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OAK RIDGE
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MARTIN MARIETTA

HEMP Emergency Planning and Operating Procedures for Electric Power Systems

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POWER SYSTEMS TECHNOLOGY • PROGRAM •

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ABBREVIATIONS AND ACRONYMS

A/C	air conditioning
ASD	adjustable speed drive
CT	current transformer
DOE	Department of Energy
dc	direct current
EMP	electromagnetic pulse
EM	electromagnetic
EMF	electromagnetic field
ERCOT	Electric Reliability Council of Texas
ECAR	East Central Area Reliability Coordination Agreement
E-field	electric field
EMC	Energy Management Centers
FEMA	U.S. Federal Emergency Management Agency
HEMP	high-altitude electromagnetic pulse
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
LSI	large scale integrated
MHD-EMP	magnetorydrodynamic electromagnetic pulse
MAAC	Mid-Atlantic Area Council
MAIN	Mid-Atlantic Interconnected Network
MAPP	Mid Continent Area Power Pool
NERC	U.S. National Electric Reliability Council
NUG	nonutility generation
NPCC/US	Northeastern Power Coordinating Council/United States
OC	Operating Committee
ORNL	Oak Ridge National Laboratory
PTS	public telephone systems
RF	radio frequency
SFSD	steep front short duration
SERC	Southeastern Electric Reliability Council
SPP	Southwest Power Pool
T&D	transmission and distribution
TVA	Tennessee Valley Authority
VAR	volt ampere reactive
WSCC	Western Systems Coordinating Council

ABSTRACT

Investigations of the impact of high-altitude electromagnetic pulse (HEMP) on electric power systems and electrical equipment have revealed that HEMP creates both misoperation and failures. These events result from both the early time E_1 (steep-front pulse) component and the late time E_3 (geomagnetic perturbations) component of HEMP. In this report a HEMP event is viewed in terms of its marginal impact over classical power system disturbances by considering the unique properties and consequences of HEMP. This report focuses on system-wide electrical component failures and their potential consequences from HEMP. In particular, the effectiveness of planning and operating procedures for electric systems is evaluated while under the influence of HEMP. This assessment relies on published data and characterizes utilities using the North American Electric Reliability Council's regions and guidelines to model electric power system planning and operations. Key issues addressed by the report include how electric power systems are affected by HEMP and what actions electric utilities can initiate to reduce the consequences of HEMP. The report also reviews the salient features of earlier HEMP studies and projects, examines technology trends in the electric power industry which are affected by HEMP, characterizes the vulnerability of power systems to HEMP, and explores the capability of electric systems to recover from a HEMP event.

1. INTRODUCTION

1.1 HISTORY

On July 8, 1962, a nuclear weapon was detonated at a height of 400 kilometers over the Johnston Atoll in the Pacific Ocean; this event is known as the Starfish burst. Coinciding with the burst in neighboring Oahua, Hawaii, 1300 kilometers from ground zero, the simultaneous failures of 30 strings of streetlights (serial connected loops) occurred [1]. Thirty years of study and debates have been spawned regarding the significance of high-altitude electromagnetic pulse (HEMP) as a killer of electrical equipment and systems. This event has been the focus of several investigations [1] to determine the precise role of HEMP in the electrical failure in Hawaii. The findings [1] support HEMP as the culprit in the streetlight failure and also in some other electrical equipment failures.

Since the Starfish burst, extensive studies of HEMP and its role in failures of electrical equipment in facilities and electric power systems have focused largely on components. Investigations of potential system-wide failures of electric power systems have been limited. In 1983, the U.S. Department of Energy's Oak Ridge National Laboratory (DOE/ORNL) was directed to commission a series of assessments on the effects of HEMP on electric power systems. Some of those findings are recorded in a recent report [2]. In general, HEMP does create electrical equipment misoperation and failures; however, the significance of such events on electric power systems are not universally embraced [3].

This particular study attempts to answer some of the system-wide implications of HEMP effects. There is overwhelming evidence to support the notion that significant power system failures will occur from HEMP. Consequently, attention has been devoted to preparing for a major power disruption and expediting recovery from it. In recent years, major weather disturbances (hurricanes, ice storms, and earthquakes) have tested the electric utility industry's and the government's (both local and federal) ability to rapidly recover from a major power disruption. These incidents provide good insight to the recovery process.

1.2 STATEMENT OF THE PROBLEM

Although electric power systems will experience failures when exposed to HEMP, the extent of such failures remains an unanswered question. This issue is not clarified in this report. Instead, this report addresses the issue of how electric power systems are likely affected by HEMP and how electric utilities can reduce system-wide consequences of HEMP. The fundamental thesis of this study is summarized as follows:

- The vulnerability of electric power systems to HEMP is determined by two facts: 1) the severity of the HEMP disturbance, and 2) the robustness of the system relative to the particular HEMP event, that is, how capable the system is for sustaining system operation and integrity following the loss of generation, failures of delivery systems (transmission and distribution), and/or major disruption or dislocation of electrical load.
- Operating strategies can relieve the system design or configuration from deficiencies and thus reduce the vulnerability of the system.
- Preparation of appropriate plans for restoration of a power system following a major failure will reduce down time and expedite service recovery.
- Modification of some present electric system practices (both design and operations) can reduce HEMP impacts.

In summary, the report reviews the salient features of earlier HEMP studies and projects and examines technology trends in the electric power industry and their relationship to HEMP disturbances. It characterizes the vulnerability of power systems to HEMP and explores the readiness of the process of recovery. The assessments are conducted on a qualitative basis and rely upon published industry data and experience to forecast HEMP impacts.

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2. THE HIGH-ALTITUDE ELECTROMAGNETIC PULSE ENVIRONMENT

A nuclear detonation in or above the earth's atmosphere produces an intense electromagnetic pulse (EMP) [1,2] that is referred to as a nuclear EMP. A detonation at an altitude above 40 km produces an EMP that is denoted as a HEMP. This environment lacks the blast and shock waves that are typically associated with nuclear detonations within the atmosphere and consists entirely of electromagnetic field (EMF) disturbances. A large portion of the radiated EM energy is contained in the radio frequency portion of the spectrum. Consequently, these pulsed fields can induce large transient currents in power lines, communication cables, and antennas. This may lead to failure or misoperation of electrical equipment and possibe permanent damage to sensitive electrical components.

For convenience in describing the HEMP environment, the electromagnetic (EM) disturbance is divided into three components: E_1, E_2, and E_3. This division is based on the different production mechanisms and on the time scales of the disturbance. The transient EM fields radiated from such a detonation can vary significantly with the weapon design characteristics. The device yield, the detonation height, and the position of the observer to the detonation point are all factors.

The early-time E_1 component of HEMP is a steep-front, short-duration pulse with a rise time of a few nanoseconds. This waveform rapidly decays in times of about 1 μs or less. A single high-altitude nuclear burst can subject much of the continental United States to an E_1 HEMP electric field (E-field) on the order of tens of kV/m. Following this early-time HEMP environment, a slower varying and less-intense EM field is observed. This is the intermediate-time E_2 environment. It has an E-field strength of about 100 V/m with a typical time scale on the order of hundreds of milliseconds. This waveform component is followed by a very low-amplitude late-time signal with an amplitude of less than 1 V/m. This quasistatic field, denoted as E_3, results from geomagnetic perturbations caused by a high-altitude nuclear detonation. It has a duration of up to several hundreds of seconds. This later component of the HEMP signal is also referred to as magnetohydrodynamic EMP (MHD-EMP). E_3 can affect power systems similarly to geomagnetic storms [3].

In comparing these three environments, Fig. 2.1 presents a qualitative view of the E-field components found in HEMP, with the various production mechanisms indicated. As noted, the various parts of this environment have different properties; therefore, it is difficult to compare them in a single plot on a quantitative basis. For example, the E_1 field is an incident field that does not take into account the presence of the earth. The E_3 environment, however, is a total (incident plus earth-reflected) field. The polarization of these components of HEMP are different.

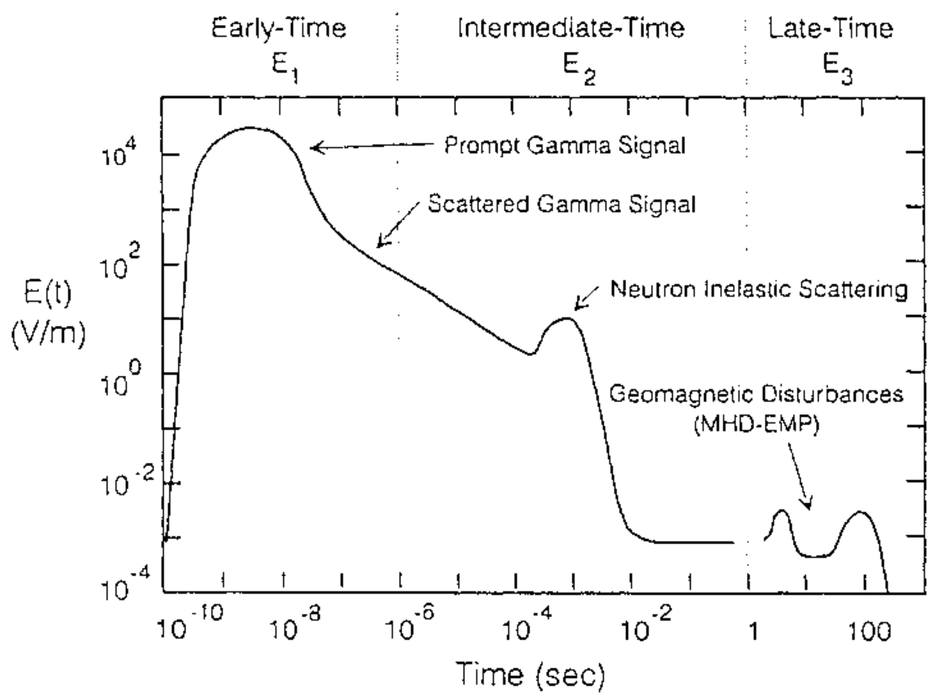


Fig. 2.1. Qualitative example of transient high-altitude electromagnetic pulse electric-field environments.

To assess the effects of EMP on electric power systems, appropriate specifications of the E_1, E_2, and E_3 field components are required. These excitation fields, together with a specification of the initial condition, or state, of the power system, are used to determine the probable response of the power network. Because it might be possible to infer information about a weapon design from actual EMP environments, such detailed information cannot be provided for unclassified assessments. For such assessments, different unclassified EMP waveforms have been developed and utilized in the literature [4,5,6,7].

It is important to recognize that these generalized waveforms do not represent an actual EMP but attempt to incorporate the potentially damaging features of EMP, such as a large-peak amplitude, a fast rise time, and a long fall time. This type of EMP waveform is referred to as a "bounding waveform," and is used most effectively in designing a hardened military system where survivability is a key concept. Typically, this worst-case HEMP environment is applied with the angle of incidence and polarization chosen so that the induced system response is maximized. The design of a HEMP-hardened system proceeds with this worst-case response as a design criterion for the expected system excitations.

When performing a realistic assessment of the effects of HEMP, a worst-case definition of the environment is inappropriate. The expected HEMP environment can vary considerably in pulse shape, amplitude, polarization, and angle of incidence at different observation locations on the ground. The variation of these parameters away from the set of values providing the worst-case response gives system responses to HEMP that are typically much smaller than those for the bounding waveform. If a bounding EMP definition were to be invoked in the assessment of the civilian electric power network, the significant geographic size of the power system and the nature of the network properties would provide unrealistically large estimates of the system responses. Thus, the resulting assessment of the power system response would be too pessimistic.

To provide a reasonable definition of the HEMP environment for power system assessments, a set of unclassified E_1, E_2, and E_3 fields has been developed. These nominal

HEMP environments are based on both observed HEMP response data and on calculations of actual environments and are summarized in the following sections.

2.1 E_1 — EARLY-TIME COMPONENT

The production of the early-time E_1 HEMP environment has been studied intensively and is well understood. The primary mechanism responsible for the production of the E_1 pulse is the prompt gamma radiation from the detonation that is converted into EM energy by the Compton scattering process. Highly energetic gamma particles from an exoatmospheric burst interact with air molecules in the earth's atmosphere to produce a "source region" at an altitude of 30 to 40 km. These Compton electrons move in a spiral path under the influence of the local geomagnetic field, and as a consequence of their angular acceleration, they radiate EM energy. The rise time and peak of this early-time signal are dependent on the time history and energy spectrum of the gamma and X-ray outputs of the weapon. These values, in turn, are dependent on the weapon design. These incident E_1 fields can cover a large portion of the earth's surface under the burst location.

Theoretical models of the production of E_1 provide results that compare well with the limited measurements taken from atmospheric nuclear tests. Fig. 2.2, taken from reference [8], illustrates measured and calculated E-field responses for a high-altitude nuclear detonation. The calculated data was computed using the CHAP code [9]. Numerical computer codes, like CHAP, were developed during the 1960s and 1970s and are used for predicting E_1 fields for different weapons designs. Currently, the only improvements being introduced for the E_1 environment are refinements in the computer codes, with uncertainties in the pulse magnitude arising from the uncertainties in the weapon output and air chemistry parameters.

For a system on the ground, the E_1 pulse appears to be a transient plane wave, arriving from the direction of the burst point. This is illustrated in Fig. 2.3. Either a vertically polarized field, a horizontally polarized field, or a combination of the two are possible, depending on the relative location of the observer to the burst point. This incident field is reflected from the earth, and the sum of the incident and reflected field components is the total field that excites the system.

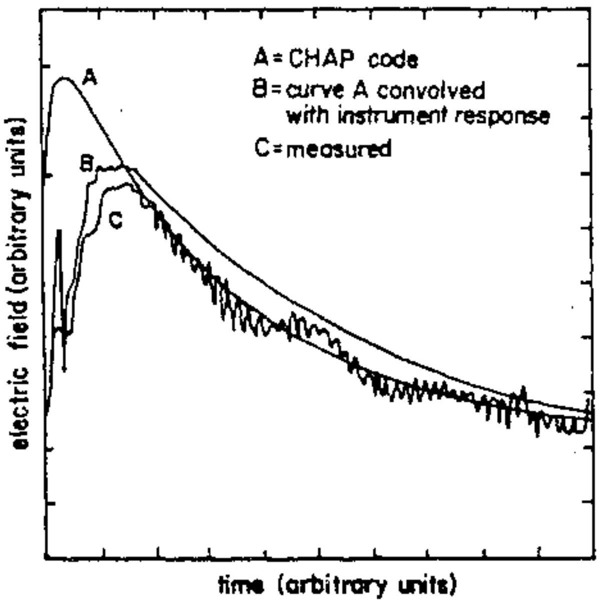


Fig. 2.2. Comparisons of experimental and theoretical E_1 high-altitude electromagnetic pulse waveforms [EMP Interaction: Principles, Techniques and Reference Data, K.S.H. Lee, editor, AFWL-TR-80-402, 1981].

