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FEASIBILITY OF ISOLATING VULNERABLE EQUIPMENT
OF THE ELECTRIC POWER SYSTEM
FROM SOURCES OF EMP

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Final Report,

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by

E. K. Stanek

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DETACHABLE SUMMARY

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E. K. Stanek

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Problems related to performing the proposed switching are discussed, including the effects of the switching on the nation's power systems and the general population. In addition, the extent to which utility personnel could be depended upon to perform switching was discussed.

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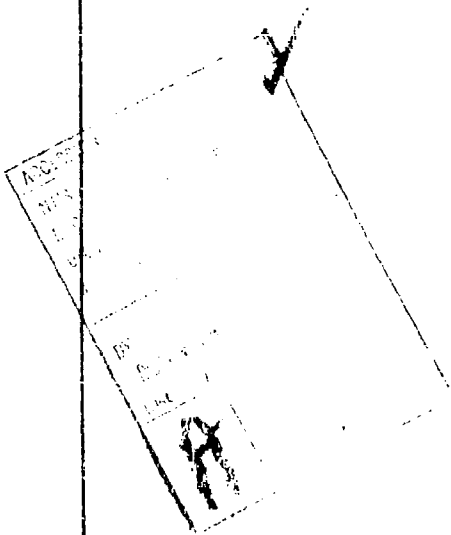
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The data contained in this report were obtained primarily through interviews of electric utility personnel. The conclusion drawn from these data is that it is possible to isolate a significant portion of the vulnerable equipment in the distribution system from sources of EMP. This would not only reduce the number of failures of equipment in the distribution system (and hence system faults), but would also configure the system in a more secure state with respect to electromechanical stability. Problems associated with the transition from the normal system state to the new operating state and the restoration of service to loads after the attack are discussed.

The report also contains information on the development of a new lightning arrester design that has better EMP characteristics than existing designs.



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SCOPE OF WORK

The contractor shall furnish necessary facilities, personnel, and materials in order to conduct a study to explore the feasibility of electric system operators isolating circuit breakers and transformers from transmission lines through remote switching by supervisory control panels, and manual switching at the substations in order to avoid power failures caused by electromagnetic pulse (EMP). A minimum of 15 minute advance nuclear attack warning is assumed. Specific work and services shall include:

1. Extensive and thorough review of available research reports on the EMP phenomena as it relates to (a) electric power systems, and (b) single-line diagrams for power systems in the State of Colorado.
2. Determine the feasibility of manual isolation of vulnerable equipment upon receipt of attack warning. Feasibility should be studied in Colorado Springs (risk area) and Fremont County (host area) of Colorado.
3. Report findings for Colorado and generalize the results to electric systems nationwide.
4. Nationwide projections will consider current Crisis Relocation Planning (CRP) guidance on power systems in Colorado with application to a location to be selected by the Government.
5. Prepare progress and quarterly reports as described in Article III and submit in five copies to the Contracting Officer's Technical Representative (COTR) appointed in Article IV and with one copy to the Contracting Officer.

6. Prepare a draft final report and, after review and approval, a final report as described in Article III.

FOREWORD

Work reported herein was performed by the Emergency Electric Power Administration (EEPA), Department of Energy, Economic Regulatory Administration, (formerly Defense Electric Power Administration, Department of Interior), under Defense Civil Preparedness Agency Work Order Number DCPA 01-76-C-0290. Mr. Stephen R. Birmingham served as the Contracting Officer's Technical Representative (COTR) for the Emergency Operations Systems Division (Research) within DCPA. Mrs. Lori O'Neill served as project director for EEPA. The principal technical investigator was Dr. E. K. Stanek, EEPA Representative, Morgantown, West Virginia. Work was conducted as DCPA Work Unit 2216C.

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The basis for this research report was obtained through the excellent cooperation of several persons in the electric power industry. Two individuals who provided particularly important information and direction were Mr. Julian R. Hayden of the Public Service Company of Colorado (EEPA Director, WSCC (RMPA)) and Mr. Kenneth E. Wolters of the Wisconsin Electric Power Co. (EEPA Major Utility Representative - MAIN). These gentlemen gave substantially more information than was expected with regard to system operation, both during and after the proposed actions. The following persons and organizations also provided data, personal time, and valuable comments.

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Mr. Robert Kerger and Mr. James Ware, Commonwealth Edison Co., Chicago, Illinois.

Mr. Stanley F. Smith, Allegheny Power Service Corp., Greensburg,
Pennsylvania

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Power Company, Syracuse, New York.

Mr. Thomas Overly, American Electric Power Service Corporation,
Canton, Ohio.

Mr. Harvey Hinman, Public Service Company of Colorado, Denver,
Colorado.

ABSTRACT

This report evaluates the feasibility of isolating vulnerable equipment of the electric power system from sources of electromagnetic pulses (EMP) through the use of supervisory control and dispatched personnel to perform remote and manual switching, respectively, in distribution substations.

The data contained in this report were obtained primarily through interviews of electric utility personnel. The conclusion drawn from these data is that it is possible to isolate a significant portion of the vulnerable equipment in the distribution system from sources of EMP. This would not only reduce the number of failures of equipment in the distribution system (and hence system faults), but would also configure the system in a more secure state with respect to electromechanical stability. Problems associated with the transition from the normal system state to the new operating state and the restoration of service to loads after the attack are discussed.

