ELECTROMAGNETIC PULSE AND THE ELECTRIC POWER NETWORK

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Abstract - This paper defines the nuclear electromagnetic pulse (EMP) - electric power system interaction problem. A description of high altitude EMP (HEMP) characteristics, source region EMP (SREMP) characteristics, and magnetohydrodynamics EMP (MHD-EMP) characteristics are presented. The results of initial calculations of EMP induced surges on electric power transmission and distribution lines are presented and compared with lightning induced surges. Potential EMP impacts on electric power systems are discussed, and an overview of the Department of Energy (DOE) EMP research program is presented.

INTRODUCTION

"Technical experts in and out of government are concerned that the highly computerized economy of the United States could be brought to a crippling halt by the electrical effects of the explosion of a single nuclear weapon a few hundred miles over the center of the nation." So wrote David Burnham in a recent New York Times article [1]. These electrical effects may be caused by the intense electromagnetic pulse (EMP) produced by a high altitude nuclear explosion [2].

A sizeable research program has been underway by the United States government looking at military equipment and critical communication network protection. However, very little is presently known about the impact of an EMP event on the nation's electric transmission and distribution network.

To understand this problem, it must first be clear just what type of "events" are possible from a nuclear explosion. Three types of EMP [2, 3, 4] have been identified as significant to electric power systems: high altitude EMP (HEMP), source region EMP (SREMP), and magnetohydrodynamic EMP (MHD-EMP).

The purpose of this paper is to 1) describe the nuclear EMP characteristics, 2) present the results of initial calculations of EMP induced surges, 3) compare the EMP induced surges with lightning induced surges, 4) discuss potential EMP impacts on electric power systems, and 5) present an overview of the DOE research program.

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Nuclear EMP Characteristics

High altitude EMP (HEMP) is produced by a nuclear detonation at an altitude near or, more likely, above 50 km; therefore, it is not accompanied by other nuclear weapon effects such as heat and shock waves. The gamma radiation from the burst interacts with the atmosphere at a height of 20 to 40 km. High energy Compton recoil electrons are created in a huge "pancake-shaped" zone, the area of which is limited only by the height of the burst and the curvature of the earth. The Compton electrons are accelerated by the earth's magnetic field which results in a transverse Compton current. This transverse Compton current performs as a phased magnetic dipole array and is the primary source of the EMP fields. HEMP can cover a large portion of the continental United States due to the large area of the source current.

The transient EMP fields are characterized by a high power density with a fast rise time, on the order of 10 ns. This fast rise time results in a wide excitation bandwidth with significant energy distributed over a broad range of the electromagnetic spectrum. The bulk of the EMP energy lies within the radio frequency spectrum, ranging from a few hertz to a few hundred megahertz.

A strong EMP may also be produced by a low altitude nuclear detonation. The intense source region EMP fields from these low altitude detonations exist only near the blast region, which may have a radius of only a few kilometers. SREMP fields attenuate quickly with distance and are normally accompanied by shock waves. However, the large surge induced into the power lines will propagate over long distances away from the blast and affect structurally undamaged portions of the electric grid.

A third type of EMP is MHD-EMP, an electromagnetic pulse with a very low amplitude, which results from geomagnetic perturbations caused by a high altitude detonation. The electric field magnitude is on the order of 10 V/km. With a duration of several tens or hundreds of seconds, MHD-EMP can interact with very long transmission lines to induce currents that produce harmonics and phase imbalances which can potentially damage major power system components, especially those with magnetic elements. This pulse is of very low frequency and may appear to the equipment as a direct current bias.

EMP INDUCED SURGES IN OVERHEAD LINES

Electrical conductors exposed to the EMP fields perform as inadvertent antennas by receiving energy from the EMP illumination. Power lines, phone lines, unshielded control cables, and antennas may experience EMP induced surges with amplitudes similar to those of "average" lightning strikes. For this paper, only the surges induced in overhead lines associated with transmission and distribution systems are discussed. These

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surges will electrically stress the line and equipment insulation and also couple some EMP energy to potentially vulnerable solid state components in instrumentation and control equipment.