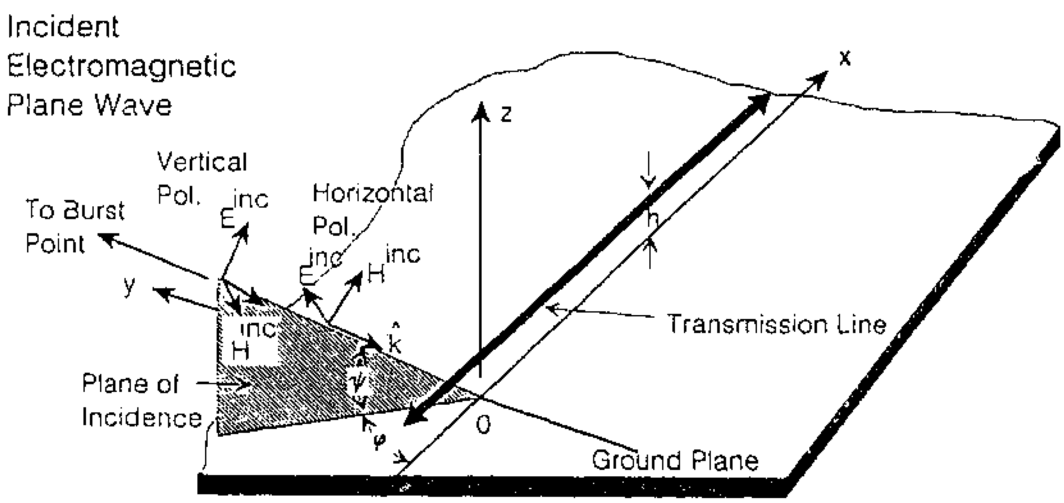


Fig. 2.3. Incident plane wave geometry for E_1.

To define an E_1 waveform for assessment purposes, an unclassified, DOE-developed EMP environment code has been used [10]. This nominal EMP environment provides peak E-fields near the maximum that can be produced by a high-altitude nuclear explosion. This environment is suitable for use in unclassified assessments, because it was developed without using specific values of weapon output parameters. This environment has electric and magnetic field pulse characteristics and polarization values that vary over the area of coverage. Consequently, it is appropriate for assessments of geographically large power systems.

As an example of the variability of the E_1 environment provided by reference [10], Fig. 2.4 shows the incident transient E-field waveforms at different ground locations, for an exoatmospheric nuclear detonation over Kansas City, Missouri. The observation locations are defined by the ground range (in kilometers) to the west of ground zero (i.e., the point directly under the high-altitude burst). These figures illustrate the total incident E-field environments that are a combination of the vertical- and horizontal-incident field components.

As noted in this plot, the peak amplitude and the waveshape of the E_1 field can vary significantly over the surface of the earth. Additional variations in the angle of incidence of the HEMP and in the polarization of the field can be determined from geometrical considerations. These variations play an important role in determining the response of long lines to HEMP. As an example of the variation of the peak amplitude of the E_1 field over the earth, Fig. 2.5 shows a plot of contours of constant peak E-field (in kV/m) for the burst over the central part of the United States. Ground zero is located at (x,y) = (0,0) km in the center of the figure. To the south of this location, the E_1 field has a maximum amplitude about 39 kV/m. Just to the north of ground-zero, the E-field has a null. This nominal E_1 environment has been used for several different studies of HEMP responses, one of which is discussed in reference [11].

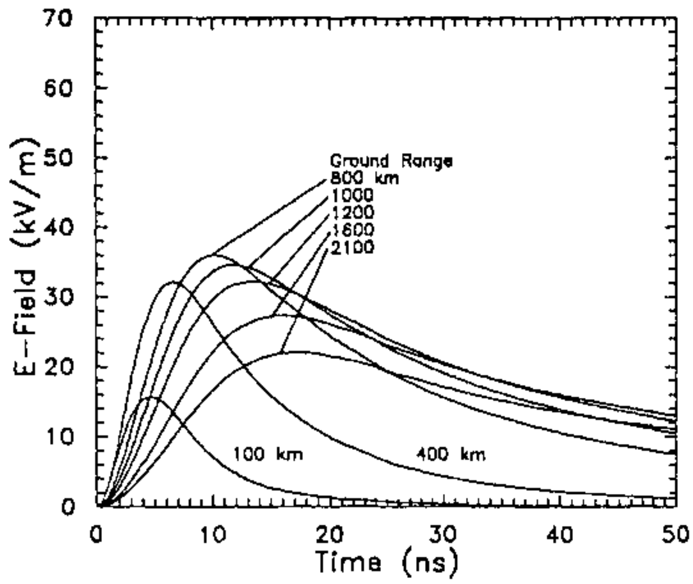


Fig. 2.4. Transient E_1 waveforms to the west of ground zero.

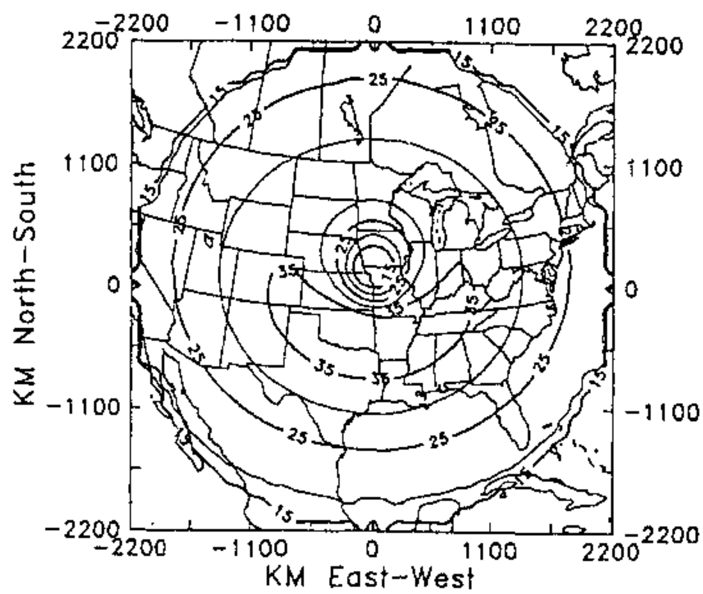


Fig. 2.5. Contour plot of the spatial variation of the peak E_1 fields.

2.2 E_2 — INTERMEDIATE-TIME COMPONENT

The intermediate-time E_2 environment pulse has an E-field pulse amplitude at about 100 V/m. The physics of the production of this environment are more complex and less well-understood than for E_1. Initially, this pulse is believed to be sustained by the interaction of the relaxing prompt gamma source and the scattered prompt gamma rays with the atmosphere in the source region. This is significant for times of several hundreds of microseconds. Later, gamma rays are produced by inelastic collisions between neutrons from the detonation and air molecules. Ultimately, these gammas begin to dominate the Compton source production, which sustains the pulse into the millisecond time regime causing this part of the HEMP environment to depend on the total neutron output and spectrum of the weapon.

The first part of the intermediate-time pulse is characterized as an incident plane wave and is considered to be an extension of the prompt E_1 pulse. The second part of this pulse closely resembles a static E-field, which is predominantly vertical on the earth's surface. This field will interact with the earth to produce a total horizontal E-field component, which is dependent on the earth conductivity.

For the purposes of power system assessments, the E_2 environment is assumed to have the same polarization characteristics and angles of incidence as the E_1 component shown in Fig. 2.3. The time behavior of the E_2 field is a single exponential waveform of the form $E_2 = 100\ e^{-1000t}$. This low-amplitude, intermediate-time contribution to the total E-field is illustrated in Fig. 2.1. Although this environment can also induce currents to flow in long lines, it is estimated that the effects of E_2 on the power system are not as severe as for those of E_1 and E_3. Thus, this environment has not been studied as extensively as the others in the HEMP assessment of power systems.

2.3 E_3 — LATE-TIME COMPONENT

The late-time MHD-EMP, or E_3, environment arises as a result of the motion of the weapon debris and ionized air in the upper atmosphere, causing perturbations in the earth's magnetic field. For times under 10 s, the expanding fireball from the explosion is highly conductive and tends to exclude the geomagnetic field as it expands and rises. Furthermore, a region below the burst point is ionized by the absorption of X-rays. This affects the geomagnetic field seen on the ground. At times over 10 s, the ionized and expanding atmosphere interacts with the partially restored geomagnetic field producing ionospheric current sources that further affect the magnetic field on the earth's surface.

Because of the resulting temporal variation of the geomagnetic field, an electric field is induced in the finitely conducting earth. This E-field is parallel to both the time varying magnetic field vector and the surface of the earth. This is the E_3 field component, and its amplitude is estimated to be several tens of V/km, depending on the local earth conductivity. This nuclear environment is similar to the earth-induced E-field naturally occurring in a geomagnetic storm, although this latter environment is usually smaller in amplitude and longer lasting than E_3.

As with the E_2 environment, research is continuing in an attempt to improve the estimates of MHD-EMP properties. From geomagnetic storm studies, it is known that power systems respond to this late-time excitation much like a direct current circuit. Information is needed on the slowly varying waveshape of the E-field and its vector direction on the earth's surface. These parameters, along with a specification of the physical layout and properties of a line, are sufficient to determine the induced currents flowing in the line. Early studies of the MHD-EMP responses of power systems have been described in reference [12]. The E_3 environment has been based on measured data from the Starfish's high-altitude nuclear detonation and MHD atmospheric calculations [13]. The maximum E-field for this environment is 24 V/km, but this occurred only for a limited region on the earth's surface.

Recent investigations [14] have provided updated information on E_3 that is useful for power system assessments. Fig. 2.6a illustrates a normalized E_3 E-field waveform that contains features characteristic of this environment. There are two distinct parts to this waveform: an early-time, or blast-wave, component occurring for times less than 10 s, and a late-time, heave contribution, lasting for several hundred seconds. The production mechanisms responsible for each of these components have been described previously, and the relative strengths of the components depend on where the observer is located on the earth. For example, if the observer is directly under the burst point at ground zero, the X-ray patch acts as a shield and reduces strength of the early-time E_3 waveform component. The later-time heave component, however, can be larger in this region. Away from ground zero, the heave contribution diminishes and the early-time component dominates. In both cases, however, the E_3 environment is so slowly varying that quasi-dc analysis models are appropriate for estimating the behavior of the induced power system responses.

These two different waveform components have distinct E-field patterns on the earth's surface. Fig. 2.6b presents the E-field direction for early times for a burst over the central portion of the United States. Under the X-ray patch below the burst point, the E-field is predominately in the east-west direction and has a slight increase in intensity toward the southern direction. Fig. 2.6c shows the field pattern for late times. This pattern is more like that of a dipole element located at the burst location. These field "footprints" develop continuously as time progresses.

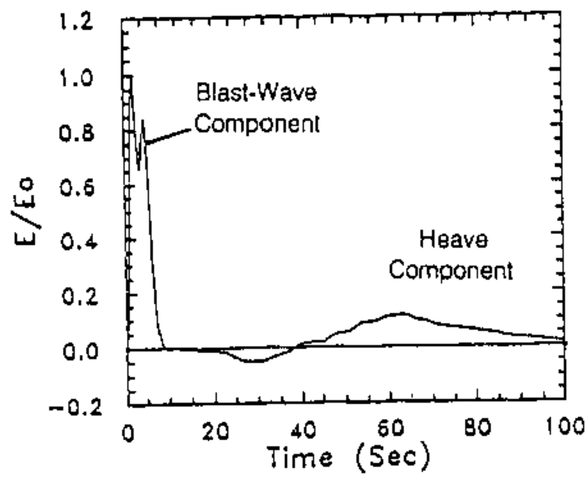


Fig. 2.6a. Normalized transient waveform for E_3.

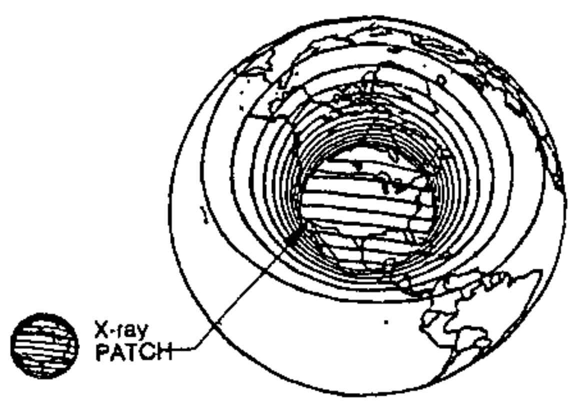


Fig. 2.6b. Electric-field pattern for E_3 blast component.

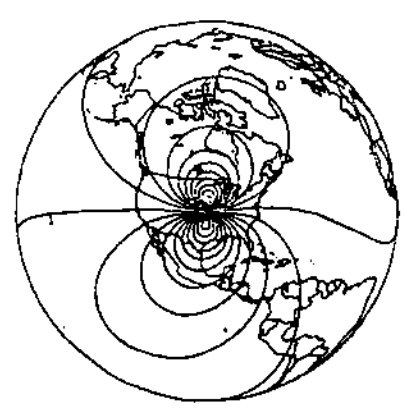


Fig. 2.6c. Electric-field pattern for E_3 heave component.

2.4 HIGH-ALTITUDE ELECTROMAGNETIC PULSE EFFECTS ON THE POWER SYSTEM

Although the preceding discussion has separated the HEMP environment into three components and has treated them independently, they arise from a single burst and occur within a second or two of each other. The response of the power system to HEMP, therefore, is due to each of these acting on the system in a sequential fashion.

Fig. 2.7 illustrates the sequence of events that determine the reaction of the power system to a HEMP event. This process, and the methodology of estimating the overall power system responses is described in more detail elsewhere [3,15]. Initially, the power system is assumed to be in a known state that is defined by its power load flow, power generation and load configuration, and other operating parameters that characterize the system. At a particular time, a single HEMP event occurs, producing the E_1, E_2, and E_3 environments previously discussed. Because these environmental components occur at different times, it is convenient to consider their effects separately in the time sequence shown in the figure. The incident E_1 environment excites voltages and currents on long distribution lines, or other long communications cables within the power system, in a process that is referred to as coupling. These transient surges produce responses in the power system, such as flashovers of insulators on the transmission and distribution (T&D) lines, and possible burnout of communication components. Such system upset or damage can cause a change in the operating conditions in the power system, and lead to a new system state. This overall process is referred to as E_1 interaction.