The report also contains information on the development of a new lightning arrester design that has better EMP characteristics than existing designs.

EXECUTIVE SUMMARY

Feasibility of Isolating Vulnerable Equipment of the Electric Power System from Sources of EMP

by

E. K. Stanek

The possibility of protecting vulnerable items of equipment in the electrical power system from EMP by remote and manual switching, is explored in this study. The remote switching would be performed using existing supervisory control equipment. Manual switching would be performed by dispatched personnel. The extent to which the required switching could be performed in the nation's power systems was investigated through data available in the literature and a series of interviews with personnel from electric utilities. The conclusion is that about one half of the nation's power system could be switched to protect equipment on the distribution system. If this switching is properly coordinated with changes in generation, it would not only protect vulnerable equipment from EMP, but would also place the system in a more secure state with respect to system stability.

Problems related to performing the proposed switching are discussed, including the effects of the switching on the nation's power systems and the general population. In addition, the extent to which utility personnel could be depended upon to perform switching was discussed.

The impact of new arrester designs using zinc oxide semi-conducting material was assessed as not important in the short run, even though their characteristics are superior to those of existing designs. This is due to the long useful life of units in the field.

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I. INTRODUCTION

A. Purpose of the study

A high-altitude nuclear detonation causes current to flow in the atmosphere due to Compton scattering. This current generates an electromagnetic pulse (EMP) which propagates to the earth's surface where it induces currents and voltages on conductors over a wide geographical area. The purpose of this study is to determine the feasibility of isolating vulnerable equipment of the electric power system through the use of the supervisory control system to perform remote switching or by dispatching personnel to perform manual switching.

B. Review of EMP

The physical phenomena that account for the production of an EMP when a high altitude nuclear detonation occurs have been reviewed in many reports.¹⁻⁷ A deep understanding of the physics leading to an EMP is not required to understand this report. It is only necessary that one have a knowledge of the effects that the EMP can produce on an electric power system.

When a nuclear device is detonated 50 km or more above the earth's surface, primary gamma rays are produced which interact with the atmosphere between altitudes of 20 and 40 km. This interaction is primarily by Compton scattering with electrons of air molecules. These electrons move downward away from the burst in a trajectory that is bent by the earth's geomagnetic field. It is these accelerated electrons that radiate the EMP from the region of the atmosphere that

is both within the line of sight of the burst and between the altitudes of 20 and 40 km. In addition, secondary electrons are produced by the primary electrons which are accelerated in the opposite direction by an electric field produced by the charge separation. This secondary electron current flows roughly in the opposite direction as the primary current.

Based on calculations, the EMP from a high altitude burst of a large nuclear device may have an electric field strength of 90 kV/m and a risetime of 10 nanoseconds.⁸ Its time to half value would be in the range of 30 to 200 nanoseconds. Because of the long, unshielded conductors in a power system, very large transient voltages with rapid risetimes result. The surges are similar to lightning surges but the risetimes are much faster (by a factor of 100).

The emphasis in this discussion has been on high altitude detonations. Near-surface detonations also produce EMP, but they don't have the large geographical coverage that are characteristic of high-altitude bursts. In fact, the heat and over - pressure effects of the blast are more severe than the EMP effects. An important point is that for a high-altitude burst, the entire atmospheric umbrella defined above radiates. Thus, the EMP field below this atmospheric umbrella does not decrease in intensity as r^{-1} from the burst location. The EMP field occurs everywhere within line of sight of the burst.⁹ This is illustrated in Fig. 1. Clearly, EMP is different than other power system disturbances, such as lightning or switching surges, in that the EMP covers a large percentage of the nation's power systems at essentially the same instant, rather than a single line or sub-station.