A recent study [5] was performed which made an initial assessment of reasonable "worst case" EMP induced surge characteristics using unclassified canonical HEMP and MHD-EMP electric field waveforms. The early time HEMP produced by a high altitude nuclear detonation behaves as a plane electromagnetic wave that sweeps across the earth's surface. A representative double exponential EMP electric field waveform given by Equation 1 was used to calculate representative HEMP induced surges.

$$E = E_0(e^{-\alpha t} - e^{-\beta t}) \qquad (1)$$

where:

$$E_0 = 52.5 \text{ kV/m}$$

$$\alpha = 4.0 \times 10^6 \text{ sec}^{-1}$$

$$\beta = 4.78 \times 10^8 \text{ sec}^{-1}$$

The interaction of this plane electromagnetic wave pulse with a single wire remote from the earth results in a large EMP induced surge. Fast-rising surges with peak amplitudes ranging from several kA to well over 10 kA can be induced. For example, Figure 1 shows the current surges induced on a single perfectly conducting wire with a radius of 2 cm for various EMP incident angles Θ ranging from 18° to 90°.

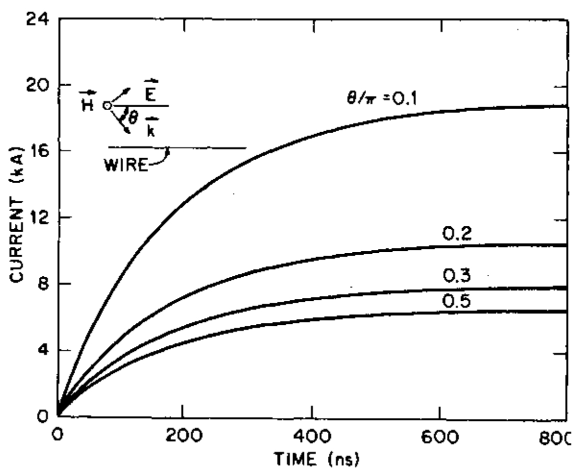

Fig. 1. Early time HEMP current surge induced in a single perfectly conducting wire for a range of incident EMP angles.

Additional calculations showed that the current peak is reduced by only a few percent when the wire resistance is included in the analysis.

The surges induced in typical three phase (3Ø) transmission and distribution lines are less than those shown in Figure 1 due to the effects of the multiple conductors and the earth. For a ground conductivity of 0.01 mhos/m and a relative permittivity of 10, the surge peaks are over 2 kA for a typical 765 kV single-circuit transmission line, as shown in Figure 2. The peak rate of rise of the current is over 100 kA/µs. The current surges induced in a typical 13.2 kV 3Ø distribution circuit are shown in Figure 3. The peak current is several hundred amperes with a peak rate of rise of about 100 kA/µs. The voltage gradient (induced electric field normal to the wire) on the 765 kV transmission line is a few tens of MV/m on the shield wires and less than one MV/m on the phase conductors. For the 13.2 kV distribution line configuration, the voltage gradient is several MV/m. The rate of rise of the voltage gradient is very large for both the transmission and distribution line configurations - - on the order of 10^9 MV/m/sec.

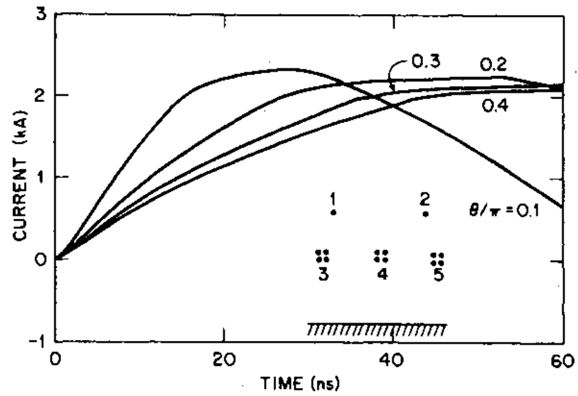

Fig. 2. Early time HEMP current surge induced in a typical 765 kV line configuration for a range of incident EMP angles.

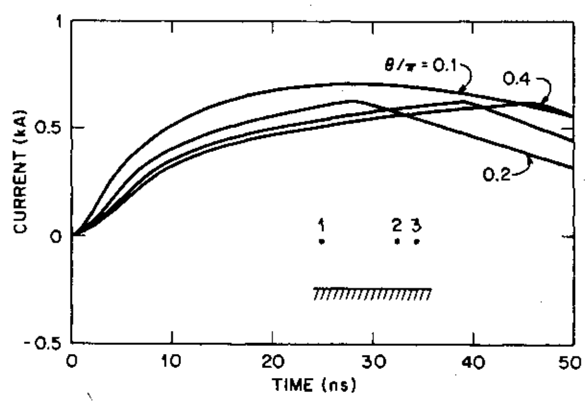

Fig. 3. Early time HEMP current surge induced in a typical 13.2 kV distribution circuit for a range of incident EMP angles.