The E_2 component of the environment excites the system several milliseconds after the detonation and encounters the system in the new state that was induced by the E_1 stress. The E_2 interaction process is similar to the first, because it causes the power system to respond to the EM field excitation and a change in the operating state of the system ensues. As previously mentioned, the E_2 stresses on the power system are usually considered to be unimportant compared with the E_1 and E_3 stresses, and consequently, the E_2 interaction

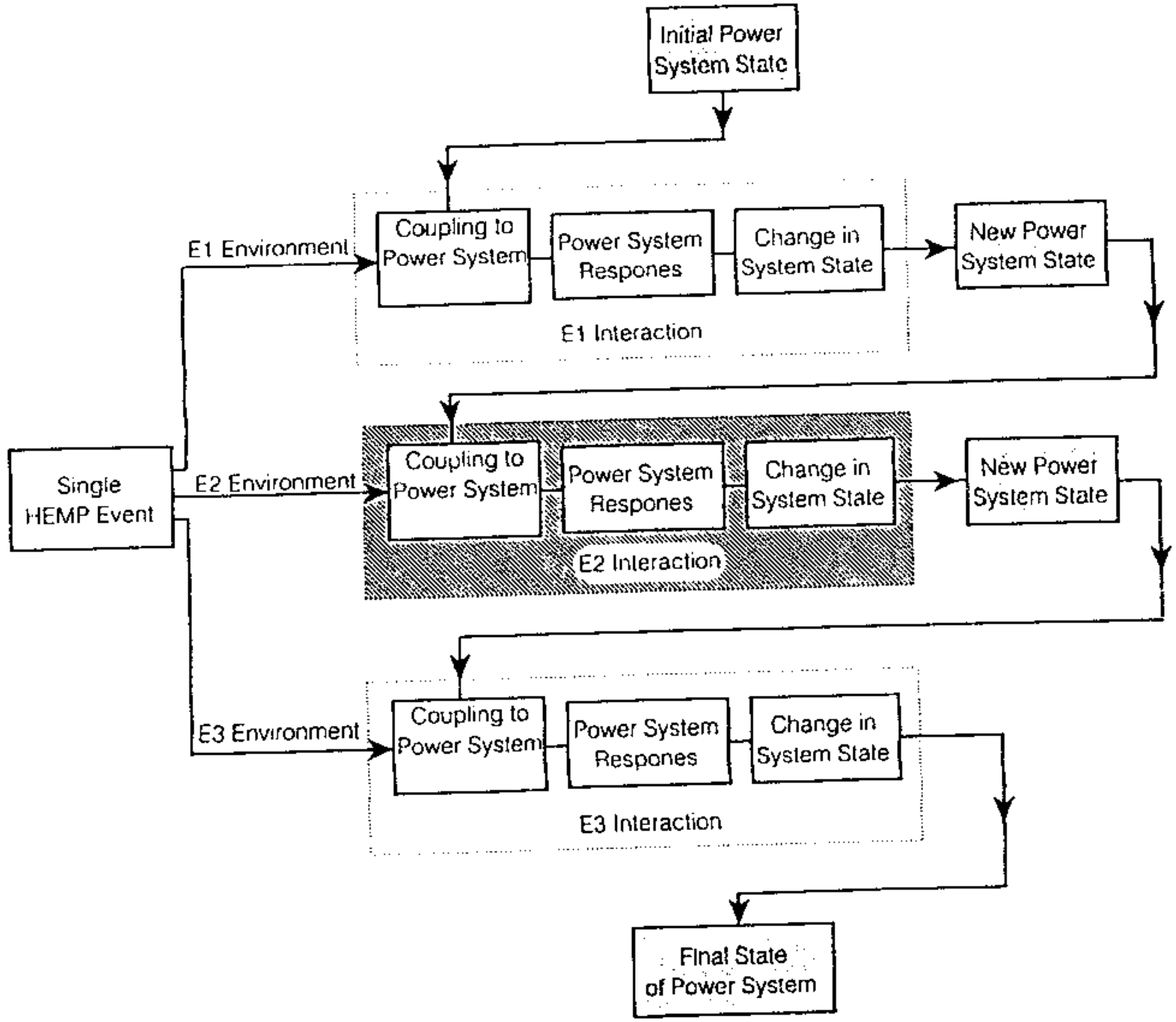


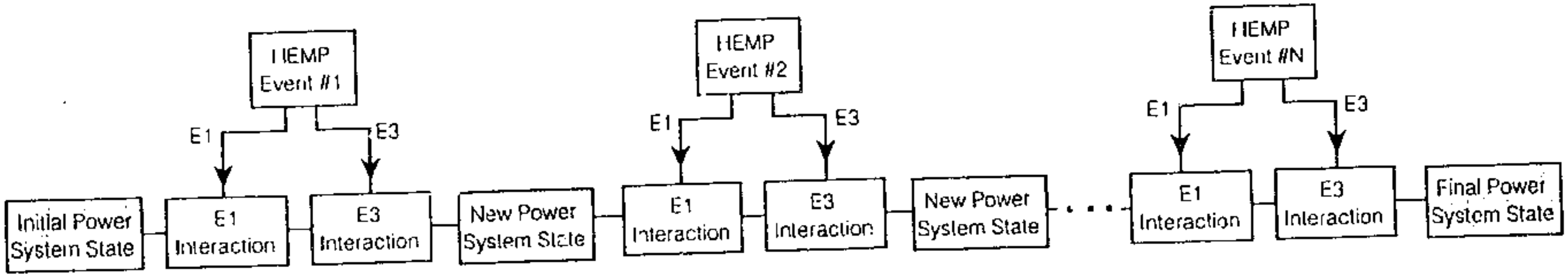
Fig. 2.7. Power system assessment procedure for a single high-altitude electromagnetic pulse event.

process is usually neglected. This fact is indicated in the figure by the darkened area around the E_2 interaction process.

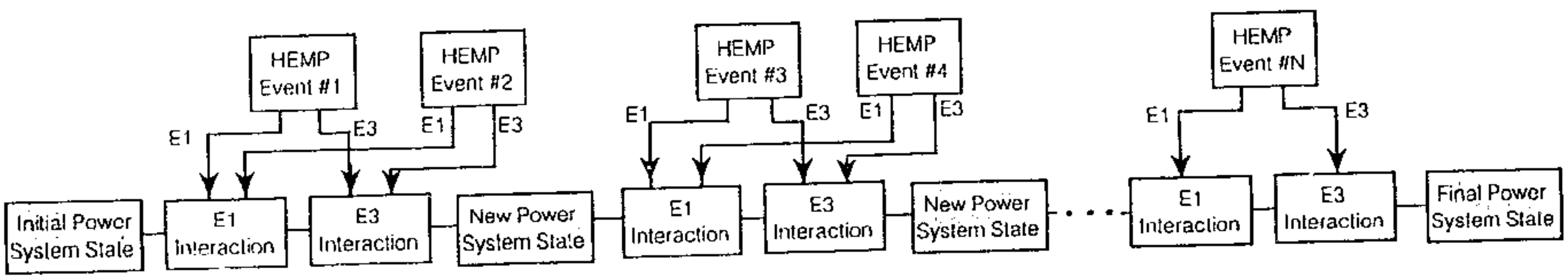
Finally, the MHD-EMP environment excites the system at times around 1 s after the detonation, and the E_3 interaction process leads to a further change of state. This sequence of events leads to the final power system state, the determination of which is the goal of the overall assessment process.

It is important to realize that all three of the HEMP components come from the same burst and are usually present together. Certain special cases can be envisioned, in which the E_1 component would be nearly absent, as in the case where the system is located in the region of the E_1-field null. Similarly, a low-altitude, low-yield burst might have an E_3 environment that is very small, with the E_1 component being the major excitation. However, it is usually true that all the environments must be considered together in assessing the effects of HEMP on a power system.

The case of multiple bursts may also be treated in this manner. Fig. 2.8a illustrates the assessment procedure for a multiburst scenario, in which each burst is sufficiently delayed in time so that the HEMP environmental components do not overlap. This implies that the bursts are at least several hundreds of seconds apart. In this figure, the E_2 interaction process has been omitted. A more complicated multiburst scenario is shown in Fig. 2.8b where the bursts are timed such that the E_1 and E_3 environments overlap in time. In this case, the E_1 and E_3 interaction processes must take into account the combined excitations from each burst.



a. Nonoverlapping multiple bursts



b. Overlapping multiple burst

Fig. 2.8. Power system assessment procedure for multiple high-altitude electromagnetic pulse events.

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3. CHARACTERIZATION OF HIGH-ALTITUTE ELECTROMAGNETIC PULSE IMPACTS AND ASSOCIATED SYSTEM EFFECTS

3.1 BACKGROUND

DOE/ORNL initiated a research program in 1983 to provide the theoretical foundation, data base, and analysis techniques needed to determine the response of electric power systems to HEMP and to develop appropriate emergency operating and restoration procedures to be employed to reduce disruptions caused by such events. Many studies and field projects have been conducted to this end. Specifically, the focus was on E_1 and E_3 events that are characterized by either steep-front short-duration (SFSD) transient electric fields with peaks of tens of kilovolts per meter occurring in less than 1 μs or by late-time MHD-EMP displaying peaks in the tens of volts per kilometer range occurring over a period of a few seconds to many tens of seconds.

In the course of the investigations, a number of practical limitations for assessing HEMP impacts on power systems, which include the following have been uncovered.

- The component and system technology has a range of age and diversity.
- The expense of comprehensive component testing has limited the development of statistically significant component level data bases.
- The impracticality of total system HEMP simulations prevail.
- The difficulty of measuring embedded component responses to HEMP events exist.

Studies have concluded that it is not possible to protect entire systems against HEMP even if the technology existed. Retrofitting of existing components is prohibitive for cost reasons. However, characterizing component failures and extrapolating them to system level events provides a basis for assessing consequential damage and assessing recovery.

3.2 IMPACTS ON THE GENERATING SYSTEMS

Electric generating facilities tend to lean toward the use of "standardized" equipment consisting of large pieces (generator, turbine, and "burners") with accompanying instrumentation. The need for access to equipment, including sensors and cabling, precludes comprehensive use of shielding against EM radiation. Such problems are considered on a point of application basis. However, traditional plant EM interference is low frequency and of little concern.

A conventional HEMP analysis of a complete power plant would be extremely difficult to conduct. Further, extrapolation of those results to other power plants in general is unlikely due to the unique designs of each plant both in configuration and choice of site electronics. Limited testing of power plant instrumentation has occurred. A pressure transmitter (part of power plant instrumentation) was subjected to a HEMP equivalent disturbance under laboratory test conditions [1] to determine its survivability. The results showed it did not fail under test and continued to work properly.

Power plants are most likely to be affected by loss of supporting systems. For example, unprotected dc circuits [2] have shown a tendency to fail. This tendency translates into a potential loss of backup dc power sources, which jeopardizes both safe shutdown and restart. Step-up transformers offer significant exposure to a power plant where generator trips occur by serving as a source of phase-unbalance negative sequence currents [3] due to potential transformer saturations. Geomagnetic storms [4], with properties similar to MHD-EMP, are causes for such generator trips by imposing harmonics and negative sequence on the generator windings. Potential reactive power overloads of transformers could also result in tripping the power plant. Switchyard facilities and supporting cooling tower operations are coupling mechanisms for HEMP through unprotected low-voltage motors and cables rendering the support systems ineffective [2]. As central dispatch of power plants has evolved as an operating strategy, communications to the plant becomes an essential part of operations. Loss of communication has a high probability of occurrence.

Although little or no direct damage to generating facilities is likely to occur, the operability of the generating plants is clearly at risk. The availability of a particular power station is largely determined by its supporting systems.

3.3 TYPICAL POWER LINE RESPONSES TO HIGH-ALTITUDE ELECTROMAGNETIC PULSE ENVIRONMENTS

When exposed to HEMP, all electrical conductors have a transient current and charge induced on them. Due to their long lengths and isolation from the earth, electric power transmission and distribution (T&D) lines can have rather large response levels, and these constitute the major HEMP energy collection mechanism for the power system. A number of studies were conducted to estimate the response levels of power lines [5,6,7], and it was found that the line responses depend on line parameters such as the height over the ground and the conductor radius, the line orientation relative to the burst point, and the local ground conductivity.

3.3.1 E_1 Responses

The effects of the E_1 component of HEMP on T&D lines have been studied extensively in [7] using the unclassified environment discussed in this report. This study showed that for T&D lines with a nominal voltage rating at above 34.5 kV, the E_1 environment is not sufficiently large enough to cause flashovers on the line. Consequently, this early-time component of HEMP probably will not affect these classes of lines. However, it was determined that the E_1 environment might cause insulation flashovers and possible consequential damage for lines operating at 12.5 kV or lower. As an example of typical E_1 calculated responses, Fig. 3.1 illustrates spatial contours of constant peak open-circuit voltages at the end of a semi-infinite 12.5-kV power distribution line. This line was assumed to be located over a lossy earth of conductivity $\sigma = 0.01$ S/m, and had other physical parameters typical of distribution lines in this voltage class.

To the southwest and northeast of ground zero, the line responses are seen to have the largest responses, well over 200 kV. Elsewhere, the line responses are considerably lower. Figure 3.2 shows the region within the United States where the 12.5-kV power distribution system would be expected to have at least one flashover, if the lines are uniformly oriented in all directions.

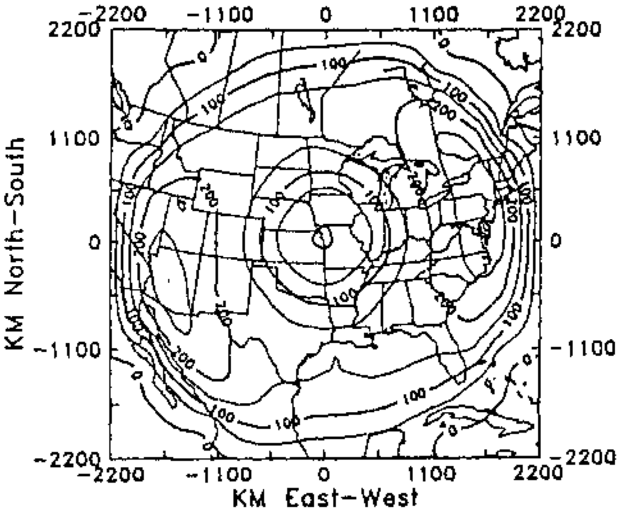

Fig. 3.1. Peak open circuit voltage for a 12.5-kV power distribution line for E_1 excitation and earth conductivity σ = 0.01 S/m (contours in kV/m).

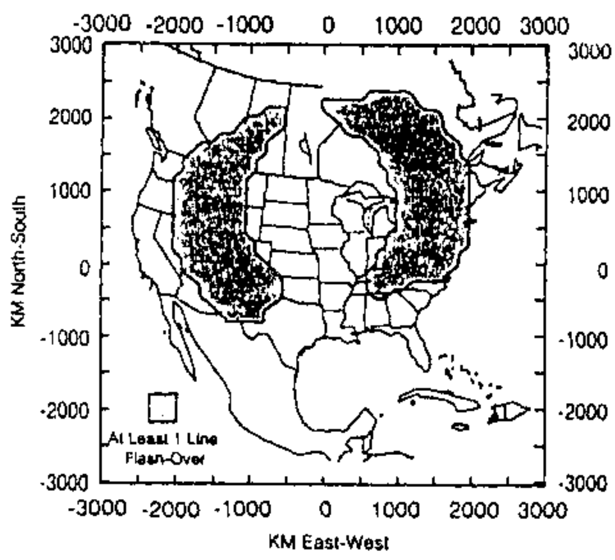

Fig. 3.2. Regions of at least one flash over for 12.5-kV power distribution lines.

3.3.2 E_3 Responses

Calculations of the current induced in long power lines by the E_3 environment have been reported in reference [8] for seven different T&D line classes. Each line class has a distinct per-unit-length resistance for the phase conductor, and different grounding schemes. Consequently, the currents on the lines are different. Fig. 3.3 presents the normalized E_3-induced currents (I_c/E_o) for each of the different line classes, as a function of the line length. The normalization factor, E_o, denotes the E_3 amplitude.

For the assumed peak E_3 environment of 24 V/km from reference [9], Fig. 3.3 indicates that currents on the order of 60 A will flow on distribution and subtransmission lines having a length of about 10 km. Larger currents will flow in longer sections of high-voltage transmission lines. Recent experimental evidence suggests that dc currents on the order of 3 to 5 A injected into the neutral of a power distribution transformer can cause serious harmonic distortion and a reactive power demand [3]. The E_3-induced quasi-dc current is expected to be over 10 times the experimentally observed injection levels, and consequently, it is likely that MHD-EMP would have serious consequences for the power system operation.

