research should focus on the power system of today as well as that of tomorrow. The electric power industry must continue to evolve to effectively serve its customers, and the industry must rely on research to determine what to design into its systems and operating practices.

Two directions are important for future research into the effects of EMP on electric power systems: evaluation of refinements of previous work and investigation of EMP impacts on future power system operations and design. Trends must be identified and the necessary research integrated into development.

Knowledge of EMP as a quantified threat is the first step in mitigating its effects, but a realization of the limitations of current HEMP research data and knowledge of the trends of power-system design provides the direction for subsequent efforts.

Several areas of EMP research could yield substantial benefits to the power system industry. These can be classified into four main categories.

- E_1 Research and Experimental Work
- E_3 Research
- Communications Research for Restoration
- Evaluation of EMP Impact on Future Trends in The Power Industry

These suggestions are not meant to be all-encompassing, but do indicate some important areas needing investigation.

9.1 E_1 Research and Experimental Work

In terms of broadly based research, evaluating the effects of HEMP on customer load would be useful. Previous studies have focused on the utility side of distribution, but little coordinated emphasis has been given to evaluating the loss possible from HEMP effects on the customer side of the distribution transformer. Most load is end-user controlled, and HEMP could conceivably reduce load from this source.

There is also a need for specific experimental work. Excellent work has been accomplished to date in defining HEMP strength of power system components, but continued testing with statistically significant sample sizes would refine those estimates of withstand strength. Statistical distributions of HEMP withstand strength would certainly improve accuracy in evaluating system effects.

Several specific types of equipment suggest statistical testing due to their importance and relatively low cost.

1. Control cable could be tested to better determine its HEMP strength. Present withstand estimates are probably low. Both new and aged control cable could be tested while either terminated in its own impedance or energized with 120 Vac or 125 Vdc. The 120 Vac tests would show whether faults would truly be self-clearing, while the 125 Vdc tests would show if dc current can be interrupted.

2. Relay racks and cabinets should be irradiated with direct HEMP illumination at several field strengths. Both electromechanical and solid-state relays should be included in the assembly and should be energized with normal current and voltage. There is little data on direct illumination of relays, and this testing

would provide a means of exploring the impact of improperly installed shielding.

3. Energized motors of 480- and 240-volt design should be tested to determine both turn-to-turn and line-to-ground withstand strength. This would provide insight into present estimates regarding steep-front surges. This testing could confirm work done by Gupta et al. [55,56,57] which implies that strength for fast fronts is much greater than indicated by the published IEEE committee envelope. This envelope appears to drastically underestimate turn-to-turn withstand capability for 480- and 240-volt motors.

4. Solid-state and electromechanical relays could be tested to determine a statistical distribution of HEMP strength. It would also be quite useful to work with relay-standards committees to evaluate present SWC "fast transient" tests on relays. Present test procedures specify pulse parameters for the generated pulse instead of for the pulse applied to the relay.

5. Surge capacitors on relays could be investigated for effectiveness in mitigating steep-front pulses. These one-half microfarad capacitors are currently used to protect solid-state relays and microprocessor-based equipment from transient overvoltages. Specifications for maximum capacitor-grounding lead length and relay lead length could be established for protected equipment.

Besides HEMP-withstand testing, it would be beneficial to scan the impedance of insulators, particularly distribution insulators, over HEMP frequencies. Better estimates of insulator impedance would allow refined calculation of flashover probability for distribution circuits. While major changes from previous calculations are not expected, the flashover vulnerability could be refined.

Additional testing of transformers with emphasis on transferred-surge characteristics is indicated. The transfer response of a power transformer with and without directly mounted surge arresters would be applicable in several areas of power-system EMP analysis, such as substation evaluation and generation.

Also of great use would be an investigation into the effects of steep-front surges on all types of arresters. This is particularly important for metal-oxide arresters since these are becoming the standard for the industry, although gap-type surge arresters are still widely used on distribution circuits.

It might also be beneficial to extend previous corona research. It is remotely possible that corona may lessen the voltage peak and modify the shape of the HEMP-induced surge. If so, the estimated impact of HEMP on power systems would be lessened. However, methods would be required to work around difficulties in testing.