A late time effect of a high altitude nuclear detonation is the MHD-EMP with an associated electric field on the order of 10 volts per kilometer. For a long EHV transmission line of about 320 km and grounded at both ends, a MHD-EMP induced surge with a peak amplitude on the order of 1000 A, a rise time of a few seconds, and a duration of tens to hundreds of seconds [5] can result in the substation grounds. The induced current is a function of many parameters such as length and orientation of the line, characteristics of the earth, grounding impedance, height and distance from the burst, etc. The induced current waveform varies greatly with these parameters. However, for the purpose of discussion, a representative waveform can be used. The time history of a representative MHD-EMP induced current surge in the substation ground associated with a 320 km 765 kV transmission line is shown in Figure 4. This waveform does not represent the surge induced by the MHD-EMP associated with any burst scenario but does represent MHD-EMP induced surges in general. The actual MHD-EMP induced ground current can be large if several lines run in the same general direction out of a grounded substation or if the MHD-EMP is associated with multiple detonations. For example, two 160 km 765 kV lines going in the same direction out of a substation can also result in a MHD-EMP induced ground current of about 1000 A.

Power lines that are near a surface burst will have very large electrical surges induced by SREMP.

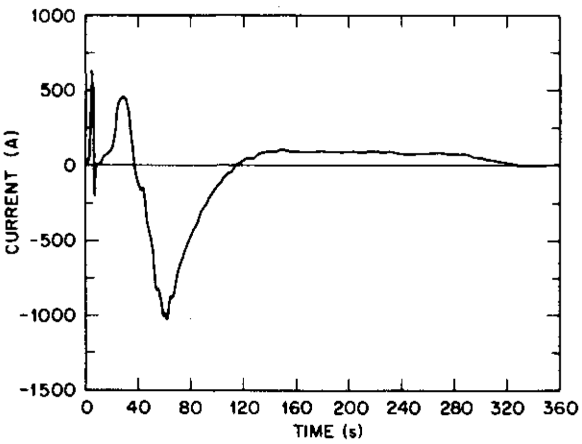

Fig. 4. Late time MHD-EMP current surge induced in the substation ground of a long 765 kV line.

These surges will propagate relatively long distances away from the blast and affect the structurally undamaged portion of the grid due to the significant energy content at low frequencies.

The SREMP induced surge can have an amplitude well over 100 kA. An example calculation for a SREMP surge induced in a power line was performed by Graham [6]. The surge through a 0.1 ohm resistive load at 2 km from the burst appears similar to a double exponential waveform with a peak current of 180 kA, rise time to peak of about 0.5 ms, and the 1/e fall time is about 3 ms. As the surge propagates down the line it is distorted; the rise time and fall time increase and the amplitude decreases [7].

For the purpose of discussion, consider a representative SREMP induced surge with a double exponential waveform at a point on the line 12 km from the blast. The current surge rises to a peak value 100 kA after one ms and decays to 37 percent of the peak value (1/e) after 4 ms. This waveform is described by Equation 2.

$$I = I_0(e^{-\tau t} - e^{-\lambda t}) \qquad (2)$$

where:

$I_0 = 180.3$ kA

$\tau = 3.8 \times 10^2 \text{ sec}^{-1}$

$\lambda = 2.0 \times 10^2 \text{ sec}^{-1}$

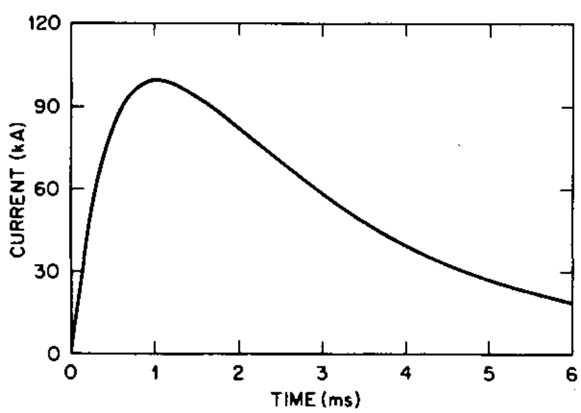

Fig. 5. Representative SREMP induced surge.