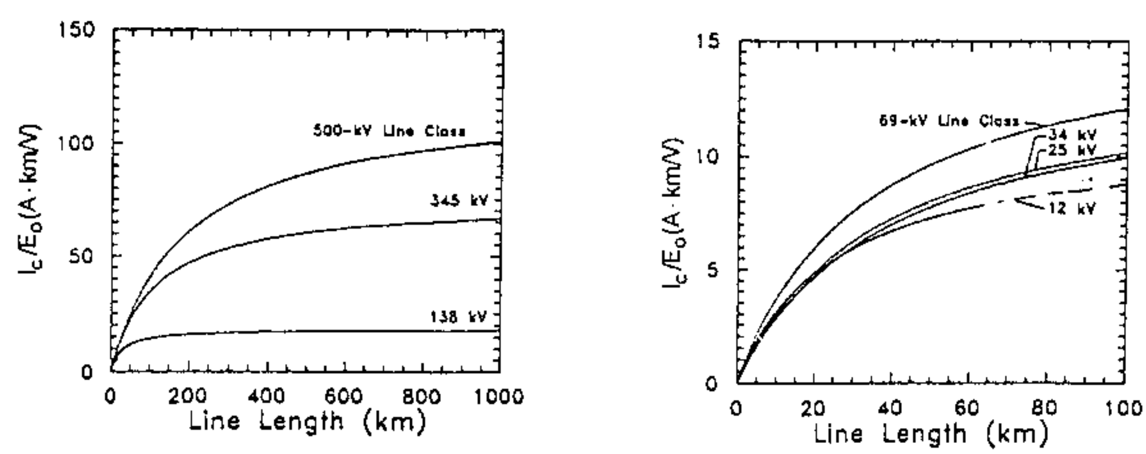

Fig. 3.3. Normalized E_3-induced currents for various transmission and distribution lines.

3.4 IMPACTS OF ELECTROMAGNETIC PULSE ON ELECTRIC POWER SYSTEM LOADS

The orderly operation of an electric power system involves maintaining a balance between production and consumption. Previous studies have focused on the significance of loss of supply; however, it should be recognized that loss of load is just as critical. As such, understanding the impact of loss of load from HEMP is required. In previous investigations the loss of distribution system [2] has been considered, but this investigation considers the exposure of loads to HEMP.

The particular focus here is on the following elements of power consumption:

- damage to end-use appliances and equipment;
- reduced demand for electricity due to societal disruptions; and
- reprioritization of critical loads (for example, service to mass communications media becomes more important).

3.4.1 Disruption of Electricity End-Use Systems

The potential for HEMP-caused damage to appliances has been investigated further [10] in conjunction with nuclear weapon test activities. Recently, incidents caused by geomagnetic storms have further indicated the potential for HEMP-induced damage to electric systems [4,11] as HEMP can be expected to subject the power systems to surges and stresses many times greater than solar storms.

The results of the investigations, testing, modeling, and theorizing, can be summarized in the following points:

- HEMP-induced voltage and/or current surges can blow fuses, trip circuit breakers, and fuse or damage electronic components. The damage may or may not be repairable.

- Appliances connected to unshielded cables that can act as an antenna are particularly susceptible [10,12].
- The components most likely to be damaged include motors, batteries, switching power supplies, capacitors, transformers, and solid-state components, particularly those that act as (RF) inputs to the appliance [4,10,13].
- Surges of "a few kV/m" may not degrade electronics. A test of 20 kV/m at 50 m (AESOP, to represent a TEMPS pulse of 50 kV/m at 50 m) showed minimal damage. The number as well as strength of HEMP pulses will affect the degradation [10,13].
- Surge suppressors that can attenuate 6-kV voltage waves to less than 1 kV will help protect consumer appliances [13].

In viewing the trends to increased microprocessor control of electric loads, there are some clear danger signs to the HEMP survivability of end-use loads. Switching power supplies, such as ubiquitous components of most computers and microprocessor-based controllers, are among the loads most susceptible to surge damage [13]. (Linear power supplies, however, show much more resistance to surges.)

The Electric Power Research Institute estimates that 35 to 45% of electric power flows through electronic devices, and this will increase to 60% by the year 2000 [14]. The susceptibility of electronic equipment; for example, the power supplies especially, means that a major portion of the control systems for commercial and industrial loads (for example, process control systems, building energy management systems) may be inoperable.

The susceptibility of motors to damage, both appliance motors and industrial process motors [13,15], augurs that further damage to electric loads will occur. The motor-based loads of electric systems in this country include industrial processes and heating ventilation and air conditioning (HVAC) systems, which account for the majority of the demand in many areas of the country, especially in the summer. While disagreement exists over how susceptible "conventional" industrial motors may be to HEMP [15,16], the higher reliance on adjustable speed drives (ASD) and computer-based controls that cannot be easily overridden [14], suggests that the vulnerability of this type of electric load is growing.

In summary, it can be reasonably hypothesized that 50 to 80% of the loads in the United States are susceptible to HEMP damage. These loads include the following:

- computer and control systems powered by switching power supplies (and the end-uses the computerized control systems regulate),
- motors,
- batteries, and
- solid-state loads with RF antennas.

It is beyond the scope of this report to estimate the percentage of these "at risk" loads that would actually be out of service as a result of specific EMP scenarios. However, areas with high air conditioning (A/C) loads can be expected to be more affected (e.g., the southern United States in summer). In a large commercial or industrial building, damage to a few components of an HVAC control system or an industrial process/control system may be enough to disable the entire building's load. Thus, a "weak link" assessment may be more appropriate than a "percentage of system damaged" assessment of the load effects of HEMP.

3.4.2 Changes in Electricity Consumption Patterns

Another factor to be considered in the effects of HEMP on electric loads is that the societal disruption likely to be caused by events associated with a nuclear blast will have major consequences for United States electricity consumption patterns. The need for mass communications and intracity transportation will be critical (see New York City Blackout Study [17]). The incentive to report to work, however, for nonpublic safety related industries (other than police, fire, medical, utility, etc.) will be low. Indeed, the civil authorities may request that nonessential workers remain home to facilitate transportation for critical repair/restoration personnel. The result is that much of the commercial and industrial demand for electricity could be significantly reduced.

Some of the resulting higher priority loads, however, such as mass communications, telephone, traffic control, etc., may have sustained damage due to their physical structures acting as RF antennas and inducing EMP-related damage to the facilities.

3.5 IMPACTS ON POWER SYSTEM COMPONENTS AND SUBSYSTEMS

The strength of a system is often miscalibrated by focusing on the major components, when in actuality it is the supporting role components that determine the system's effectiveness. Previously, it has been noted that the failures of various supporting systems to a power plant create its greatest weakness. These supporting systems include transformers, relays, plant auxiliaries electronic controls, and cooling water systems. Many of the supporting systems are exposed in the switchyard and lack complete protection systems.

MHD-EMP has a significant impact on transformers. In particular, it causes dc current in transformer cores which generates harmonics and increases the reactive power consumption, a result of magnetic core saturation on alternate half cycles [3,4,8]. Such phenomena is applicable to both high- and low-voltage transformers and is observed in Y-connected configurations. Varying effects are observed including thermal degradation, increase in gas content in transformer oil, and increased noise levels of the transformer, all direct results of operating the transformer in a core saturated state [4]. The potential for transformer failure exists.

E_3 simulations [3] have been made on a 12.47 kV/208-V 75 kVA Y-Y step-down transformer by injecting dc current into the neutral of the transformer. The impacts on harmonic content and reactive power consumption by the tranformers are shown in Fig. 3.4 and 3.5, respectively.

Protection systems and circuit breakers have also shown a tendency toward misoperation. Harmonic distortion causes relays to mistake harmonic rich currents as a fault

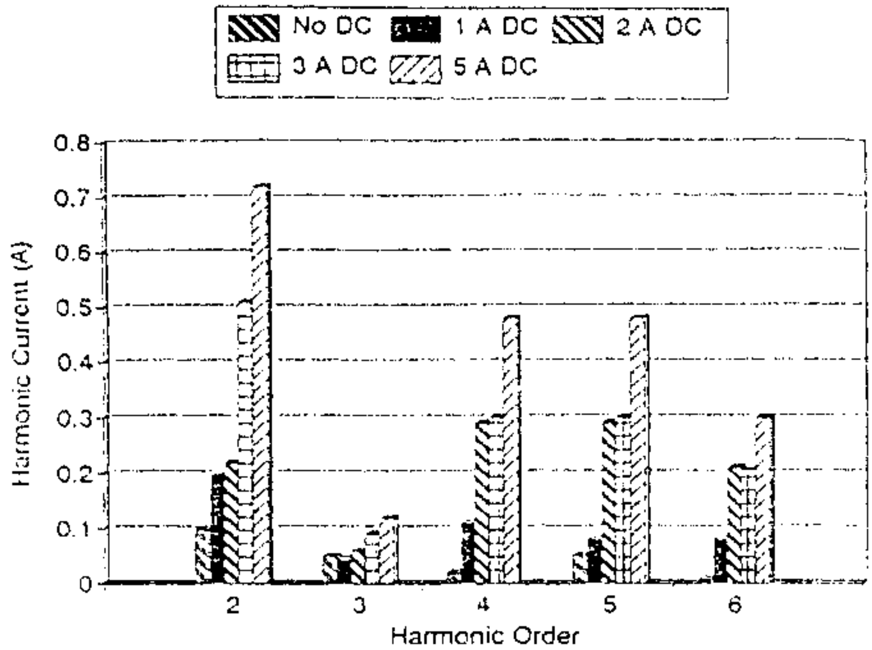

Fig. 3.4. Harmonic content for direct current (dc) injection in the neutral of a three-phase 480-V/12.47-kV/208-V power transformer test set. (*Source:* B. W. McConnell, et al., "Impact of Quasi-DC Currents on Three-Phase Distribution Transformer Installations," ORNL/Sub/89-SE912/1, June 1992.)

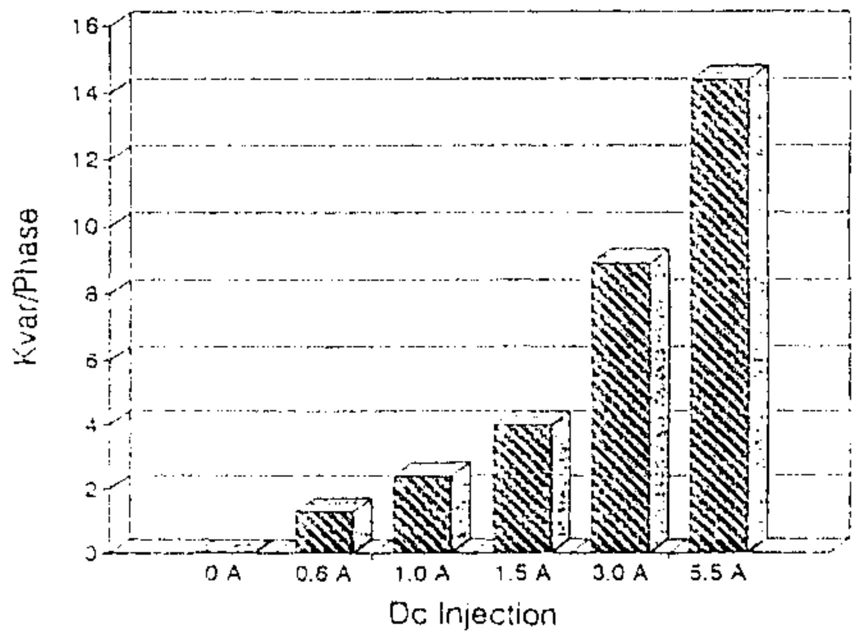

Fig. 3.5. Reactive power demand for the 480-V/12.47-kV/208-V power transformer test set. (*Source:* B. W. McConnell, et al., "Impact of Quasi-DC Currents on Three-Phase Distribution Transformer Installations," ORNL/Sub/89-SE912/1, June 1992.)

or overload, and they trip at an inappropriate time [4]. Other malfunctions include current transformers (CTs) misreads due to current distortion under fault conditions and slow operation of CTs due to the presence of remanent flux [4].

Capacitors and static (VAR) compensators have also experienced trips during system disturbances [18]. Primary problems stem from incorrect protection system operation due to unbalanced currents and harmonics, a consequence of a MHD-EMP type disturbance.

3.6 SYSTEM-WIDE IMPLICATIONS

Translating the HEMP impacts into generic system effects is the first step in determining system reliability and operational impacts. In this study the generic (not system specific) effects considered are the following:

- damaged unprotected distribution transformers and isolator flashovers,
- generator trips and distribution system insulator flashovers and punctures,
- failed electronics and control circuitry,
- auxiliary system failures due to motor insulation damage,
- MHD-EMP induced transformer saturation due to harmonics, and
- HEMP induced breaker misoperations.

The extent of system-wide implications of power system component failures has been the speculation of several efforts. In a recent paper [2], an effort was made to estimate the potential power system response to HEMP. Power system failures are characterized as follows:

- loss of system load due to flashovers on the distribution system;
- direct load losses from failed power electronics in motor drives and computer-based control technologies;
- failure of dc power sources for relays and control circuitry thus preventing some protective actions;
- failure of auxiliary systems in power plants;

- transformer overloads and trips due to excessive harmonics, reactive power, and phase current unbalances; and
- compounding of these failures from multiple HEMP events.

3.6.1 Power System Response

Power system failures can cause a variety of system responses. These include the following:

- complete shut down of the system,
- islanding of the system into small areas,
- voltage depressions, and
- local outages affecting small numbers of customers.

The degree of service disruption and degraded reliability depends on the overall state of the power system, the degree of interconnection of individual regions, the specific operating condition of the regions at the time of the event and the severity of the HEMP event. These issues will be addressed in some detail in subsequent sections to capture the very important point that a HEMP event will cause different effects on particular systems.

3.6.2 Power System Load Response

Load losses are caused by two different phenomena. One is the loss of the distribution system [2], while the other is the direct loss of loads that are connected to the distribution system like ASD powered motors. The former is less consequential because the power system's protection capability allows for quicker recovery and the actual damage to system components is easier to repair. The latter is largely unprotected and protracted recovery is likely to exist. In both cases, the initial system response to loss of load is similar; however, the recovery from the two events is very different.

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4. A QUALITATIVE ASSESSMENT OF THE VULNERABILITY OF ELECTRIC POWER SYSTEMS TO HIGH-ALTITUDE ELECTROMAGNETIC PULSE

4.1 INTRODUCTION

In an effort to portray the possible impacts of HEMP on electric power systems, two exposure models are considered. One model consists of representing the power system when exposed to a low level of HEMP including both E_1 and E_3 type effects simultaneously. Reliability models as represented in North American Electric Reliability Council (NERC) [1] are indicators of potential weaknesses in North America power systems and are good proxies for characterizing potential impacts from low level HEMP events. Power systems models for characterizing significant exposures to HEMP require alternative representations of the system including the separation of E_1 and E_3 effects. These alternative representations focus on the specific system properties in response to large amounts of E_1 and E_3.

4.2 SYSTEM RESPONSE MODEL TO LOW LEVELS OF HEMP EXPOSURE

When power systems are exposed to HEMP at light levels, the power system will be exposed to a few contingent events. System impacts are likely to behave in ways which are characterized by reliability data as collected and assembled NERC. Consequently, such data and information provide insight into potential power system responses and problems. Therefore, a study of effects on reliability of a light exposure to HEMP for North American power systems can be viewed from reviewing NERC reliability assessments of its regions as a barometer of potential problems.

Using the NERC analysis as a proxy, then potential reliability problems are those as determined by NERC which characterize the robustness of each region to conventional disturbances. Therefore, an understanding of current and future reliability issues and the factors influencing reliability goals of the NERC regions will provide insight into regional vulnerability.

Currently, the electric utility industry is influenced by forces which appear to be pushing power systems to limits of acceptable reliability. The economic-reliability balance, public policy disincentives, and the increasing pressure to accommodate nonutility entities or third party transactions are among those forces.