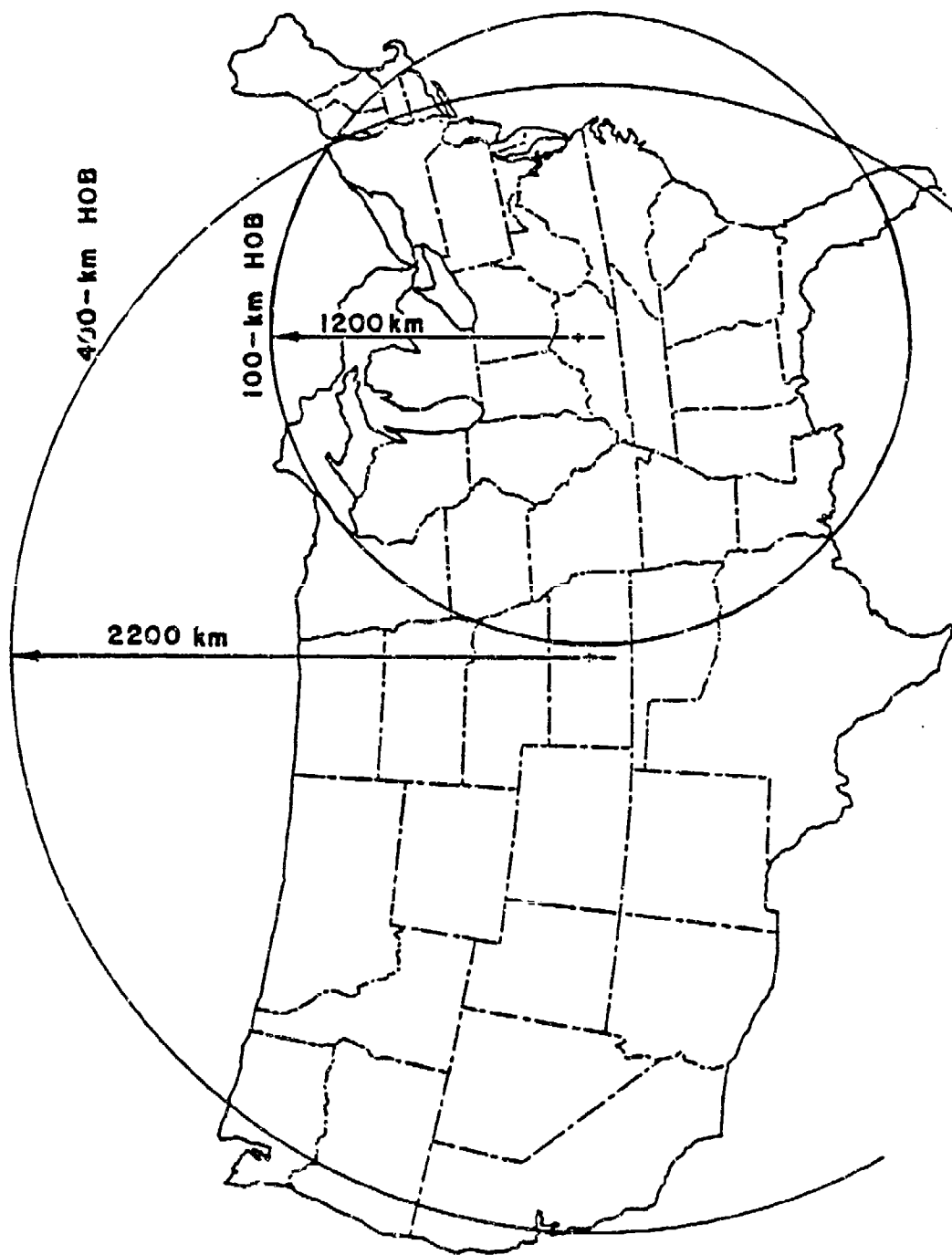


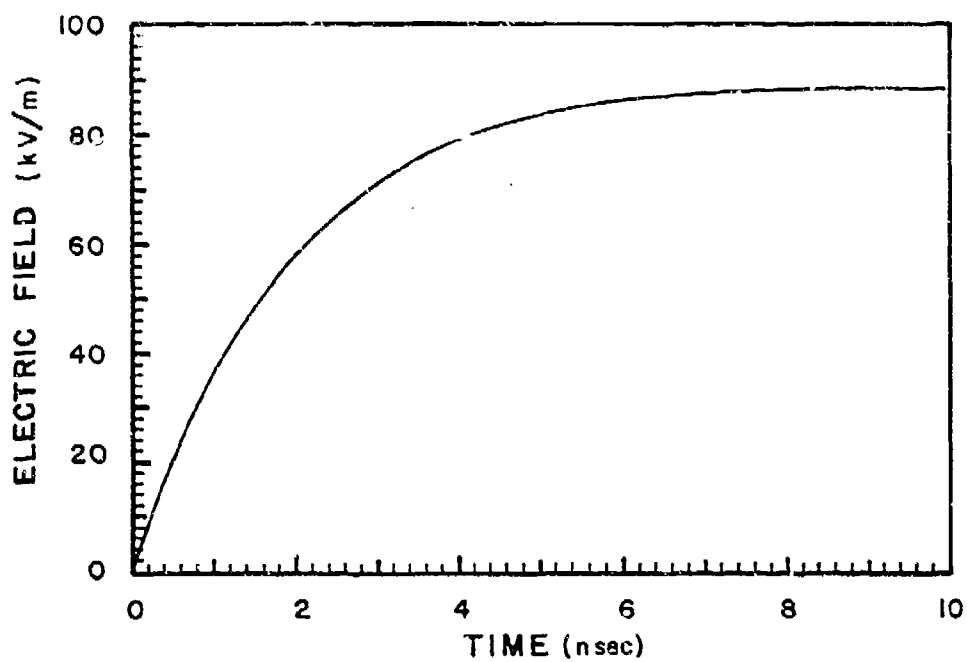
Figure 1. AREA OF COVERAGE OF EMP FROM HIGH ALTITUDE DETONATIONS

Based on calculations it is possible for a long line, oriented for worst case (maximum) pick up of voltage, to experience an EMP induced transient voltage of 4 MV. A typical waveform might have a magnitude of 1.5 MV and a risetime of 10 nanoseconds with a duration of 1 microsecond. Fig. 2 shows a typical EMP waveform.⁹