There is also a need to improve steep-front measurement techniques for power system equipment. The size of typical power system equipment makes it extremely difficult to test and measure HEMP-type surge phenomena.

9.2 E_3 Research

Several areas of possible MHD-EMP research could prove quite useful to utilities. It is important to remember that MHD-EMP is quite similar to geomagnetic storm phenomena, and that any new mitigation techniques developed for MHD-EMP would be useful to counteract GICs. The research would have to address the economic impact of any proposed technique as well as approach mitigation from a direction different from that of prior work. Since the sunspot cycle is presently at its peak for geomagnetic storms, it would be a useful opportunity to monitor these quasi-dc effects and relate them to MHD-EMP.

In terms of experiments, it would be informative to further investigate MHD-EMP/GIC effects on energized power system components. Of particular interest is the response of a current transformer during extreme half-cycle saturation of a power transformer. While in the past GIC has not occurred with enough intensity to cause major problems with current transformers, MHD-EMP as well as future GIC could.

9.3 Communications Research for Restoration

Communications have been shown to be an important, if not vital, part of power system restoration. For that reason, it is of interest to investigate communications in terms of restoration. It would be important to do this in some detail. Prior work exists, but a new focus could address communication strictly in terms of restoration. It would also be beneficial to address possible communication problems for other disasters as well, and a probabilistic evaluation of communication system survival could be of use in contingency planning for power system restoration.

An investigation into computer-communication interfaces for HEMP surges would be important for power system control centers. If similar tests have been accomplished for classified situations, these tests should be stripped of sensitive material and published for the benefit of utilities. If not, communication interfaces in the utility environment should be evaluated for sensitivity to HEMP effects with an emphasis on new installations. Cost-effective methods of hardening new designs should be addressed.

Special attention should also be paid to the hardening requirements of fiberoptic systems. Fiberoptic strands are by nature quite hard, but the light-to-electricity interfaces might be susceptible. These may be subjected to direct HEMP illumination by a burst or may require extensive EMI/EMC shielding to function in the hostile electromagnetic environment of a power system facility.

9.4 Evaluation of EMP Impact on Future Trends in the Power Industry

It is important to address future trends in the electric power system industry. Future installations must consider the possible threat posed by HEMP. Retrofits of currently installed equipment to accomplish HEMP hardening are seldom cost-effective. It is a fact of life that utilities exist in a regulated environment, and revenue structures are often dictated by regulatory environments. In order to be cost-effective, hardening must be designed into new equipment; HEMP hardening must be considered as just another aspect of equipment design. To foster this approach, EMP research must focus some energy on future power industry designs and operations.

Note that not only system design but also power system operations are important. The power system industry is moving in several directions, and EMP research must address these. For example, satellite communications for Energy Management Systems (EMS) is a long-term consideration, while a more immediate change is the increased reliance on cogeneration in utility systems.

There is still work to be done on EMP effects on electric power systems, and this work must be approached in a coherent, goal-oriented, and planned manner. Research incurs substantial costs, but it greatly enhances the reliability of the electric power system.

APPENDIX A

The survival of load on the system is a function of surviving load at each component level. Each component level is a factor in the expression for surviving load for each voltage class.

To better illustrate this, Figure A.1 depicts the component levels of Figure 4.1 as a survivability tree. Note that there is one major path for each distribution voltage class and that each major path branches in two. A separate calculation for each voltage class is necessary because of the differing probabilities of flashover. Secondary branching of each major path reflects differences in survivability of sublateral load served directly by the substation feeder and indirectly through the downstream feeder.