The economic-reliability equation is very complex but has a tremendous effect on the ability of an electric utility to survive a HEMP event or other system contingencies. Examples of several major equation elements are the following:

- operation closer to thermal, voltage, and stability limits to avoid new construction;
- reliance on economy transfers to avoid using more expensive local generation resources;
- reduction in maintenance to diminish operating costs;
- acquisition of nonutility generating capacity;
- addition of economic benefits via demand-side management;
- reliance on more specialized and complex monitoring, communication; and control equipment to provide economic benefits.

Each of these elements creates operating scenarios that are stressed and vulnerable to events like HEMP.

Public policy disincentives force electric utilities to operate in ways rarely experienced before. Such disincentives stem from regulatory forces that delay projects, which disallow the recovery of costs for reliability improvement, or that force premature retirement of facilities. All NERC regions have not faced such issues. Acid rain legislation typically results in lost generation capaçity and electromagnetic field (EMF) legislation results in lost transmission capacity which translates into smaller transmission reserves. These losses are often made up by the use of complex, highly automated technologies of advanced monitoring and control to carefully manage available resources. These technologies are in most cases more susceptible to HEMP events than the basic generation and transmission facilities themselves.

The growth of NUGs add new system elements that are often beyond the direct management and control of the utility. The attractiveness of wheeling, economy power transfers, or just general trends towards deregulation of the industry have all impacted system reliability by decreasing system flexibility and increasing management complexity. Transmission systems are undergoing increased stress. The addition of third party power can create operational phenomena that are difficult to predict, monitor, or control. Operational planning is more difficult because of hidden dynamics introduced by these new third party transactions. If HEMP system effects were added to any of these scenarios, the outcome would be an overall degradation in reliability.

One aspect of preparing electric power systems for HEMP events is transforming the system into a more robust state. Such initiatives may compromise the economics of operation in the short-run, but it can improve the electric power system's ability to absorb a stressful event. For example, off-loading of otherwise heavily loaded transmission facilities by terminating economy transfers or third party wheeling permits the import of emergency power. Such an emergency operating opportunity will reduce the vulnerability of the power system to a HEMP event. A broader initiative would suspend the critical pressures of competition brought on by deregulation that limit the capability of the systems. In this sense the industry may need to put in place emergency communication and coordination procedures specifically for HEMP type events. Formal understanding of the role NUGs should play in such a situation would be critical. Since NUGs are achieving significant increasing penetration levels in some of the NERC regions, they could play a major role in abating some disruptive effects of HEMP events because some could be stand alone generating sources.

4.2.1 NERC Reliability Issues

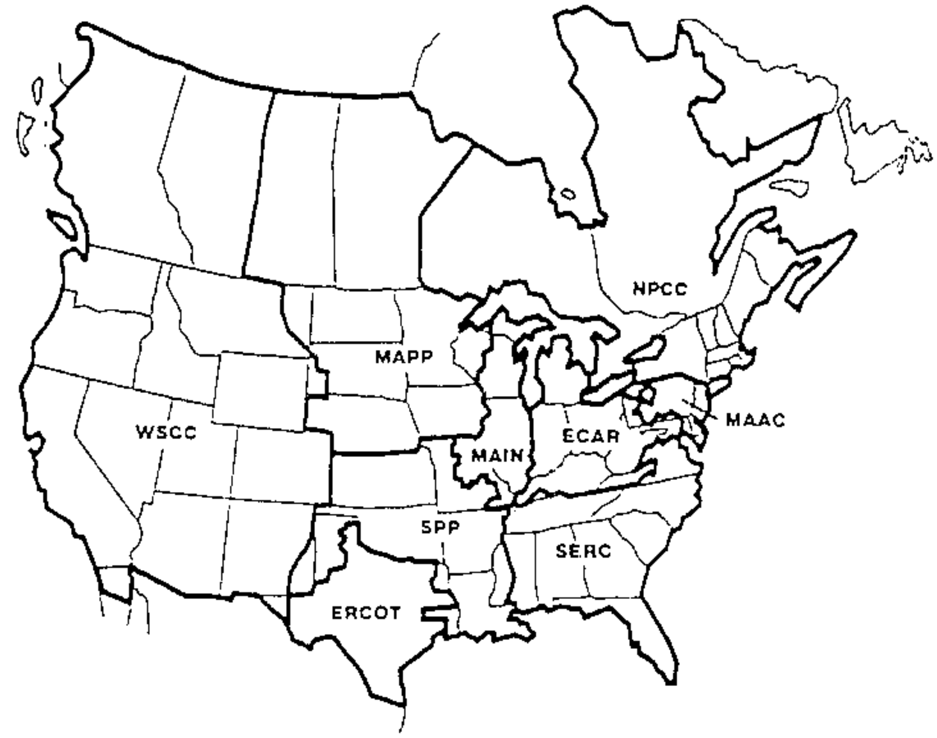
It is important to understand the current level of reliability and the forces that tend to degrade a system's ability to survive a contingent event. A discussion of NERC reliability issues and their reliability characteristics follows. Figure 4.1 defines and depicts the NERC regions.

The details of the NERC reliability criteria as well as the criteria for the operation of the interconnected system are outlined in references [1,2]. NERC rightfully expresses its concerns of reliability in terms of degradation in human comfort, safety, and lost productivity. The following are examples of unacceptable system reliability typically cited are:

- The 1965 northeast blackout that directly affected 30 million people and resulted in $100 million in economic loss.
- The 1989 geomagnetic storm that caused five transmission lines in Quebec to trip resulting in the loss of nearly 10,000 MW of generating capacity; the collapse of the Hydro-Quebec system; and finally, the interruption for up to 9 hours of almost 20,000 customers. This event typifies an E_3 event.
- The 1987,Tokyo, Japan blackout caused by voltage disturbances that affected nearly 3 million customers.
- The 1988 Buenos Aires generation shortage due to plant outages and insufficient hydro capacity due to a drought that threatened a city of 11 million people.

Except for the latter incident, the disruptions were caused by misoperation of protective systems or components, malfunctions or failures in transmission system equipment, equipment outages due to extreme weather events (lightning, geomagnetic storms), or the lack of adequate voltage control. These are very serious degradations in system reliability , likewise HEMP events could induce similar effects.

The literature on geomagnetic storms provides some very specific guidelines adopted by selected NERC regions to implement emergency operating procedures to dampen the



ECAR
East Central Area Reliability Coordination Agreement

ERCOT
Electric Reliability Council of Texas

MAAC
Mid-Atlantic Area Council

MAIN
Mid-America Interconnected Network

MAPP
Mid-Continent Area Power Pool

NPCC
Northeast Power Coordinating Council

SERC
Southeastern Electric Reliability Council

SPP
Southwest Power Pool

WSCC
Western Systems Coordinating Council

AFFILIATE

ASCC
Alaska Systems Coordinating Council

The North American Electric Reliability Council (NERC) was formed in 1968 by the electric utilities to promote the RELIABILITY of their generation and transmission systems. NERC consists of nine Regional Reliability Councils and one affiliate encompassing virtually all of the electric systems in the United States, Canada, and the northern portion of Baja California, Mexico.

RELIABILITY, in a bulk electric system, is the degree to which the performance of the elements of that system results in electricity being delivered to customers within accepted standards and in the amount desired. The degree of reliability may be measured by the frequency, duration, and magnitude of adverse effects on the electric supply (or service to customers).

Bulk electric system reliability can be addressed by considering two basic and functional aspects of the bulk electric system — adequacy and security.

ADEQUACY is the ability of the bulk electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and unscheduled outages of system components.

SECURITY is the ability of the bulk electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components.

Fig. 4.1 North American Electric Reliability Council.

disruptive effects of the associated induced quasi-dc currents. Specifically, NPCC [3] suggests that operators implement the following:

- discontinue maintenance work and restore out-of-service high voltage facilities such as transmission lines;
- control voltages to within an acceptable operating range to protect against voltage swings;
- adjust loading on HVDC circuits to be within the 40 - 90 percent range of normal rating;
- reduce generator loadings to provide reserve power and reactive capacity by adding additional capacity or curtailing load;
- prepare for the loss of shunt capacitor banks and VAR compensators;
- dispatch generation to manage system voltage, line loadings, and to distribute operating reserves;
- bring synchronous condenser capacity on-line if available; and
- coordinate with adjacent control areas.

Each of these "action items" result in moving the NPCC region into a more robust state to ensure a greater level of system reliability. This list, although not comprehensive, is typical of how most regions could prepare for a HEMP event.

The seriousness of a power system disturbance caused by HEMP depends on the fundamental robustness or weakness of the generation, transmission, and distribution systems. Generation system reliability depends on the following:

- planned capacity additions,
- regulating/licensing procedures and development,
- construction delays,
- environmental rules and regulations,
- operating reserve requirements,
- transmission transfers capability,
- capacity purchases and sales,

- performance of generation and transmission facilities,
- performance of NUG,
- demand projections, and
- load management strategies

Note that demand projections for the U.S. summer peak have a 2.5 to 3% error band. The effect on system reliability of the uncertainty in projected system demand could change the predicted effect of a HEMP event on a system because adequate generation capacity is one way of riding out major disturbances. Furthermore, the mix of capacity could have some effect on the vulnerability of the nation's generation system to survive a HEMP event. Some power generating facilities, like hydro are less vulnerable to restart. The projected (1997) NERC capacity in the United States is illustrated in Table 4.1.

Table 4.1. Projected U.S. generating capacity for 1997 in percentages

Fuel	Percent of total
Coal	41.6
Nuclear	14.4
Hydro	9.2
Oil/gas	27.6
Pumped storage	2.6
Other	0.6
NUG	4.0

The interconnected transmission system of the NERC regions (see Fig. 4.2), consists of four major interconnected areas: the Eastern Interconnection, the Western Interconnection, Texas Interconnection, and the Quebec Interconnection. These areas are interconnected by HVDC lines to allow for asynchronous operation of the individual interconnections. The flow of energy between interconnected areas can be more easily controlled with the HVDC links rather than by an alternating current transmission system. Within each of these interconnections, individual companies operate synchronously and are themselves interconnected with high voltage transmission lines which are obviously exposed to HEMP events. Note that this extensive degree of interconnection ties all systems together electrically. A HEMP event in any one of the NERC regions could propagate service disruptions into any other region. The bulk transmission system (230 kV and above) consists of almost 200,000 circuit miles of alternating current transmission lines and 1,500 circuit miles of dc transmission lines. Given the impact of HEMP on breakers, insulation, electronics, and line operation, the role the transmission system unreliability plays a major role in determining the magnitude of the disturbances induced by HEMP.

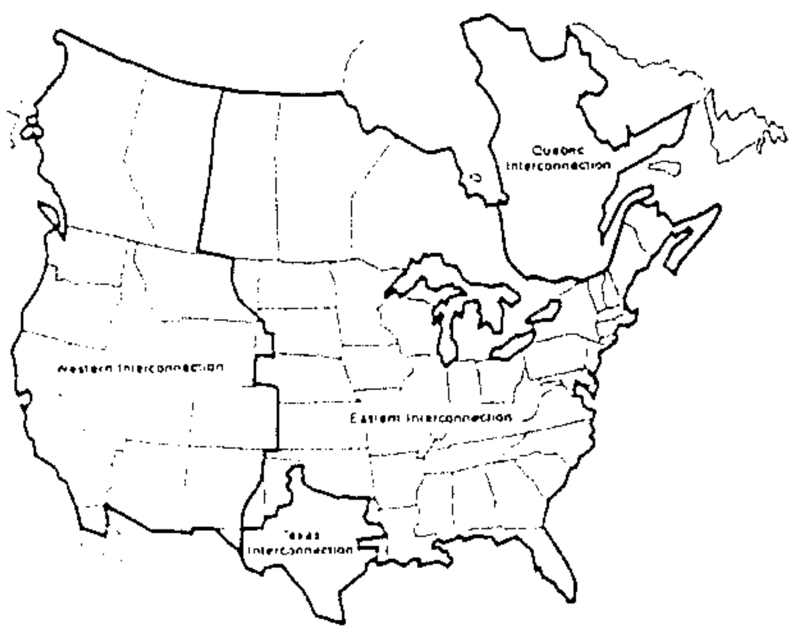


Fig. 4.2. Interconnections of the North American Electric Reliability Council.

The bulk transmission system plays a major role in overall NERC reliability. Note that ERCOT, MAAC, MAIN, and SERC are of major concern. Because of disincentives and delays in constructing new transmission facilities, their reliability is degraded due to limited simultaneous emergency transfer capability and continuously heavily loaded transmission facilities. A HEMP event that impacts the transmission system in these regions could cause major disruptions in service.

When putting into perspective the current uses of transmission in the modern electric power industry, the concern for reliability becomes even more pressing. Today's transmission systems are used for the following:

- delivering generation to load;
- providing flexibility for handling contingencies; and
- allowing sharing of generation among several utilities.

It is also critical to account for the increased complexity of system operations. This complexity can have an adverse effect on system reliability under normal circumstances and can greatly compound the reliability issue when a system is subjected to a HEMP event. It is becoming more difficult to operate systems within acceptable reliability boundaries even without HEMP. This fact is causing the electric utility industry to make improvements in system monitoring, data base management and exchange, communication of plans and procedures, on-line security analysis, joint studies, and more intensive operator training.

Particular operating issues affect the overall reliability of electric power systems. These include the following issues.

- Special protection systems of remedial action schemes for tripping loads, generation, or transmission facilities allow the operation of the system closer to its thermal and reliability limits.
- Parallel paths flow in interconnected systems and they are hard to detect and control.
- Voltage and stability limits that become more critical for heavily loaded transmission systems are difficult to monitor and control and usually involve the use of electronic equipment that may be susceptible to HEMP events.
- The addition of more central management capabilities would allow a reduction of system problems and increase the operators ability to control voltages,

power flows, and reactive power resources. Such control requires the use of more equipment and components that increase the power systems exposure to HEMP events.

- Increased communication and controls are needed to again enhance the operators ability to push the system closer to its limits to avoid or delay the construction of new facilities. Communication systems are vital to the operation of individual utilities. Whether the communication is powerline, radio, microwave, cable television, fiber optic or satellite, its complexity and vulnerability tends to compromise system reliability.
- Electronic motor controls have added immeasurably to the complexity and problems of system operation. By the year 2000, it is believed that 60% of motor loads will contain electronic control elements. In the HEMP environment such penetration of electronics can cause major system problems if the generation-load balance is severely altered.

Because HEMP can be regionally localized, it is beneficial to characterize the existing reliability of each NERC region. These bench mark measures the susceptibility of the region to disrupting events like HEMP and other disturbances.

ECAR region consists of 28 companies (19 systems) which serve all or part of the states of Michigan, Indiana, Kentucky, Ohio, West Virginia, Virginia, Pennsylvania, Maryland, and Tennessee. With peak demand of 79 GW and an installed capacity of 99 GW, its primary reliability threat is loss of 9,000 MW of generating capacity due to acid rain legislation. With 2,000 miles of 765 kV, over 850 miles of 500 kV, and nearly 12,000 miles of 345 kV and future expansion plans, their transmission system is deemed satisfactory.

ERCOT is comprised of 26 municipalities, 52 cooperatives, 6 investor-owned utilities, and 2 state agencies, and is totally within the state of Texas. Its peak demand is 42 GW with 54 GW of installed capacity. The reliability concerns in ERCOT are related to transmission wheeling, transmission construction delays due to EMF concerns and availability of natural gas on which they have a 40% dependence.

MAAC consists of 11 member systems and 5 associates. The region includes all of Delaware, the District of Columbia, major portions of Pennsylvania, New Jersey, and Maryland, and a small part of Virginia. Its projected peak demand is 43 GW with an installed capacity of 51 GW. The major reliability issues are low-generation reserve margins, heavily loaded transmission systems and construction delays, and loss of generation capacity due to environmental related legislation.