The representative SREMP induced surge is shown in Figure 5. This waveform is not associated with any particular burst scenario, but it is useful to illustrate some important properties of SREMP induced surges; namely, a relatively large peak value and the significant energy content at low frequencies. The representative SREMP induced surge does not include the effects of corona and arcing across insulators which will modify the surge time history.

COMPARISON WITH LIGHTNING

To put the EMP transient in perspective, this section will compare HEMP induced surges on typical transmission and distribution line configurations to lightning induced surges. Present knowledge about lightning reveals three characteristics:

1. Lightning strokes to transmission and distribution lines are statistical events. The number of lightning strokes per square km per year is a function of geography and is usually estimated from isokeraunic maps.

2. The mechanism of the lightning flash is very complex, and lightning performance is usually simplified using empirical methods involving probability.

3. The current magnitudes and waveshapes of lightning strokes can also vary on a random basis.

A typical range of composite lightning stroke characteristics [8, 9, 10] used for calculating lightning performance are summarized in Table I.

Table I: Typical Range of Design Lightning Surge Characteristics

Peak Current (kA)	Rate of Rise (kA/μs)	Front Time (μs)	Tail Time (μs)
5-100	5-30*	.5-30	20-200

*Clayton's paper [11] on very fast surges references measured lightning stroke rates of rise of over 100 kA/μs.

Typical characteristics for the surges induced in the typical 765 kV and 13.2 kV lines for the HEMP waveshape described in Equation 1 are summarized in Table II.

Table II: Summary of HEMP Induced Surge Characteristics

Line Configuration	Peak Current (kA)	Rate of Rise (kA/μs)	Front Time (μs)
1. 765 kV			
Shield Wires	2.5	30-95	< .1
Phase Conductors	2-2.5	70-160	< .1
2. 13.2 kV			
Phase Conductors	.3-.7	30-80	< .1

Comparing the typical lightning and HEMP induced surges, the following similarities are observed. First, they are both "fast surges" - - both surges have a rapid rate of rise and fast rise times. However, the HEMP induced surges are "very fast surges" compared to typical lightning surges. HEMP surges have faster rates of rise and much shorter front times than typical lightning induced surges. Second, they both have high peak currents, although typical lightning surge peak currents are larger than the HEMP currents induced using Equation 1. In addition, both surges are expected to have a relatively short duration, although the surge duration was not calculated in the early time (front-of-wave) HEMP calculations.

The primary differences between HEMP and lightning induced surges on power systems are that:

1. HEMP simultaneously illuminates the whole power system while lightning strikes at one point. HEMP induced surges present a global systemwide problem, with surges simultaneously induced on all exposed transmission lines and distribution lines.

2. Both shield wires and phase conductors are exposed to HEMP. Thus, the shield wires which protect transmission lines from lightning surges do not "shield" them from the HEMP.

3. Lightning surge characteristics are a statistical event. The HEMP wave characteristics are a function of line geometry and the nuclear burst location relative to the earth.

Comparing SREMP induced surges with lightning, SREMP can induce about the same or higher peak current magnitude - - over 100 kA. However, the time frame for SREMP is an order of magnitude slower than typical lightning strokes used for lightning performance calculations, as the front times of SREMP induced surges are measured in 100's of μs and the tail times are measured in ms.

Potential EMP Impact on Electric Power Systems

The potential EMP impact on electric power systems is a function of both the nuclear burst locations and the electric power system characteristics. As previously discussed, there are two types of EMP events - - a high altitude nuclear burst and a low altitude (near surface) nuclear burst. The high altitude nuclear burst and the low altitude or surface nuclear burst generate different surges.

The high altitude EMP scenario is a principal concern when assessing the impact of EMP on an electric power system because the total United States' power system can be simultaneously illuminated by HEMP, and MHD-EMP can cover a large area of up to several hundred km in diameter. On the other hand, the SREMP induced surges are more severe but less global.

Functionally, an electric power system can be described as shown in Figure 6. Various types of power system control equipment are used to control the generation, transmission and distribution system in response to load requirements. In general, power system loads are not presently controlled. However, in the future as distribution automation and control schemes are implemented, load can also be controlled. Power system control includes surge protection, relaying, communication, generating plant control, and power system dispatch functions.

Potential problem areas for electric power systems where the impact of an EMP event may be experienced include:

- Overvoltage
- Overcurrent
- Communications
- Electronic Control Equipment
- Power System Stability
- Power System Dispatch

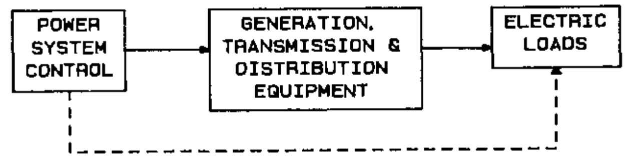

Fig. 6. Functional diagram of an electric power system.