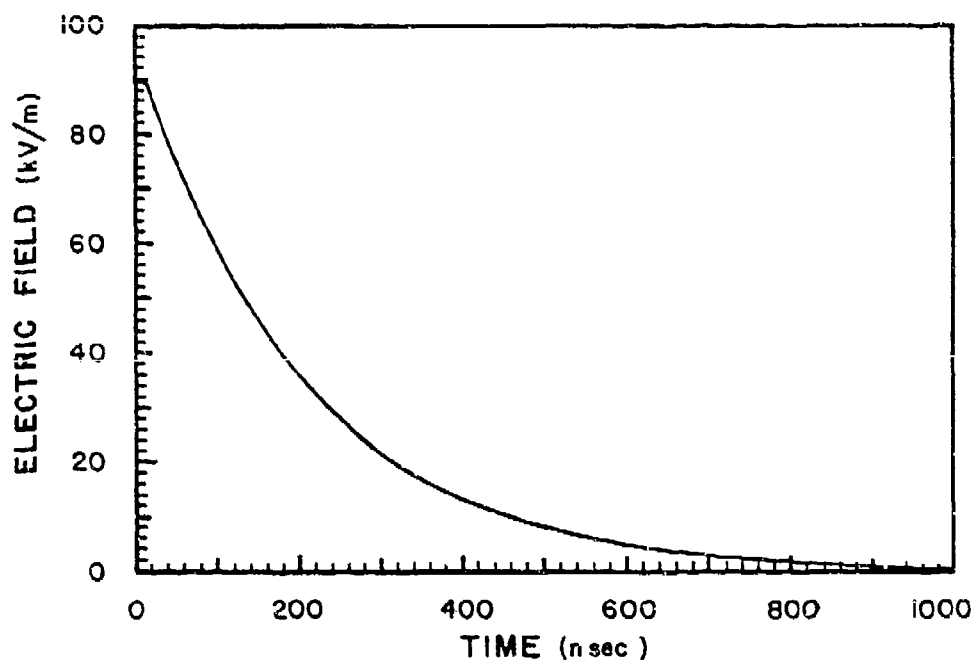
C. EMP effects on power systems

Manweiler¹⁰ enumerates possible EMP disturbances that might result on an electric power system. A short summary of these effects will now be presented, with emphasis placed on the equipment that might be damaged by EMP.

1. Faults on overhead lines - The voltage induced on an overhead line is basically a common mode effect. That is, all phases are affected equally so that line-to-line voltages are minimal but line-to-neutral values are significant. The induced voltages at line discontinuities (terminations, junctions, changes in direction, etc.) are more severe than the long straight portions of the line. Thus, faults in substations are quite possible. This is true in spite of the presence of lightning arresters which have a significant turn up of sparkover voltage for the fast rise-time EMP waveform.⁸ The problem of lightning arrester turn up will be covered in detail in Chapter IV. The insulation level of transmission lines will probably allow them to withstand the stress of one or even repetitive EMP's. On the distribution lines, this is probably not the case. The EMP induced surges may cause numerous faults on the distribution system. Once these faults are initiated by the EMP they will be maintained by the flow of power frequency current. Faults that occur on overhead



(a) EARLY TIME



(b) LATE TIME

Figure 2 TIME HISTORY OF THE REPRESENTATIVE EMP.

lines may be cleared by the operation of relays and circuit breakers. In addition, if the line is reclosed after the fault is cleared, the reclosure will probably be successful since no permanent conducting path for current exists. However, successive EMP-induced faults may cause reclosing circuit breakers and reclosers to lock out.

2. Lock out of reclosers and reclosing circuit breakers. - Most distribution lines are protected by some sort of device that recloses the line after a fault is cleared. All such devices have a common characteristic; if they count a certain number of faults (usually 3 or 4) in a specified period of time they will lock out or not reclose until they are reset manually. If a series of EMP induced faults occurs in a short period of time (a matter of minutes), this will be interpreted by the recloser or reclosing circuit breaker to be a permanent fault. This could result in a sudden loss of load on the electric power system.
3. Destruction or malfunction of relays - Most relays in the electric power system would not be vulnerable to damage or malfunction due to EMP surges. Only solid-state relays would be vulnerable. These modern relays are normally applied to EHV lines and frequently have an electromechanical back-up set of relays. This is a particularly vulnerable item. The EMP may cause these relays to fail in an unsafe mode (causing the line to trip out).
4. Generator trip out - Generators may be tripped out by two separate and distinct effects. First, the EMP may induce voltages and currents in the generator control circuits that cause the generator to trip out.

Second, the disturbances caused in the power system (distribution system faults, etc.) may cause the generator to trip out due to overspeed or underspeed.

5. Interference with tie-line monitoring or control - Various transmission systems are connected by tie lines. The flow of power on these lines is constantly monitored and controlled. These monitor and control circuits could suffer direct damage due to EMP or they could cause tie lines to be severed due to abnormal power flows during the period subsequent to the EMP-induced faults on the systems.