MAIN consists of 14 regular member systems. The region includes Illinois, the eastern two-thirds of Wisconsin, most of the upper peninsula of Michigan and, eastern Missouri. The summer peak demand is 39 GW and the installed capacity is 49 GW. Acid-rain legislation could reduce available capacity as could air quality standards. Reliability could be jeopardized by demand growth higher than forecasted, capability of manufacturers to supply gas turbines for low-capital cost, short lead-time orders, and competition. Transmission system is deemed adequate.

MAPP membership includes 43 systems consisting of 11 investor-owned, 8 generation and transmission cooperatives, 3 public power districts, 4 municipal systems, and 1 federal agency. The associate participants consist of 2 Canadian Crown Corporations, 13 municipals, and 1 investor-owned system. Its projected peak demand is 25 GW with an installed capacity of 31 GW. The region consists of all or part of Iowa, Minnesota, Nebraska, North Dakota, Illinois, Michigan, Montana, South Dakota, and Wisconsin, and the provinces of Manitoba and Saskatchewan. The main reliability issues are acid rain legislation threatening 8000 MW (35%) of their generating capacity, EMF regulations affecting transmission system operation, and increased use of transmission capacity for exchange agreements, purchases, etc., peak demand growth exceeding forecasts.

NPCC/US represents 23 investor and publicly owned utilities covering the region consisting of northeastern United States and eastern Canada. NPCC members participate in the New York Power Pool and the New England Power Pool. Its projected peak demand is 47 GW with 57 GW of installed capacity. Its major reliability concerns include the need for more generation capacity in New England. Significant reliance on load management is also a concern. To meet projected demands a heavy reliance on NUG capacity is envisioned, 42% in New York and 20% in New England.

SERC members include 29 systems in the southeastern United States. The region is divided into four diverse subregions and includes Florida, Southern Company, Tennessee Valley Authority, and the Virginia-Carolina area. Its projected peak demand is 122 GW with an installed capacity of 145 GW. The major reliability issues are transmission wheeling, compliance of NUG's to reliability criteria and environmental EMF issues that could compromise transmission projects.

SPP includes 43 electric power suppliers serving Kansas, Oklahoma, Missouri, Arkansas, Mississippi, Louisiana, Texas, and New Mexico. Its projected peak demand is 51 GW with and an installed capacity of 67 GW. Their major reliability concerns are the timely completion of NUG's and purchased power arrangements. Acid rain legislation is particularly because since 55% of the predicted capacity will be coal-fired.

WSCC consists of 62 member systems and 3 affiliates in 14 Western States, 2 Canadian provinces, and the northern portion of Baja, California. The region has two distinctly different areas: Northwest Power Pool area, and the California-Southern Nevada Power Area. Its projected peak demand is 92 GW with installed capacity of 126 GW. Their major reliability concerns are deregulation and increased competition leading to increase use of transmission facilities with resulting reductions in operating margins. Increased competition reduces communication and coordination that is deemed vital to maintain an adequate level of reliability. Economics versus reliability could compromise reliability by increasing utilization of facilities. Because NUGs account for 34% of WSCC's planned net resources, there is concern about their dedication to preserving existing high standards of reliability. Parallel path flows jeopardize reliability because they are difficult to monitor and control.

From the previous descriptions of the individual NERC regions and their existing reliability concerns, HEMP initiated disturbances will impact reliability differently in each. Those regions that tend to rely more heavily on complex systems to operate the generation and transmission systems at the edge of their capabilities are particularly vulnerable to the known impacts of HEMP events. This vulnerability could be further compounded by lack of adequate reserves stemming from environmental legislation, economic priorities, strained coordination and communication procedures resulting from deregulation and competition, and a high-density, electric-energy-dependent population mix. Regions populated by large cities heavily dependent on electric energy to provide for the safety and well-being of its citizenry will find a disabling event much more disruptive than a region in which loss of service is categorized as an inconvenience.

4.2.2 Assessment Approach

Because little or no data exist to support a rigorous numerical reliability analysis of various HEMP scenarios, knowledge of industry operation and published data have been used to construct potential problem scenarios. These projections could be improved through interviewing the NERC staff.

A simple model has been constructed to characterize electric power system response to HEMP. The model is based on the March 13, 1989, geomagnetic storm that disrupted service in the MAAC and NPCC regions that cover the northeastern part of the United States and eastern Canada. The profile of the combined area and associated system effects of the storm are summarized in Table 4.2. The model profiles the system characteristics, recognizes basic reliability concerns, and states the system response due to the geomagnetic storm.

Table 4.2. MAAC and NPCC combined system with geomagnetic storm effects

Profile	
Installed cap	169,000 MW
Summer peak demand	126,000 MW
Energy served	775,000 GWH
Population	65.0 million
Customers	26.7 million
Area	1,048,700 Mil
Circuit miles of HVT	43,700 Mil

Reliability concerns
high-growth rates extensive use of NUGs transfer capability limits coordination complexities construction problems

System effects
Voltage fluctuations/alarms
Negative sequence/alarms
Phase imbalance/alarms
Underfrequency load shedding
Overcurrent in neutrals/trips SVAR compensators High voltage lines Capacitor banks Plants Transformers

In simple terms, the reliability indicators for the period covering the storm are as follows:

- Load not supplied is 17,500 MW.
- Energy not served is 157 GWH.
- Loss of load duration is for 9 hours.

Putting these indicators in perspective, they represent about 10% of the installed capacity of the combined regions, approximately 0.2% of the annual energy served and an annualized availability of 0.9998. Recognizing that the major portion of the disruption occurred in the Hydro-Quebec service area, the number of customers affected would be 4 to 6 million people. Computing a familiar index of reliability, the loss of load expectation, would be approximately 0.001, which is calculated from the aforementioned indicators. The usual interpretations of the index reflect that on average only 0.1% of the time will outages occur due to a geomagnetic storm.

In this example, data exist to help quantify the impact of a geomagnetic storm. In the case of HEMP, no events exist to provide data, and thus, the following generic system effects used:

- damaged distribution transformers and isolated flashovers,
- generator trips,
- failed electronics and control circuitry,
- auxiliary system failures due to motor insulation damage,
- MHD-EMP induced saturation in power transformers and CTs, and
- MHD-EMP induced breaker misoperations.

4.3 SYSTEM IMPACTS OF A LARGE HIGH-ALTITUDE ELECTROMAGNETIC PULSE DISTURBANCE

Electric systems respond very differently under a major HEMP disturbance than the low level events described previously. A large event significantly disrupts the equilibrium state of the power system and imposes near, if not, catastrophic effects on the power system. Modeling the power system under such conditions requires separating E_1 and E_3 effects.

4.3.1 Major E_1 Event

The primary effect of a major E_1 event is to significantly affect the distribution system (flashovers) and power electronic driven loads. The principal effect is to remove significant load from the system thereby causing major stability problems. The power system response is relegated to one involving an acceleration of system frequency due to loss of load and all the consequences following such an event. Typically, generator tripping (overspeed), followed by line tripping, islanding, and likely system failure. The amount North American power system that will be affected by the disturbance is directly related to the area of exposure. All NERC regions will have equal susceptibility.

4.3.2 Major E_3 Event

The primary effect of a major E_3 event is to cause system voltage to collapse as a result of excess reactive power on the system due to power transformer magnetic core saturation. Secondary problems include harmonic problems, relay misoperation, and static VAR compensator failure. The power system is doomed to failure from an inability to manage voltage and reactive power problems. E_3 is coupled to the power system via transmission lines. Areas of the country with long transmission lines are more susceptible to E_3 disturbances; however, a large disturbance could affect any area of the country.

4.4 ASSESSMENT SUMMARY

The lack of data and a thorough quantitative understanding of HEMP and its system related effects makes a comprehensive analytical assessment of North America power systems impossible. The study has focused on generalized system effects in the context of each of the regions' existing reliability characteristics. Capacity shortages, complex system operation, exposure, population density, geographical location, etc., have been considered in making quantitative statements about a given region's susceptibility to HEMP events. In general, it is clear that MHD-EMP events that induce dc currents are capable of degrading system reliability and damaging equipment. It is less obvious what the specific effects of E_1 events might be because it is not known how each region would respond to SFSD transient electric fields. The experimental data available is component specific and far from comprehensive. Reliability analysis, however, requires system-wide information including reliability models for all components to be included in the analysis, none of which exist at this time. However, if E_1 cause widespread flashovers in the distribution system resulting in significant loss of load (40% greater), it is likely a major blackout will occur.

4.5 REFERENCES

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2. NERC Operating Manual, published by NERC, February, 1991.

3. System Operation Guidelines During Geomagnetic Storms, J. Z. Ponder, IEEE PES, Panel Session, July 17, 1990.

5. POWER SYSTEM OPERATIONS - EMERGENCY PLANNING AND THE RESTORATION PROCESS

5.1 OPERATING REQUIREMENTS

Modern electric power systems are interconnected; extremely complex; and utilize modern computing, communications, and control technology for reliable operation. Many thousands of distributed data points are monitored and controlled from central and regional Energy Management Centers (EMC) via wide area communication links. Monitored values are transferred from the remote or field located equipment, substations, power plants, etc., to the EMC within seconds where the data are managed to sustain a smoothly operable system configuration. The overall performance is dependent on the systematic processing of information (real-time operation) and the execution of mutual agreements and covenants (contracts for power) among the electric power entities.

5.1.1 Basic Power System Operation

U.S. and Canadian electric interconnected power systems operate per criteria as established by guidelines of the Operating Committee (OC) of the NERC. The reliability criteria [1] promotes the reliable operation of the interconnected electric systems in North America through the criteria and guides, and the OC provides a forum for the coordination of interconnected operation. These objectives are achieved through voluntary compliance by participating utilities. The electric utility industry recognizes the need, and accepts the responsibility, to operate in a manner that will enhance interconnected operation and not burden other interconnected systems.

Reliability in the operating environment is dubbed as power system security. Security is concerned with the short term use of available resources and is a measure of the ability of the power system to respond to a contingency list of mishaps. Sufficient operating reserve the power system to respond to a contingency list of mishaps. Sufficient operating reserve is maintained to account for the loss of the largest unit plus some additional contingency.

Elements of security include the following [1]:

- management of real and reactive power resources,
- operation of the transmission system within limits,
- coordination of relays,
- monitoring of interconnection parameters,
- information exchange on system conditions with neighboring utilities or control areas, and
- coordination of maintenance.

Electric power systems are characterized by the term "state," which categorizes the system's security. The states include: normal, alert, emergency, and restorative.

Normal operation represents the system as "business as usual." During normal operations the EMC acquires data on system status, directs the use of generators and transmission, conducts forecasts, and manages interchanges with neighboring utilities. The primary objective is to meet load requirements through dispatch of all resources including generation scheduling, interconnected economy power, and load management.

As system conditions translate into that of reduced security, or the alert state, preparatory actions are initiated. An alert state may be a direct result of some contingent condition on the system (failed transmission line, loss of generating, etc.), or it could be anticipation of a potentially disruptive event (earthquake, storms, solar disturbance, EMP, etc.). Under such conditions the following become candidate actions:

- postpone maintenance on generation and if feasible, place any idle combustion turbines on turning gear;
- curtail daily and monthly supplemental power to industrial customers;
- curtail interruptible loads in accordance with availability and need,

- curtail emergency deliveries to neighboring companies,
- redispatch generation, and
- reduce transmission system loading.

An emergency state defines crisis. The system security has been compromised; that is, firm system load cannot be satisfied. Under such conditions, actions are initiated to secure the system and prepare to restore lost load. Such actions might include the following:

- request assistance from neighbors,
- curtail any utility wheeling transactions,
- peak load combustion turbines and curtail any remaining interruptible,
- exercise all load management equipment in the event of a sudden emergency,
- override environmental generation curtailment,
- implement in-house load reduction,
- implement public appeal for voluntary load reduction,
- curtail energy exchange deliveries, and
- implement firm industrial and interchange load curtailment.

The restorative state defines the operable actions to return the power system to normal following a disruption. The initial steps may only ease the crisis, not remove it. Often a sequence of steps are taken to return the system to normal by first restoring firm load.

In the event of an emergency, the power system is poised to respond. Several automated transactions will initiate with preservation of the system as its fundamental objective. The following actions occur:

- Automatic generation control is in operation to manage control area generation supply to match load.
- The supervisory control and data acquisition (SCADA) system monitors delivery system performance.
- Load management systems are on automatic.
- Person-to-person communication via telephone is initiated.

- Coordinated under-frequency protection is available to reduce load to match available generation during an emergency.
- Generating unit protection is provided for overspeed to protect the unit but is not coordinated with the system protection plan. Once generators trip the under frequency plan will respond.
- Voltage and VAR protection may trip lines and transformers.

5.1.2 Operational Strategies for HEMP Disturbances

A number of prudent operational strategies can be developed to reduce the vulnerability of electric power systems to widespread failures resulting from HEMP events. The consequences of several of these actions are largely economical causing difficulty in achieving the consent and cooperation of the electric utility industry. Establishing a priority for alternative operational strategies will require special agreements to be struck between the electric utility industry and the U.S. government. Presently, the electric utility industry does not subscribe to the concepts that HEMP events are a primary concern. Consequently, the willingness to invest in new and potentially costly operating strategies is unlikely.

There is no overall governmental policy that establishes requirements and standards for EMP hardening of commercial electric power systems. Policies for hardening of power facilities at government facilities reflect the requirements of individual programs, agencies, and departments, and the standards vary among particular applications. The specifics on many government programs are classified and thus are not available to commercial power users.

A HEMP event will certainly invoke power outages across significant areas of U.S. power systems and prompt the use of emergency systems. Any prudent operational strategy will rely on positioning the power system during pre-HEMP events to facilitate and expedite post event recovery. Such initiatives will reduce electric system disruption.

Although explicit operating plans have not been derived for HEMP disturbances, some insight is available as to how the electric utility industry could prepare for such an event, at least from an operations standpoint. Plans [2] have been constructed by some utilities to prepared for geomagnetic storms, an E_3-like event. These operating guidelines cover several broad topics which include the following:

- operations planning,
- operations procedures, and
- transformer damage mitigation.

Of the utilities and the NERC regions reporting [2], several common features appeared in their respective plans:

- establish that a problem exists; that is, confirm a high level of activity for solar disturbances;
- monitor unusual activity in transformers, including increases in reactive power consumption and increases in hydrogen gas production that are associated with the presence of dc or harmonics;
- monitor system performance where voltage limits are attained;
- observe strict operating limits on HVDC schemes;
- observe relay operations relative to neutral current flows;
- evaluate capacitor bank performance;
- provide for wider operating margins on transmission lines; and
- operate the system conservatively.

These particular measures respond to potential technical problems that could emerge during geomagnetic storms and would be helpful for some E_3 events.

Each of these action items results in moving the power system into a more robust state, to ensure a greater level of system reliability. This approach is indicative of preventative actions that can be employed to improve the security of their system, reduce vulnerability to failure, and expedite post event recovery.

5.2 LOAD-GENERATION MISMATCHES

Depending upon the size, number, and location, HEMP events can be expected to have major disruptive effects on electricity-using processes, equipment, and appliances. This is likely to cause severe load-generation mismatches in power system islands, especially for those systems that have generation remote from non-HEMP-affected loads. The resultant power system disruptions have the potential to be widespread and difficult to correct.