EMP induced transients have the potential to cause overvoltage stresses on power system surge protection equipment including insulation, air gaps, and surge arrestors. For example, the magnitude of HEMP induced surges on the 13.2 kV distribution line described previously can cause a transient voltage of about 300 kV which exceeds the typical insulation BIL level of 13.2 kV distribution lines. Although there is presently little experience in assessing the distribution line BIL performance for very fast HEMP induced surges, there certainly is the potential for widespread distribution system flashover due to overvoltage stress from HEMP. Other potential overvoltage stress problems such as inadequate surge arrestor performance may be caused by the "very fast" dI/dt and dE/dt characteristics of HEMP induced surges.

EMP induced transients also have the potential to produce overcurrent conditions on electric power systems. HEMP induced insulation failure will cause faults or overcurrent problems. Also, overcurrent problems may be caused by MHD-EMP induced currents of several hundred amperes in grounded transmission systems. This large MHD-EMP current is essentially DC and flows through substation transformers on grounded transmission systems. This MHD-EMP induced overcurrent has the potential to cause relaying problems, transformer heating, or unusual VAR flows mainly due to the DC saturation of magnetic materials, i.e. transformer cores. Similar effects due to solar induced currents (SIC) from geomagnetic storms [12] have been observed on a smaller scale. These do, however, give insight into the impact a more severe EMP-MHD event might have.

Electric power systems make extensive use of communications media such as power line carrier (PLC), microwave radio and mobile radio, telephone, and private wire circuits. These communication media are extensively used for relaying, power control centers, and system control and data acquisition (SCADA) systems. In addition, extensive use of electronic control equipment consisting of low voltage (less than 600 V) circuits and sensors are used for power system relaying, monitoring, and control functions. This equipment, which may or may not be shielded, is thought to be very sensitive and vulnerable to EMP induced surges.

Systemwide EMP induced transients may also cause significant power system stability and/or dispatch problems. For example, significant amounts of load may be dropped due to widespread overcurrent problems in distribution circuits. This could cause islanding and large generation and load mismatches resulting in potential power system stability problems even if the transmission system can withstand EMP surges. In addition, there may be significant power system dispatch problems, both second-to-second load/frequency and minute-to-minute automatic generation control (AGC), if the power system remains stable. Further, if the power system does go down for an EMP event, there may be significant problems in bringing the power system back up due to damage of generation, transmission, distribution, power system control equipment, or the lack of experience of restoring a regional blackout.

DOE RESEARCH PROGRAM

The Electric Energy Systems Division of the Department of Energy (DOE/EES) is actively pursuing a research program designed to assess the potential impact of an EMP event on the nation's transmission and distribution systems [13]. One cannot view the impact on power transmission and distribution equipment isolated from the associated control and communication links. The transient wave may damage any of these links, i.e. power components or communication/control equipment, with equal potential to disrupt the network as described in the previous section.

This research program is, above all else, motivated by national security issues. Without a viable, operating electric network the security of the nation is at risk. Therefore, the DOE/EES EMP program is designed to develop technologies and systems to enable electric power systems to 1) provide power to essential loads such as military installations, civil defense facilities, and critical industries; 2) reduce damage to the overall power system; and 3) minimize power outage time to the public. The development of a systemwide approach to accomplish these goals results in these objectives:

1. To develop scientific and mathematical models for representing the influences of EMP on electric power systems.
2. To develop analytical methods of assessing the effects of EMP on electric power systems.
3. To develop a data base from simulation studies and experiments for characterizing power system response to EMP.
4. To develop and evaluate measures designed to minimize the influence of EMP on electric power systems.
5. To provide information and recommendations for electric power structural and operational requirements when subjected to EMP disturbances.

The technologies and systems include analytical and modeling techniques, assessment methodologies, protection hardware, and special operating and control strategies. Recommendations for protecting the power systems will result, but implementing EMP protection and contingency strategies is not a part of this program.

The approach is iterative. That is, there are numerous assessment points to allow new research data to change the course of the program. If it is found, for example, that the impact is minimal, the program will end. If, on the other hand, it is found that a major amount of testing is required because the impact may be substantial, the plan would be changed to reflect that.