6. Damage to or malfunction of computerized control and dispatch centers. - Several large systems and power pools have installed computerized control and dispatch centers to monitor the system operation with the goal of optimal economic operation as well as monitoring and control for system security. The digital computers in these system security centers are subject to memory erasure and/or upset due to EMP unless the buildings in which they are located are specially shielded from EMP. Operational malfunctions create temporary problems with the use of a device (such as false tripping of a relay), as opposed to permanent physical damage to the device. The protection of computers from EMP involves known technology, but it is accompanied by significant additional cost.

From the above it can be seen that there are numerous items of equipment that can be damaged due to EMP, either directly or indirectly. In subsequent chapters, the feasibility of protecting some of these items of equipment by performing remote switching with the

supervisory control system or manual switching using dispatched personnel will be explored.

D. Importance of EMP protection of electric power systems

The possible damage that could be caused on an electric power system by EMP was reviewed in the previous section. The importance of this potential damage is that it is very widespread geographically. When heat and over-pressure effects are present, they are generally much more serious than possible EMP effects. Damage radii for various items of power system equipments have been established for different sizes of weapons.¹¹ These are shown in Table I. From the table it can be seen that many power system components will not be damaged unless they are relatively close to a target (within 4 to 22 miles). Apparently no quantitative analysis has been made to use these data with an assumed list of targets and weapon yields to determine the percentages of power components that would be damaged. Depending upon the number of weapons, it is conceivable that a sizable portion of the nation's power systems would escape damage from the blast, unless targeted, but would be subjected to damage by EMP.

One could envision the possibility that the combined effects of faults caused by lines broken or knocked down by blast effects and faults induced by EMP could lead to a nationwide blackout. Little can be done to alleviate the effects of the blast. However, the combined effects of moving some of the vulnerable equipment off-line (thus reducing the number of EMP-induced faults) and placing the power system into a more secure state could avoid a nationwide blackout.

TABLE I
BOMB DAMAGE SUMMARY
SUMMARIZED FROM (DEPA, 1962)

Feature	Damage Radii (Mi)			Type & Extent of Damage
	1MT	5MT	10MT	
Transmission line radial orientation	3.7	6.3	8.0	Inside damage zone, lines are broken & down - not operating. Outside zone line is easily repaired.
Transmission line transverse orientation	5.0	8.6	10.8	More severe damage than radially oriented. Difficult to repair.
Transmission line underground	8.2	17.7	22.3	Less severe than to surface lines. Damaged by secondary effects. Many still usable.
Buildings used to house generating facilities	3.7	6.3	8.6	Building damage occurs but equipment inside is generally undamaged although possibly inoperable.
Distribution transformers, outside	4.0	6.8	8.6	Usually undamaged up to 5 psi. At over 5 they are overturned & damaged.
Fire zone	4.5	7.7	9.7	Widespread fires in these areas. Poles may be destroyed and repair operations delayed.

One could idealize the configuration that one would like to achieve for the electric power system in order to make it as resistant to blast and EMP effects as possible. First, one would like to move as many vulnerable items of equipment as possible off-line and second, reduce the system load to as small a value as possible. If possible, it would be desirable to increase the spinning reserve by bringing extra units on line. In the assumed warning period this would be difficult. When the inevitable faults occur, the tendency for the generators to accelerate and loads to decelerate are reduced sharply if the load is as small as possible.

Justification for the above remarks is as follows. An electric power system is always in a more secure state when its spinning reserve is greater. This can be visualized by the equal area criteria for stability or other analytical means. EMP effects may cause a reduction in load but the resulting dynamic response of the system could cause the system to break up into islands. With the maximum number of units on-line, there is a greater possibility of each island having adequate generation. This is a very complex subject and has been the focus of an extensive report.⁷

E. Scope of research

The primary goal of the research was to determine the feasibility of isolating the vulnerable equipment of the electric power system from sources of EMP by remote switching through the use of supervisory control or by manual switching by personnel dispatched to substations. This was to be done for the power systems in the host and risk areas used in crisis relocation planning studies

(Freemont County and Colorado Springs), the state of Colorado and the United States. The feasibility of isolating equipment was to be determined for assumed warnings of 15, 30 and 45 minutes. One must recognize the distinct possibility of a precursor EMP attack from a submarine, in which case there may be no warning at all.

Secondary goals included the evaluation of the most vulnerable items of direct power system equipment (generators, transmission and distribution lines, transformers, circuit breakers, disconnect switches, etc.), as well as auxiliary equipment (potential and current transformers, relays, control circuits, etc.). An additional goal was to evaluate the impact of new power system technology on EMP susceptibility, in particular, new lightning arrester designs.

F. Methodology of data collection

The primary goal is actually to determine the feasibility of taking any meaningful action during the short period of time available between the first warning of an attack and the occurrence of the first few high altitude detonations. Thus, the most vital information is quantitative data on the percentages of substations in which switching could be performed in assumed warning periods of 15, 30 or 45 minutes. Switching at power plants will not be considered since switching at power plants will cause unit trip out due to overspeed when load is lost suddenly. The two primary vehicles for performing switching are by remote switching using supervisory control equipment or by manual switching by qualified personnel of power companies dispatched to individual substations.