An electric power system's response to a major disruption is often to break into "islands" in an attempt to contain the damage/blackout. As generation is lost, the frequency declines, and load is shed automatically. If too much load is shed, generators operate in a potentially damaging mode ("overspeed"), and to protect them, they are shut down automatically. The overspeed trip protection is not coordinated with system protection, rather it is designed to protect the plant only. This further reduction in generating capacity leads to more load shedding [3]. In many major blackouts, this cycle of load shed-generation trip-load shed, etc., caused by mismatch of load (demand) and on-line generation has continued uncontrollably until major areas are without power.

HEMP-induced disturbances can be expected to have similar effects. Indeed, because HEMP may directly knock out significant blocks of load, generator trips due to overspeed operation may occur even if the power system generators are not markedly affected by the initial HEMP incident.

Southern California Edison has also found system problems when circuits where there is a high saturation of single-phase A/C experience a "voltage dip." The A/Cs may stall, creating a high inrush current that could cause ground fault relays to trip [4]. This phenomenon would worsen the load-generation imbalance.

Geographic imbalances of load and generation may also accentuate the problem. Generation situated close to industrial areas may find itself suddenly without load as industrial processes are stopped (suddenly or voluntarily). Areas of the country importing large amounts of power (e.g., California importing power from the northwest) may find large load centers isolated from generating centers if transmission lines are put out of service.

Computer-controlled loads and processes (powered by switching power supplies), motor-based loads, and solid-state loads into which RF pulses can be transmitted are among the most potentially vulnerable. Any type of load is subject to loss where distribution system failures occur.

Within the scope of this study, the magnitude of the mismatch or possible blackout cannot be estimated; however, the failure modes are clear.

5.3 COMMUNICATIONS

Electric utilities and communication companies are dependent upon one another for quality system operation. Electric power is essential to operate communication systems and electric utilities require the use of communication systems. Following an electric power system disruption, high priority is placed on its communication needs to restore service to interrupted customers. Recent experience by utilities in power system restoration indicates that communication problems rate at or near the top of their list of major concerns.

Electric utilities use a variety of communication technologies to monitor and control the power system. They include company-owned and leased telephone lines, microwave systems, fiber optic links, radio, and power line carrier. A majority of utilities rely heavily on leased communication lines from the local telephone company, both voice and data communication.

Telephone companies have backup supply capability to support their operations following an outage or natural disaster. This includes batteries and generators with fuel reserves that are adequate for extended periods. Following an EMP event, public telephone systems (PTS) may be overloaded and unavailable due to a major increase in the public's use of telephones. This means that the utility's wide area communication links, a majority of which are leased from the telephone company, may not be capable of supporting the data traffic for monitoring and controlling the power system.

Several studies of PTS have been conducted under the influence of EMP. PTS have been shown to exhibit a degree of survivability [5,6], that is, the equipment and systems tested did not suffer significant permanent damage when exposed to simulated HEMP free-field illuminations but upsets did occur that caused the systems to become inoperativeable for a period of time. The technologies in PTSs are constantly evolving. The addition of fiber optics lessens the vulnerability of the links but does introduce new potentially vulnerable electro-optics technologies. One study [6] shows the impact of introducing computer controlled switches to replace older manual or mechanical switches. Findings indicate that these systems are more susceptible to transient interference. In most cases, the systems returned to normal or near normal operation in 30 to 80 min.

Of critical importance are the wide-area links between the EMC and the field located equipment and personnel; that is, leased lines, company owned lines, microwave lines, etc. Microwave links consist of parabolic antennas mounted on towers that send a beam to another antenna tens of kilometers away. Microwave propagation is affected by thunderstorms and other atmospheric phenomena. Loss of one or more towers would reduce communication on the link. While the communication protocol would automatically reroute messages to keep the communication system operating, transient sensitive modems, multiplexers, codes that are based on large-scale integrated (LSI) technology may be impaired resulting in significant communication problems.

Fiber optic links consist of optical transmitters, optical receivers (photodiodes), and signal regenerators. The fibers themselves are not affected by power line surges, EM interference, or corrosive chemicals in the air, hence their use in harsh environments is desirable. However, such links are vulnerable to a HEMP event because the transmitters, receivers, and repeaters use LSI technology.

Radio communications are an important aspect of electric power system operations as well. During restoration and normal operations, communication between the EMC and field operations is critical. Much of this communication is by radio. Cellular telephones have also found increasing importance in recent years, a radio-based technology. Radio communications have been shown to be vulnerable to HEMP [7]. The radio element of greatest exposure is the locally remote control console without transient protection. Radio systems can have significantly less HEMP exposure by the use of rather simple, low-cost surge protection [7].

5.4 CASE STUDIES OF OPERATING PROBLEMS

From most investigations of HEMP impacts on electric systems, the precise consequences in terms of system failure remains unknown. A load flow system study [8] has been conducted o Arizona Public Service for a projected loss of system components from an E_3 event. This study documented voltage depression at selected points in the system. Simulation studies of other utility systems will portray a system response for the particular event. Although, none of these cases offer a general understanding of a power system's response to a HEMP disturbance.

Tables 5.1, 5.2, and 5.3 provide a perspective on power system response for varying degrees of system failure. Three levels of failure and a typical system response are presented. The consequences are summarized as follows:

- Most electric systems can absorb a 10 to 15% loss of capability and survive.
- A 15 to 25% loss of capability can cause blackouts and islanding.
- When loss of capability reaches the 35 to 40% plateau, complete system shutdown is likely.

Table 5.1. Power system response to a low level E_1 and E_3 event

Effects
Insulator failures at distribution voltage; Unprotected distribution and power transformers damaged; Electronic control equipment damaged; Low voltage motors damaged; Circuit breakers serving generating plants, substations, and distribution loads trip; and Communications damaged.
System impact
Local power failures possible, System load loss 10 to 25%, Line interruptions 15%, Generation loss 15%, and Concerns about system security.
Restoration
Assess damage; Establish priorities; Coordinate manpower, material, and equipment; Provide up-to-date operating procedures, drawings, phasing diagrams, etc.; Arrange for meals and lodging for emergency repair crews; Provide for adequate communications; Provide public information; and Arrange for good logging, reporting, and notification of emergency management agencies.

Table 5.2. Power system response to several E_1 and E_3 events

Effects
Insulator failures at distribution voltage; Unprotected distribution and power transformers damaged; Electronic control equipment damaged; Low-voltage motors damaged; Circuit breakers serving generation plants, substations, and distribution loads trip; and Communications damaged.
System impact
Some power failures probable, System load loss 25 to 40%, Line interruptions 30%, Generation loss 30%, System security at risk, Underfrequency of underfrequency relaying (usually in the range of 59.7 to 58.5 Hz) will probably control frequency, Loss of generation requiring black start possible, Help from other utilities probably not available, Islanding is possible, and Overfrequency could occur.
Restoration
Assess damage; Establish priorities; Coordinate manpower, material, and equipment; Provide up-to-date operating procedures, drawings, phasing diagrams, etc.; Arrange for meals and lodging for emergency repair crews; Provide for adequate communications; Provide public information; Arrange for good logging, reporting, and notification of emergency management agencies; Provide for manual frequency control if necessary; and Provide for black start of generating facilities.

Table 5.3. Power system response to multiple events of E_1 and E_3

Effects
Insulator failures at distribution voltage; Unprotected distribution and power transformers damaged; Electronic control equipment damaged; Low voltage motors damaged; Circuit breakers serving generation plants, substations, and distribution loads trip; and Communications damaged.
System impact
Major power failures certain, System load loss over 40%, Line interruptions over 30%, Generation loss over 30%, System security severely degraded, Islanding probable, Underfrequency and/or overfrequency conditions, Operation of underfrequency relaying will not control frequency, Loss of generation requiring black start probable, Help from other utilities will not be available, and Black start problems will result.
Restoration
Assess damage; Establish priorities; Coordinate manpower, material and equipment; Provide up-to-date operating procedures, drawings, phasing diagrams, etc.; Arrange for meals and lodging for emergency repair crews; Provide for adequate communications; Provide public information; Arrange for good logging, reporting, and notification of emergency management agencies; Provide for black start of generating facilities; and Provide for manual control of frequency.

5.5 AN APPROACH TO EMERGENCY PREPAREDNESS

Establishing an overall approach to emergency planning, including HEMP events for widespread blackout and restoration, is an essential action for all electric utilities. It is prudent to assume that any given site such as a generation station, substation, or EMC could be without off-site power for a duration of several days. Therefore, emergency on-site backup power must be provided for essential facilities.

Restoration of the power system will be a primary objective following a HEMP event. There are two key aspects of preparing for restoration: (1) establishing an infrastructure to carry-out restoration, and (2) restoring the physical well-being of the power system. Both aspects require careful planning if they are to account for the unique attributes of HEMP.

A general approach to emergency preparedness is as follows:

- A first step is a set of existing emergency plans for normal contingent power system failures and major disruptions due to weather or environmental induced disasters.
- Formulation of auxiliary plans to cover unique aspects of HEMP events are required. This includes such items as the following:
    - failures of dc circuits to prevent access to dc power supplies;
    - inability to reconnect system loads where motor drive and other electronic controls have failed;
    - potential minor damage to the distribution system;
    - unavailability of neighboring power systems, a key element in most emergency plans;
    - population panic resulting in not having access to utility personnel;
    - congested transportation roadways to prevent free movement of repair crews;
    - possible failure of repair trucks and equipment due to failed electronic components; and

impaired communications.

Provide testing of planned emergency procedures to ensure their effectiveness.

Emergency procedures are in place to mobilize supporting infrastructures from Federal Emergency Management Administration (FEMA) at the federal level and civil defense at the state and local level. These organizations provide food, shelter, fuel, and some communication to the recovery teams and the affected population. In recent disasters, the U.S. military has provided some of the quickest and most effective relief. The role of the military in restoring electric power requires some careful review, especially under the circumstances of a HEMP event.

In 1988 a new public law, the Robert T. Stafford Disaster Relief and Emergency Assistance Act, Public Law 92-388, provided authority for the federal government to respond to natural disasters and other incidents to provide assistance. The Federal Response Plan [9], hereafter referred to as The Plan, describes the basic mechanisms and structures by which the federal government will mobilize resources and conduct activities to augment state and local response efforts. The Plan applies to all federal government departments and agencies that are tasked to provide assistance in an emergency situation. The participating departments and agencies along with their assignments are shown in Table 5.4. FEMA has the responsibility to direct the federal effort.

Two areas of impact by HEMP are communications and transportation, and each is an essential part of recovery. Following a HEMP event, trouble shooting crews will need to go to the field for manual restart of equipment. A report [10] indicates that upsets in the electronics of some vehicles will result. The extent of such damage is not established. Additional testing of modern automobiles and trucks is required to understand the complete

Table 5.4. Emergency support function assignment matrix

#	1	2	3	4	5	6	7	8	9	10	11	12
ESF / ORG	TRANSPORTATION	COMMUNICATIONS	PUBLIC WORKS AND ENGINEERING	FIREFIGHTING	INFORMATION AND PLANNING	MASS CARE	RESOURCE SUPPORT	HEALTH AND MEDICAL SERVICES	URBAN SEARCH AND RESCUE	HAZARDOUS MATERIALS	FOOD	ENERGY
USDA	S	S	S	P	S	S	S	S	S	S	P	S
DOC		S	S	S	S	S	S			S		
DOD	S	S	S	S	S	S	S	S	P	S	S	S
DOEd					S							
DOE	S		S		S		S			S		P
DHHS			S		S	S	S	P	S	S	S	
DHUD						S						
DOI		S	S	S	S					S		
DOJ					S		S	S		S		
DOL			S				S		S	S		
DOS	S									S		S
DOT	P	S	S		S		S	S	S	S	S	S
TREAS					S							
VA						S	S	S	S			
ARC					S	P		S				
EPA			S		S			S	S	P	S	
FCC		S										
FEMA		S		S	P	S	S	S	S	S	S	
GSA	S	S	S		S	S	P	S	S			S
ICC	S											
NASA					S							
NCS		P			S		S	S				S
NRC					S					S		S
OFDA								S	S			
OPM							S					
TVA	S		S									S
USACE	S		P	S	S	S		S	S			S
USPS	S					S		S				

P - Primary Agency: Responsible for Management of the ESF
S - Support Agency: Responsible for Supporting the Primary Agency

impact on vehicles. If automobiles are subject to HEMP failure, then a more significant problem exists with potential clogged roadway with stalled cars. The impact on communications has been previously noted. A supplemental form of communication is accessible through "Ham" radio operators. In other disasters, this source of communication has been demonstrated as a valuable resource. Preparing for unique communication and transportation problems is an essential part of HEMP readiness.

In previous national disasters, electric utilities have been left to manage their own restoration process. FEMA has provided some technical assistance. Two potential problems exist under a HEMP-type disturbance condition. First, early warning could panic personnel into leaving their posts to return to their families. This could seriously endanger the power system due to poor execution of preparedness needs. This could define a role for military operations. Second, a large geographic power system disturbance could result in significant confusion due to coordinating problems among utilities regarding prioritization of resources. No central organization is in place to coordinate regional (at the Reliability Council level) or national resources to prioritize the reestablishment of the nation's power system. NERC infrastructure is primarily a planning function, not an operational one; however, establishment of active committee for this purpose could be achieved, perhaps through the operating committee.

As an example of the need for formal plans to manage electric power during disasters, as recent as this year, power distributors of the TVA have prepared their first formal emergency plan [11]. This document sets lines of authority to rescue the distribution systems of TVA power distributors following a major disruption. Past experience has shown a lack of formal preparation.

Technical knowledge to reassemble the power system is available. The key issue is a plan to prioritize and mobilize available resources. The emphasis in this report is to prepare for restoration under the unique properties of HEMP.

In a major large area power outage ready access to neighboring utilities, a fundamental property of electric emergency preparedness, will be absent. Each utility will likely need to care for its own needs, that is, do not count on its neighbor. This is a unique attribute of a HEMP-caused power system disruption. Coordination among utilities could likely be confusing. Each utility should be prepared to work in isolation.

5.6 WARNING TIME TO GROUND ZERO

Warning time before a HEMP event can play a key role in minimizing consequential outcomes. The warning time can be classified in the following three distinct periods:

- no warning, a spontaneous event,
- a 30 to 60 minute notice, or
- advanced notice of 1 to 3 d.

Each employs alternative awareness and consequential outcomes. Notice of a HEMP event, or suspected event will significantly reduce the consequences, if plans are available for implementation.

Under the no warning scenario, a basic response plan must be in place. This response plan must contain special preparations for unique properties of HEMP events that are not characteristic of other emergencies like weather events. Foremost, the ability to operate in isolation must exist because neighboring utilities will likely be unavailable to assist.

Acquiring time through early warning, even 30 to 60 min is very valuable. This time frame would permit early notification of emergency response teams. Depending upon power system conditions, some T&D lines could be removed from service and some generation facilities could be isolated from the wye-connected transmission system.

If warning extends into 1 to 3 d, a best operating scenario can be established that will reduce consequences to a minimum. For example, emergency disaster response teams could be completely prepared such as having emergency fuel in temporary supply tanks, equipment and material located, and a review of all emergency procedures conducted. Foremost, certain transmission and distribution lines and generating facilities could be secured as well as arranging facilities for ready service immediately following the event as needed.

Particular actions might include the following:

- prepare combustion turbines;
- fill pumped-storage facilities;
- prepare hydro-stations, renewable generating station, other systems where self starting is feasible;
- preload bunkers at coal plants;
- position for recovery through maximizing post-event actions; and
- recall key personnel who may be away.

5.7 SPARES

A critical part of power system recovery following a HEMP event will be the availability of replacement equipment. Of all components in the power system, it would appear that transformers could have the most exposure, although insulators also have a high degree of risk. On the load side of the system, power electronic-motor-drive equipment is most vulnerable.