At present there are five elements to the research plan. They are:

1. EMP surge characterization and effects.
2. Development and testing of a comprehensive EMP assessment methodology for electric power systems.
3. Development of strategies for operation and control of electric power systems under the influence of EMP.
4. Definition, development, and testing of requirements for hardware under the influence of EMP.
5. Evaluation of EMP impacts on new generation and control technology for electric power systems.

Element 1: EMP Surge Characterization and Effects

It is necessary to describe the surges induced on electric power system transmission and distribution lines and the effects of these surges on system components in order to analyze the impacts of EMP on electric power systems. Techniques to compute the EMP energy and induced transients coupled to antennas, shielded cables, phone lines, cables within partially shielded enclosures, etc. have been developed by other federal programs [14]. These techniques will be useful to assess the impact of EMP on electric power system controls and communications, but these and other less rigorous studies on single conductor overhead lines require substantial reinforcement and research to be applied to complex T&D systems and components. The impact of multiple lines, corona, and the system network on the induced surges is included.

Element 2: Development and Testing of a Comprehensive EMP Assessment Methodology for Electric Power Systems

At present, no comprehensive methodology exists for assessing the effects of EMP on electric power systems. Available assessment techniques have been developed to evaluate effects on facilities and military systems. These, while applicable to portions of electric power systems, will have to be developed further to account for the impact of system operations and control and the failure mechanisms associated with high voltage power circuits.

Element 3: Development of Strategies for Operation and Control of Electric Power Systems under the Influence of EMP

This element will investigate operation and control strategies for mitigating the effects of EMP. These will range from advanced emergency state control to special actions and procedures which could be initiated to help decrease the impact on the electric network.

Element 4: Definition, Development, and Testing of Requirements for Hardware under the Influence of EMP

New hardware may be required to protect systems being influenced and stressed by EMP. The hardware requirements will be coordinated for lightning and electromagnetic compatability where possible. This may range from modification of present state-of-the-art hardware to new materials, concepts, and techniques.

Element 5: Evaluation of EMP Impacts on New Generation and Control Technology for Electric Power Systems

As the penetration of new technologies into electric power systems proceeds, the effects of EMP on these technologies could have a significant impact on the overall power system. This element aims at determining the EMP effects on new generation and control technology being developed and integrated into electric power systems. Also, hardening requirements and specifications for new generation and control concepts will be determined. These will be crucial in the design of new technologies and test standards to meet the new stress levels.

CONCLUSIONS

A nuclear detonation in or above the earth's atmosphere produces an intense electromagnetic pulse. A single high altitude burst could subject most of the power lines, telephone lines, and unshielded control cables in the United States to a strong EMP. HEMP surges are similar to some lightning transients except rise times and durations will be shorter, and therefore stresses much higher. While lightning normally causes a local disturbance (a single entry point) to electric power systems, EMP will result in a widespread disturbance by interacting with transmission and distribution, generation, control, and communication systems in a distributed manner. Conventional power system protection may be ineffective against the fast-rising EMP surges and system control equipment may be rendered ineffective. Thus, EMP could cause a major and potentially long-term power disruption over a large portion of the nation.

The potential vulnerability of the electric power systems to EMP is recognized and is being addressed by the Electric Energy Systems Division of the Department of Energy. The initial phase of the research is underway and will involve model development for EMP transient network analysis, EMP surge characterization including nonlinear effects, assessment methodology development, and a preliminary vulnerability assessment. Once firm theoretical models and the assessment methodology are developed, the required data base will be determined, simulation and functional studies will be conducted, and a comprehensive assessment will be performed. During the final phase of the program, operation and control procedures and protection hardware will be reviewed and developed where necessary.

ACKNOWLEDGMENTS

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REFERENCES

[1] David Burnham, "U.S. Fears One Bomb Could Cripple the Nation," New York Times, June 28, 1983.

[2] W.J. Karzas, R. Latter, "Electromagnetic Radiation From Nuclear Explosions," IEEE Transactions on Antennas and Propagation, Vol. AP-26, No. 1, January 1978.

[3] EMP Engineering and Design Principles, Bell Laboratories, Loop Transmission Division, 1975.

[4] C.L. Longmire, "On the Electromagnetic Pulse Produced by Nuclear Explosions," IEEE Transactions on Antennas and Propagation, Vol. AP-26, No. 1, January 1978.

[5] H.W. Zaininger, Electromagnetic Pulse (EMP) Interaction with Electric Power Systems, Draft ORNL Final Report, Subcontract 85X-47905C, January 1984.