A quick literature review yielded no direct data on either the

degree of saturation of supervisory control or the ability to reach unattended substations within a 15, 30 or 45 minute warning period. A series of utility interviews was selected as the best method of obtaining the required data. The goal of these interviews was not only to obtain the above mentioned quantitative data but also some information on the impact of the proposed actions on the power system operation. It was felt that this could best be judged by the personnel who operate the nation's power systems on a day - to - day basis. It was also felt that the utility personnel could provide important data on the components of the system that they felt were most vulnerable to EMP induced transients. Finally, data on the location and type of lightning arresters applied in the system were sought because they offer some protection from EMP.

The questionnaire used in the utility interviews to gather information covering the above facts is listed in Appendix B.

Another source of information that was anticipated was the manufacturers of supervisory control equipment. One company was found that had performed a marketing survey on the degree of saturation of supervisory control equipment. These data were very helpful in verifying the conclusions reached from the utility interviews.

The size of the sample used for utility interviews was an item of concern. There are over 3000 electric utilities in the United States. Clearly it would not be economically feasible to survey a significant portion of this large number of companies. However, it is possible to interview a few companies that represent a significant portion of the nations generating capacity (and customers served).

This problem of statistical significance of the data gathered will be examined in detail in Chapter II.

G. Utility Objectives

Generally, electric utilities have as one of their primary goals the continuity of service to their customers. This study represents the proposal of a radical action (dropping customers) as far as utility personnel are concerned. It is assumed that it is more important to preserve or protect vulnerable equipment during an EMP threat than to maintain continuity of service. The ability to re-establish the system after an attack is more important than maintaining the system during an attack.

Utilities feel that interties to neighboring utilities are vital to system reliability. During the proposed disconnect procedures and during the attack it may be better to sever the ties between companies. This is a difficult question to answer without complex system stability analysis. Certainly the possibility of breaking the transmission grid prior to an attack should not be dismissed.

Because customers will be dropped by disconnecting distribution substations through the proposed actions there will be regions with power interruption. This condition will not be considered a blackout. The term blackout will be reserved for the widespread loss of electrical service resulting from a loss of synchronism and generating units being tripped off line.

II. TABULATION AND ANALYSIS OF DATA

A. Tabulation of Raw and Percentage Data

Complete data on the saturation of supervisory control and the ability to perform manual switching were obtained for eight electric utilities. Actually, two of these were service corporations representing a total of ten operating companies, so that the data represent sixteen operating companies.

These data will now be analyzed on a statistical basis. Redundant data are available from a marketing survey and these will be used as a check on the data collected in the survey. The statistical analysis will include the determination of the absolute percentages of substations with supervisory control, substations with attendants, plus substations without an attendant or supervisory control that can be manually switched in 15, 30 or 45 minutes.

These data are presented in a series of tables. Table II contains the raw data for the eight companies for which data were gathered. Table III contains the data for each company expressed as a percentage of the number of substations on the system. Table IV lists the data for the combination of all eight systems and Table V lists the same results with the American Electric Power Service Corporation omitted from the totals. The reasons for omitting data for the companies of the American Electric Power Service Corp. will be presented below.

TABLE II

Raw Data for Eight Power Companies Interviewed

Company*	Total # of substations	# with supervisory control	# attended	# that can be switched manually in 15 min.	# that can be switched manually in 30 min.	# that can be switched manually in 45 min.
1	200	100	0	90**	5**	5**
2	40	7	0	17	16	0
3	23	3	0	9	5	6
4	290	90	0	100***	100***	0
5	174	166	2	3****	3****	0
6	925	90	11	250	50	25
7	1000	0	12	50	25	25
8	1163	106	0	209	208	0

*Company legend: 1- Public Service Co. of Colorado
 2- Dept. of Public Utilities, Colorado Springs
 3- La Plata Electric Co.
 4- Wisconsin Electric Co.
 5- Commonwealth Edison Co.
 6- Niagara Mohawk Power Co.
 7- American Electric Power Service Corp.
 8- Allegheny Power Service Corp.

** exact data - almost all in 15 min., remainder in 30 or 45 min.

*** exact data - remainder in 15 or 30 min.

**** exact data - remainder in 15 or 30 min.

TABLE III

Data for Eight Power Companies Interviewed Expressed as a Percentage
of Number of Substations

Company*	% with supervisory control	% attended	% that can be switched manually in 15 min.	% that can be switched manually in 30 min.	% that can be switched manually in 45 min.
1	50.0	0.0	45.0	2.5	2.5
2	17.5	0.0	42.5	40.0	0.0
3	13.0	0.0	39.1	21.7	26.1
4	31.0	0.0	34.5	34.5	0.0
5	95.4	1.2	1.7	1.7	0.0
6	9.7	1.2	27.0	5.4	2.7
7	0.0	1.2	5.0	2.5	2.5
8	9.1	0.0	18.0	17.9	0.0

* Company legend same as Table I

TABLE IV

Composite Results for the Eight Companies Interviewed - Raw Data
and Percentages

Data Type	Substations	Substations with supervisory control	Attended substations	Substations that can be switched manually in 15 min.	Substations that can be switched manually in 30 min.	Substations that can be switched manually in 45 min.	Substations that can't be switched in 45 min.
Raw Data	3815	562	25	728	412	61	2027
Percentage Data	--	14.7	0.7	19.1	10.8	1.6	53.1