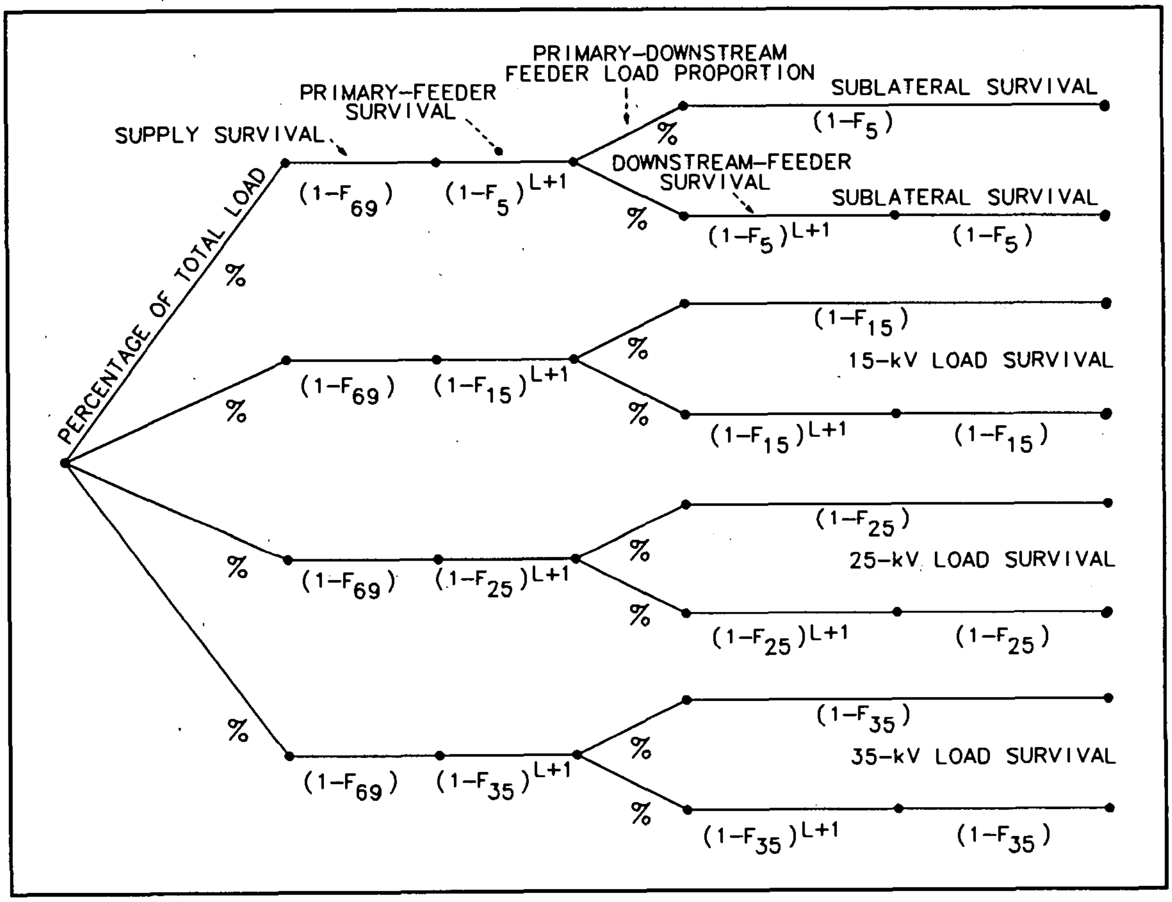

Figure A.1. Probability Tree Depicting Power-System Load Survivability.

The probability of survival for each component level is the complement of the probability of flashover. For example, the probability of survival of the 69-kV supply line can be expressed as follows:

$$P(\text{Survival}) = (1 - F_{69}), \quad (1)$$

where F_{69} is the flashover probability given in Table 4.1. Similar expressions represent the probability of survival for the sublateral component level of Figure 4.1.

A more complex expression is necessary to determine the probability of survival for those component levels containing a reclosing device. A reclosing device will operate for any flashover in its zone of protection. For these devices, load is lost if at least one of the laterals, or the feeder itself, flashes over. Students of probability will recognize the distribution as binomial and the expression as follows:

$$P(\text{Survival}) = (1 - F)^{L+1}, \quad (2)$$

where F is the probability of flashover for the appropriate voltage class from Table 4.2, and L+1 is the number of laterals, plus the feeder, having unique orientations.

Expressing all percentages and probabilities as decimals, the total surviving load is the sum of the resultant values at the end of each branch. Lost load is simply the complement of the surviving load.

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