[6] W.R. Graham, "The Electromagnetic Coupling of Nuclear Explosions to Above Ground Conductors Traversing the Source Region," Defense Nuclear Agency Report No. 5702P-2, April 1981.

[7] M. Quyang and P.G. Kendall, "Test on Distortion and Attenuation of Waves on an Overhead Line," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-04, No. 2, March/April 1975.

[8] Transmission Line Reference Book 345 kV and Above, Second Edition, Electric Power Research Institute, 1980.

[9] Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corporation, 1964.

[10] D. Fink, H. Beaty, Standard Handbook for Electrical Engineers, Eleventh Edition, 1978.

[11] R.E. Clayton, I.S. Grant, D.E. Hedman, D.D. Wilson, "Surge Arrestor Protection and Very Fast Surges," IEEE Paper No. 83 WM 112-0, Presented at 1983 IEEE/PES Winter Power Meeting.

[12] J.G. Kappenman, V.D. Albertson, N. Mohan, "Current Transformer and Relay Performance in the Presence of Geomagnetically Induced Currents," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 3, March 1983.

[13] "Program Plan for Research and Development of Technologies and Systems for Electrical Power Systems Under the Influence of Nuclear Electromagnetic Pulses," DOE/NBB-0033, May 1983.

[14] EMP Interaction: Principles, Techniques and Reference Data, Air Force Weapons Laboratory, TR-79-4-3, Edited by K.S.H. Lee, December 1979.

Discussion

Harry W. Colborn (North American Electric Reliability Council, Princeton, NJ) and **Maurice F. Hebb, Jr.** (Florida Power Corp., St. Petersburg, FL): The authors have done the utility industry a service by presenting this paper in the forum provided by IEEE. Although various federal departments have investigated the EMP phenomenon for years, and have recognized the potential for massive upsets in electric power supply systems, it is only recently that the information has been communicated openly to U.S. utility management. It seems unbelievable that the possibilities of such a disruptive occurrence have been recognized for twenty years and yet have never been the subject of an in-depth, unclassified research program. The Electric Energy Systems Division of the Department of Energy is to be commended for initiating this study and for their wholehearted attempts to maintain it at an unclassified level. Action cannot be taken by the industry if the information remains out of reach.

Interest by the utilities in this matter is high and may be exemplified by the action taken by the Board of Trustees of the North American Electric Reliability Council. The Board, made up of excutive officers of electric utilities in the U.S. and Canada, directed in early 1983 that an EMP Task Force be formed of industry personnel to stay abreast of, and keep the industry informed regarding activities related to EMP research. Additionally, a liaison arrangement has been set up between the NERC staff and the project manager for the study. Progress and milestone events are being reported to the Board of Trustees, and the liaison arrangement allows a quick dissemination of information to the utility managers, engineers and system operators who comprise the NERC organization throughout the United States and Canada.

The single area in which additional effort would probably benefit the program is in the field of simulatlion. The authors note that simulation is a part of the program but we infer that this is a simulation of effects on a network—once the coupling methodology is worked out. It seems that effects on individual pieces of equipment could advantageously be researched in parallel with the present work, even if such research is a part of an ongoing classified study in another area. Studies of the response of insulating materials confronted with HAEMP wave fronts would be invaluable. Classified studies have probably been made on solid state devices similar to those used in system control—these studies might be selectively declassified. Also, the effect of corona on dampening the pulse height should be researched. Such studies, carried on in parallel with the present program, would provide more well-rounded results.

The feasibility of the utility industry funding and operating its own EMP simulator or gaining access to an existing or planned simulator is a point the authors might comment on. Could a test facility be built to answer some of the questions on distribution insulation flashover, protection of relays, penetration of control rooms and the like?

Manuscript received July 27, 1984.

Donald R. Volzka (Wisconsin Electric Power Co., Milwaukee, WI): I would like to congratulate the authors on the development of a fine paper which adds significantly to industry understanding of a potentially serious problem. I ask for clarification and expansion on a number of points:

The statement is made that the surge induced into power lines by SREMP will be both large and propagate long distances away from the blast and effect structurally undamaged portions of the electric grid. The magnitude is not questioned, but propagation "over long distances" does not appear likely. High magnitude surges would casue localized flashover of insulation and be absorbed by the capacitance of transmission lines as it propagates outward. Since the SREMP surge is relatively slow, conventional lightning arresters should also function to limit SREMP surges to within one (1) line section of the detonation. Surges which are insufficient to cause line flashover should, thus, not cause effects of significance remote from the detonation point. Clarification of your statement is requested.