TABLE V

Composite Results for Seven Companies Interviewed (AEP omitted)-
Raw Data and Percentages

Data Type	Substations	Substations with supervisory control	Attended substations	Substations that can be switched manually in 15 min.	Substations that can be switched manually in 30 min.	Substations that can be switched manually in 45 min.	Substations that can't be switched in 45 min.
Raw Data	2815	562	13	678	387	36	1139
Percentage Data	--	20.0	0.5	24.1	13.8	1.3	40.5

Analysis of Data

Examination of Tables II to V yields some interesting information. First, the electric utilities in the sample are of a diverse nature. For instance, in Table II, it can be seen that the system with the least substations had only 23 (and no generation of its own) while the system with the most substations had 1163. In addition, one can see that the attended substation is basically not a significant factor in this study since less than 1% of all substations in the eight companies are attended. Perhaps the most important statistic from these four tables is that over 50% of the 3815 substations in the eight companies interviewed could not be switched either manually or with supervisory control during an assumed warning period of 45 minutes.

Closer examination of the tables reveals that the data from the American Electric Power Service Corporation have a profound influence on the composite results. American Electric Power Service Corporation has 1000 of the 3815 substations in the eight company totals. This is over 25% of the total and because American Electric Power (AEP) has no supervisory control in their substations, omitting this company from the averages increases the percentage of substations with supervisory control from 14.7% to 20.0%. Similarly, omitting AEP reduces the percentage of substations that cannot be switched remotely or manually in 45 minutes from 53.2% to 40.5%.

The impact of the AEP data may be critical in the final conclusions drawn about the feasibility of the proposed protective actions. For instance, if one is able to switch 59.5% of the substations in 45

minutes he can take more effective action than if he is able to switch only 46.8% of the substations in the same time frame, assuming the increase in percentage implies that more critical loads are protected.

In an effort to answer questions regarding the size of the sample and whether AEP is only an anomaly that should be dropped from the totals, further analysis of the data to obtain confidence limits will be presented.

B. Confidence Limits

When one realizes that there are over 3000 public and privately owned electric utilities in the United States, it is clear that eight utilities and service corporations (or sixteen individual operating companies) represent a very small sample size. In fact, the sample is only 0.533% of the total number of companies, if one considers the sample to consist of 16 operating companies. However, one should realize that it is the number of substations or customers that is of most interest, rather than the number of companies.

One way to analyze the data related to the saturation of supervisory control is to look at the percentage of substations with supervisory control for each company as a statistical observation, without regard to the number of substations in the system. There are eight observations available, so that one can compute the mean, standard deviation and confidence limits in these results assuming a normal distribution.

One can compute similar quantities for the percentage of attended substations, and unattended substations that have no supervisory control but can be reached to perform manual switching in 15, 30

or 45 minutes.

Using data from Table III, the mean value of percentage saturation of supervisory control is

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

Using the eight values from Table III, one obtains $\bar{x} = 28.21\%$.

Similarly, the variance is

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \quad (2)$$

Using the eight values from Table III and $\bar{x}$ calculated above one obtains $s = 31.27\%$. The fact that s and $\bar{x}$ are nearly equal indicates that one needs a large number of observations to be reasonably confident that the calculated mean is close to the actual mean. To be specific, one can calculate the 95% confidence limits in the means. The 95% confidence limits are

$$\bar{x} - t_{n-1, \alpha/2} s / \sqrt{n} < \mu < \bar{x} + t_{n-1, \alpha/2} s / \sqrt{n} \quad (3)$$

The quantity $t_{n-1, \alpha/2}$ is called the "t" statistic and is tabulated in many books on statistics.¹² For the eight observations of percentage of substations with supervisory control of Table III, the 95% confidence limits are calculated as 2.06% and 54.36%. This means that one can be 95% confident that the actual mean value of percentage of substations with supervisory control (unweighted) is in the range of 2.06% to 54.36%. Obviously, this is quite a large range. One can estimate the number of observations needed to produce 95% confidence limits with a specified width. The number required is

$$N = \left(\frac{Z_{1-\alpha/2} s}{d} \right)^2 \quad (4)$$

where $Z_{1-\alpha/2}$ is the "Z" statistic

s is the standard deviation in %

d is the desired tolerance in %

Some question may exist concerning the use of the "Z" statistic in equation 4 instead of the "t" statistic. This is justified upon the basis that the number of observations predicted will be generally quite large. To determine the mean with a tolerance of 5% with 95% confidence limits one would need

$$N = \left(\frac{(1.96)(31.27)}{s} \right)^2 = 151 \text{ observations}$$

Quantities similar to these ($\bar{x}$, s and N) can be computed for attended substations and substations that can be switched manually in 15, 30 or 45 minutes.

Table VI lists the means, standard deviations, upper and lower 95% confidence limits and the number of observations needed to get the 95% confidence limits within $\pm 5\%$. Table VII lists the same quantities as Table VI for the set of seven utilities formed by omitting data for the American Electric Power Service Corporation.