Transformers have potential failure modes due to overcurrents from harmonic imbalance, reactive power, and fault current. Because protective systems could misoperate, the current overloads could occur unexpectedly. Each utility should maintain limited inventory of available transformers within its organization.

Other power system components like insulators, relays, circuit breakers, etc., could be in short supply. Identifying and locating these spare parts is significant as well.

Perhaps the most difficult problem to address with spares is failed electronic components. Since the addition of power electronics in motor drives, the ability to "repair loads" becomes critical. No clear initiatives appear appropriate to alleviate this problem except prevention of failure through protection.

Following a HEMP event, neighboring utilities are an unlikely source of spare equipment. Some form of national priority is required to properly allocate scarce resources like transformers. A few years ago, DOE's Emergency Preparedness Group began to explore the availability of spare parts. Such a task could lead to a national data base to inventory space parts (transformers in particular). Central management of spare parts could be a vital part of a national recovery plan.

5.8 SHUTDOWN AND START UP

As the power system moves between the alert and emergency states, preparations for shutdown and restart become a primary goal in power systems operations. Under emergency conditions, focus is on stabilizing the system and preparing for restoration of full electric supply to lost firm load. To meet these objectives, system resources must be managed from both a shutdown and a restart basis. If area power is available then a routine restart is available; however, should the complete system be lost, then a black start situation exists.

Because system recovery is a key feature to an effective response to a HEMP event, transition into and out of a failed electric system is critical. Two phenomena characterized as black stop and black start describe circumstances for surviving critical power system events under a loss of station power and restarting the power system after failure respectively. Under black stop, turning gear motors in selected large power plants remain operational to prevent generator shafts from warping and bending. Oil pumps are sustained to provide bearing lubrication. Nuclear power plants are among the most prepared system component for safe shutdown. Black start is facilitated by good black stop planning and the establishment of systematic procedures for restarting a power system from a dead state.

Identifying key power plants, transmission and distribution links, and loads will facilitate power system restoration.

While a utility organization performs many activities simultaneously to begin the task of restoring the power system, none is more important than its black start capability. A vast majority of utilities do not require external power to restore their power system. Instead, utilities have designated units, black start units, that are specifically configured and retrofitted to provide the power needed to start other power plants. These units are generally thought to be combustion turbines, diesels, hydro, and pumped hydro plants that have small capacity units.

Black start units are typically started on site by plant operations staff rather than remotely by the EMC system or other means. The operating status of these units is very important and is reported to the EMC by voice and data communication links.

Black start units are started by several techniques, depending on the unit's design. Combustion turbines are started by compressed air released into the turbine. A back-up battery system powers the unit's monitor and control system, and the control room lights and other equipment. Hydro and diesel units also require battery supply systems to support their monitor and control systems. Larger units, for example fossil-fueled black start units, have diesels or combustion turbines to supply cranking power to their auxiliaries, for example feedwater pumps, pulverizer, etc. Approximately 40% of the utilities have on the order of 25 to 50% of their power plants equipped with cranking units to start the auxiliaries of main units in the plant [12].

Black start capability does receive good attention by many utilities. A recent survey [13] of international utilities indicates that understanding black start requirement is a high priority. To have good black start capability, modeling and simulation of situations under the operations planning function is considered essential. Problems of key concern for black start include voltage excursions, overvoltage, successful operation of power plants in a subdivided system, and synchronizing the subdivided system into a unified system.

5.9 RESTORATION PROCESS

In preparation for a potential shutdown of all power systems, many utilities have documented procedures for restoration based on the specific, and in some cases, unique characteristics of their power system. Some of these plans focus on total shutdown of the system while others target islands operating in the power system. These plans are specialized by region and utility to reflect particular attributes of the area. Most plans incorporate a sequential procedure for restoring the power system, and stage emergency drills to practice the plans. Other phases of these plans are often simulated using software programs.

5.9.1 Generalized Restoration

The utility's EMC is the nucleus for restoring the power system. The restoration team consists of the EMC's dispatchers and supervisors, the power plant operators, distribution district engineers and managers, along with field and construction crews. Following a power system emergency, information to evaluate the status of the power system, is first received via voice and data communication links at the EMC.

A utility's EMC is designed for high reliability in this type of situation. The computers have uninterruptible power supplies capable of supporting $\pm$ 10 minutes operation until back-up generators become available. Back-up generators such as diesels and combustion turbines can provide power for more than 24 h. Larger utilities have a back-up EMC that duplicates many of the monitor and control functions of the main center in the event the main control center becomes unusable.

Establishing the state of the power system during an emergency is extremely important. Dispatchers must understand the power system configuration to make correct decisions to safely restore failed parts of the system. Impaired communications between the EMC and the power system, including both data and voice links, will slow the restoration process. Data from the remote terminal units that are missing or corrupted by an event will cause problems for the state estimator software program. Normally, the state estimator performs the function of defining the state of the entire power system, however, missing data will cause a lengthy search for a state solution. Corrupted data will produce inaccurate results.

Without adequate data communication links it is very difficult to begin the restoration process. Normally, utilities directly monitor generators, the transmission system, etc., and compare present performance with referenced data on operating limits stored at the control center. If voice communication is available, dispatchers can slowly rebuild the system by talking to plant operators, field crews, etc. If the wide-area communication links are unavailable, rebuilding the transmission system is a difficult task because a vast majority of utilities have their transmission system under direct supervisory control from the control center.

Following an event, dispatchers would rely on the state estimator: (1) data exchange communication links with neighboring utilities, power pools, etc., and (2) voice communication with power plant operators, district managers, filed crews, etc., to identify the boundaries of islands in the power system and to receive reports on the status of various equipment. Outside power possibilities would be identified as would the status of black start units. Critical loads are also considered first for restoration. The process of rebuilding the system is slow but systematic in procedure.

5.9.2 Restoration Following a High-Altitude Electromagnetic Pulse Event

This study attempts to characterize HEMP-initiated disturbances on the power system as events that test the robustness of the system (technical survivability) and the preparedness plans (ability to manage under adversity). From all accounts, a HEMP event will inflict significant disruption on the power system and disrupt service for days in duration. Further, it is likely to create an aura of chaos and hysteria in the civilian population. Consequently, the conditions under which the system fails has a direct bearing on its ability to recover. The process of restoration must be dynamic to respond to the plethora of unique consequences that a HEMP scenario might provide.

Throughout this report, focus has been on the marginal effects produced by EMP over other classical disturbance events for which the electric utility industry is prepared. However, most weather and natural disasters tend to be highly regionalized, that is neighboring utilities can help, and they are understood by the civilian population, a set of conditions not applicable to a HEMP disturbance. Recognizing these assumptions, the following special conditions apply to restoration under HEMP:

- Communications are vital to restoration, and it appears that major disruption will have occurred. Extra effort is required to firm communications capability.
- Coordination with neighboring and regional utilities is essential. The Eastern, Western, and Texas interconnections will require special cooperation to successfully reconnect the systems.
- Transportation is a given during traditional disturbances, but could be unavailable following a HEMP event. Movement of personnel and material could be difficult.
- Damage assessment of power facilities will require longer time periods to determine their status. Extended outage time will cause supporting battery systems to lose their electric charge.
- Possible damage to loads could prevent quick restoration of service. Many loads contain electronics that are likely damaged.
- Availability of utility personnel could be a serious problem. Effective deployment of personnel is critical.
- The length of time to complete all transactions will be significantly longer than traditional emergencies.

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6. OBSERVATIONS, CONCLUSIONS, AND RECOMMENDATIONS

6.1 BACKGROUND

This report has evaluated the potential vulnerability of U.S. electric power systems to HEMP. The consequences of HEMP have been determined by examining the power system response to both E_1 and E_3. The fundamental approach has been to utilize the results of previous significant study efforts and to combine them with simple models for characterizing power system reliability and operations under the influence of HEMP events. This assessment has provided a macro-level assessment of power system impacts of HEMP.

Previous studies have focused primarily on the performance of various power system components and subsystems. Such studies have combined field and laboratory tests along with simulation models to evaluate potential component failures, like transformers, insulation, systems relays, breakers, etc. Some power system simulation studies have been conducted to obtain system level response to particular subsystem failures. These results are utility specific and do not present a global understanding of HEMP consequences on U.S. power systems.

The triangle of supply (production and delivery), load, and communications form the backbone of modern electric power system management and operation. Both probabalistic and deterministic enumeration of component and subsystem failures are evaluated in simulation models to determine the consequences of system contingencies. Such simulations identify the key role each element of the power triangle plays in overall electric system performance. These assessments require specific data (magnitude, duration, etc.) on contingencies to obtain meaningful analytical results. In particular, HEMP deployment strategies and consequential impacts on power system components would be required. Such quantifications are required for rigorous analysis, but have been judged beyond the scope of this study.

6.2 POWER SYSTEMS RELIABILITY AND OPERATIONS

Two approaches have been used in this study that are qualitative in nature and characterize both the reliability and operations of U.S. power systems at the macro level. Each approach extrapolates the components and subsystem failures to bulk power system response properties, by reducing HEMP phenomena to contingent failures of aggregations of major power system events.

The U.S. power system has been viewed from a reliability perspective by using the nine NERC regional reliability councils. The vulnerability (reliability) of each region has been assessed with information obtained from NERC documents on potential weaknesses within individual councils.

A susceptibility model has been used to characterize the operations process. Using such techniques, system susceptibility has been assessed for HEMP-initiated system failures under various generation, transmission, and load scenarios. System components have been represented on a functional basis with the basic system response being governed by working knowledge rather than numeric simulations. The power system has been described as transitioning through four states: (1) normal state (business as usual), (2) alert state (system protect mode), (3) emergency (adverse system conditions with power failures), and (4) restoration (reassembling the system after failure).

The overall findings of this study fall into the following three categories:

- impacts of HEMP on electric power systems,
- preventative actions to reduce exposure and expedite recovery and restoration of the power system, and
- post-event restoration and recovery.

Each category represents the candidate consequences of a major HEMP event on the nation's power system.

6.3 OBSERVATIONS AND CONCLUSIONS

The following observations and conclusions are distilled from this report.

Impacts of HEMP on electric power systems

- Significant blackouts will occur should the U.S. power system be subjected to class widespread intense HEMP disturbances. The breadth of these outages on a geographic basis will be determined by the number and distribution of the HEMP events.
- The general vulnerability of U.S. electric power systems to light HEMP disturbances as viewed through the NERC Regional Reliability Councils is dictated by the inherent weaknesses in the respective systems. The determining factor in causing interruptions is the degree of robustness of the power system at the time of the HEMP event.
- Precise relationships between HEMP disturbances and some power system component failures are known; however extrapolation of these data to specific bulk power system interruptions remains an open question. Detail simulations of particular electric systems will determine precise overall impacts.
- Operational impacts on electric power systems begin to occur at the 10% loss of system capability level. As the system failures migrate toward 25% system loss of capability, major problems emerge. At 40% loss of capability, virtually complete system failure will occur.
- The susceptibility of motors and other end-use loads where significant amounts of computer-based control and ASDs are utilized leads to potential load failures approaching 50 to 80%. Such failures cause problems from both loss of system load leading to serious generation mismatch and control problems as well as major restoration problems.

- Paralysis of communication systems will delay restoration of failed power systems. Excessive load on telephone systems will restrict their effectiveness as a communications medium. Microwave systems, a key part of utility communication, may be vulnerable. Fiber optic communications and "ham" radio operators can serve as critical backup communications paths.
- Progressive addition of power electronics system and other computer-based technology in domestic systems including transportation tends to increase the vulnerability of electric power systems and reduce its ability for quick restoration.
- DC power is critical to an orderly shutdown and restart of electric power systems. Unprotected dc circuits have shown a propensity to failure when exposed to HEMP. Relays and backup power supplies depend upon dc power for operation. Archived equipment under shutdown conditions (or black stop) require dc power to maintain their integrity. Black start operations also require dc power. Extended outages will deplete battery systems.
- Because HEMP blackouts are likely widespread, restoration procedures based upon neighborly assistance from other utilities is ineffective. Therefore, emergency planning should reflect approaches to restoration in electric system isolation, both for electrical linkage and labor to implement restoration plans.
- Factors influencing the reliability of U.S. power systems, and hence a measure of system vulnerability, are undergoing significant changes from a decade ago. Several key factors are diminishing system reliability margins and pushing electric systems to limits of acceptable reliability. The key forces influencing reliability today include economical reliability trade-off of quality power system design, public policy disincentives that prevent swift implementation of system capacity requirement, the growth of nonutility generation, and the general impacts of deregulation.

Preventative actions to reduce exposure and expedite recovery and restoration of the power system.

- Emergency planning is the most significant initiative for reducing system vulnerability and expediting restoration and recovery of a failed power system. This report has identified exceptional events that are peculiar to HEMP disturbances and are not factored into the requirements of present emergency planning procedures. Implementation of additional procedures will best prepare utility personnel to deal with the consequences of a HEMP event.
- Warning time in anticipation of an event serves as an effective mechanism to reduce the consequences of a HEMP event. Advanced notice will permit actions to reduce system exposure and maximize recovery following a system failure.
- A data base system to manage and provide information on the availability of spare parts would be extremely helpful and facilitate the recovery process.
- All emergency plans need to be rehearsed, not merely prepared. Practice of the plans will improve execution and can reveal flaws in the approach.
- Maintaining up-to-date records of field equipment status is essential. One key tool is three-phase phasing diagrams for field crews because it is likely that transmission and high-voltage distribution lines may be reconfigured in the field. Knowing the reconnection strategy is critical.
- A bold requirement to preventing many problems and maximizing the ability to recover from a post event is shifting the system into a protective mode a priori. These actions may include changing dispatch patterns, dropping certain loads, and rendering some transmission lines inactive. Such actions have economic consequences and are disruptive, thus they may be unacceptable to U.S. power industry. Government intervention will likely be required for implementation.

Postevent restoration and recovery of electric power systems:

- First step to recovery is putting the emergency recovery plan into action. Under the plan, the initial actions are to assess the damage and establish priority areas for restoring power.

- HEMP power failures are likely to cover large geographic areas requiring coordination with other power companies and Reliability Councils. Establishing regional and national priorities for restoration of power is a major goal and potentially a major flaw in global restoration efforts.
- Establishing a national coordination center to manage the assembly of the nation's power system would facilitate recovery.
- State governments take first responsibility for disaster relief. A major power failure would constitute a disaster and coordination between state and federal entities for power restoration will require review and evaluation.
- FEMA takes a lead role for federal initiatives in national disasters. Recent experience shows that they support infrastructure but are not directly involved in power system restoration. Often, mobilization of FEMA resources has been criticized as too slow as quick response capability. Military action has been viewed as the most efficient mechanism for infrastructure restoration efforts.

6.4 RECOMMENDATIONS

The following overall recommendations are made from this study:

- An emergency plan that concentrates on the unique attributes of HEMP-induced problems in power systems should be prepared and rehearsed.
- A national emergency coordination center is needed to allocate resources and establish priorities to expedite a national power system recovery.
- Emergency restoration plans should be developed for electric systems managed and operated by distributors, municipals, and cooperatives is needed.
- Clear definition of the military role in large scale domestic power failures including mobilization of equipment and operations of facilities is required.
- Further research is required to extrapolate power system component failure due to HEMP into power system-wide failures.

- It is necessary to understand the impact of HEMP on domestic electric loads where computer based and power electronics technology are present.
- Defining the limitations of dc power supplies is essential to measuring the speed of recovery of failed power systems.

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