The discussion of voltage gradients appears to be in need of clarification. If the authors are quantifying the longitudinal voltage gradient on a 765 kV line induced by an EMP transient, it appears that their estimate differs from many others by a factor of about 10^3. The substantial variation in the gradient between 765 kV shield wires, phase conductors, and 13.2 kV phase conductors is also in need of explanation. If the authors are quantifying the axial voltage gradient associated with conductors raised to high potential by an EMP transient, I would observe that an important factor was not mentioned. I request that they comment on voltage magnitudes and the nonlinear fashion in which it divides across the capacitive elements of insulator strings. Are the authors suggesting that high field strength associated with line conductors is a problem? Utility practice is generally to ground the shield wire on transmission lines at each structure. How is any voltage of significance induced on such a conductor?

On Page 4 of your reprint, the authors estimate the transient voltage which could be induced on a "typical" 13.2 kV distribution at about 300 kV. This does not appear to be consistent with their previous estimate of induced voltage of several MV/(k)m unless either the line was very short or other factors were introduced. Please comment.

Under the assumption that the goals of your research program are met, it would appear that the next step is implementation. The expense involved in accomplishing a retrofit program on a nationwide basis would be substantial, to put it mildly. It also appears that this expense is one that should not come to rest on the shoulders of the utilities since, as you say, it is an issue of National security. What do you foresee as the methodology for implementing EMP protection and contingency strategies?

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K. W. Klein, P. R. Barnes, and **H. W. Zaininger:** The authors would like to thank the discussers for showing their interest in the paper and providing valuable comments.

Regarding Mr. Volzka's comments on source region EMP induced surges, our statement in the paper is that SREMP induced surges will propagate *relatively* long distances away from the blast and affect the structually undamaged portion of the transmission system. To put distance in perspective, our paper presents an example representative SREMP induced surge at a point 12 km from the blast.

Regarding Mr. Volzka's comments on high altitude EMP induced voltage gradients, first, the voltage gradients were calculated normal to the wire, not longitudinal. This is mentioned on page 2. Second, regarding differences between our estimate and others, our estimates are based on calculations using typical HEMP characteristics and realistic 30 line configurations. We are not aware of any other HEMP/30 line calculations to date.

Regarding Mr. Volzka's comments on the substantial variation in the magnitude of voltage gradients calculated for 765 kV phase conductors, shield wires, and 13.2 kV phase conductors, this can generally be explained by relative conductor size. The relatively small diameter 13.2 kV phase conductors and small diameter 765 kV shield wires will be expected to have much larger voltage gradients induced in them compared to relatively large 765 kV phase conductors consisting of four conductor bundles spaced 18 inches apart.

Regarding Mr. Volzka's comments on voltage magnitudes, 300 kV is an induced voltage estimate on the distribution line based on an induced peak current of about 700 amps and a surge impedance of about 400 Ω. As discussed before, the induced voltage *gradient* estimates in MV/m are normal to the line not longitudinal voltages. This HEMP induces voltage may be significant when distribution system BIL is typically less than this. The distribution of EMP induced voltage surges such as across insulator strings is expected to be addressed in future work, as this is beyond the scope of the results of initial calculations presented in this paper. Regarding shield wire insulation, present utility practice is generally to ground shield wires at each structure on HV transmission lines. However, shield wires may or may not be insulated on EHV structures dependig on utility design philosophy.

Regarding Mr. Volzka's comments on implementation, the discusser puts his finger on a substantial future problem, i.e., if a serious impact to the electric system is found, who will pay for the hardening? This is a question which cannot be answered as yet. First, the degree of hardening must be determined, and this will directly impact the cost. The magnitude of the cost will somewhat determine who will make that commitment. Since national security and major costs could be involved, these policy decisions will likely be made at the highest level of government.

Regarding Mr. Colborn's and Mr. Hebb's discussion, the points raised on the need for additional parallel work are sound. In fact, unknown to the discussers, this work is already beyond the planning stage and is being implemented.

The feasibility of the utility industry funding and operating its own EMP simulator is an interesting concept. Certainly such a facility will be needed to test selected equipments to determine their resistance (or lack thereof) to an EMP transient. This will be a vital part of the final system impact assessment. It is unclear to the authors just how the utility industry would arrange for such a facility, but the concept deserves further discussion.

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