The preceding analysis assumes that all systems have the same number of substations and that the number of systems in the population is infinite. Because this is not the case, it is possible to select 20 or 30 of the largest companies in the United States and cover the majority of the nation's customers and have reasonable confidence that the results are close to the actual values. To a lesser extent,

TABLE VI

Means, Standard Deviations, 95% Confidence Limits and the Number of
Observations Needed to Get 95% Confidence Limits for the Eight
Companies Interviewed

Observation Quantity	% substations with supervisory control	% attended substations	% that can be switched manually in 15 min.	% that can be switched manually in 30 min.	% that can be switched manually in 45 min.
Mean ($\bar{x}$)	28.21	0.45	26.60	15.78	4.23
Standard Deviation (s)	31.27	0.62	16.78	15.28	8.93
Lower 95% Confidence Limit in Mean	2.06	0.00	12.57	3.00	0.00
Upper 95% Confidence Limit in Mean	54.36	0.97	40.63	28.56	11.70
Number of Observations Needed to Get 95% Confidence Limits within $\pm 5\%$ (N)	151	1	44	36	13

TABLE VII

Means, Standard Deviations, 95% Confidence Limits and the Number of Observations Needed to Get 95% Confidence Limits for Seven Companies (AEP omitted)

Observation	% substations with supervisory control	% attended substations	% that can be switched manually in 15 min.	% that can be switched manually in 30 min.	% that can be switched manually in 45 min.
Quantity					
Mean ($\bar{x}$)	32.24	0.34	29.69	17.67	4.47
Standard Deviation (s)	31.46	0.59	15.48	15.46	9.62
Lower 95% Confidence Limit in Mean	5.93	0.00	16.75	4.74	0.00
Upper 95% Confidence Limit in Mean	58.55	0.83	42.63	30.60	12.51
Number of Observations Needed to Get 95% Confidence Limits within $\pm 5\%$ (N)	153	1	37	37	15

this is what occurred with the sample that was actually used. Of the eight companies selected, six would be considered large companies. These six companies represent the bulk of the generation capacity and substations in the eight company sample used.

It should be remembered that the primary interest is the ability to perform switching operations to protect the system by moving vulnerable equipment off line. Thus, the sample size in companies is not as important as the sample size in terms of load or number of substations.

With this in mind, the size of the sample was examined from a second point of view. The nation's generating capacity is in the range of 500,000 MW or 500,000,000kW. The eight companies interviewed have a total capacity that is over 50,000 MW or 50,000,000kW. Thus, the eight companies have over one-tenth of the nation's generating capacity.

It may seem odd that such a small number of companies could produce such a significant percentage of the nation's electric power when there are around 3000 companies in the United States. However, many of these 3000 companies are very small municipal power companies and rural electric association cooperatives. Most of these companies serve customers directly but buy their electric energy from larger companies or government agencies such as TVA or BPA.

In summation, it may be stated that the confidence limits as predicted by the statistical techniques are much broader than they should be because the sample included several large companies. Due to these large companies, it is felt that a significant portion of the

nation's substations have been included in the percentages calculated.

It should be pointed out that data from another source have been obtained to verify the percentage of substations with supervisory control. However, it is important to show the statistical significance of the data obtained by interviews on attended substations and the ability to perform manual switching in unattended substations without supervisory control in 15, 30 or 45 minutes since no other data are available for these quantities.

C. Comparison of Data from Various Sources

The primary source of data other than the interviews of electric utilities was a survey of electric utilities conducted by Moore Systems and presented in a special report that appeared in the July 15, 1977 issue of Electrical World.¹³ This survey included more companies although it is not as thorough as the utility interviews conducted during this study. It was addressed to companies in North America serving a peak load of 100MW or more. It is not clear whether the survey included Canada and Mexico. The results presented are limited to the total number of substations and the number of substations that are equipped with supervisory control. It is interesting that the data were separated into transmission substations and distribution substations. The essential data are summarized in Table VIII.

TABLE VIII
Data From Moore Systems Survey

Type of Substation*	Total Number	With Supervisory Control
Transmission	18600	8200
Distribution	57800	6800

* companies in North America serving 100MW or more

Analysis of the data in Table VIII reveals some interesting facts. The percentage of total substations with supervisory control is 19.63%. This is remarkably close to the percentage of substations of the utilities interviewed that had supervisory control if the data for the American Electric Power Service Corporation are omitted (20.0%). It is apparent that the American Electric Power Service Corporation incorporates unusual design and operating philosophies in their operating companies. This design philosophy leans heavily on automated response to system disturbances and de-emphasizes the use of dispatcher control of the system through supervisory control. Thus, inclusion of AEP distorts the statistical analysis. This is a very important conclusion because the data for American Electric Power Service Corporation not only affect the percentage of substations with supervisory control but also the percentage of substations that can be reached for manual switching in 15, 30 or 45 minutes. Because there are no other data available for these quantities it is important that one can imply that the percentages for these quantities with AEP omitted are applicable. Thus, one can have significant confidence in the data of Table V which indicate that almost 60% of the substations could be switched either remotely or manually in a 45 minute period. These data are presented graphically in Fig. 3 for all eight companies while Fig. 4 shows the same data with AEP omitted.

Another important conclusion drawn from Table VIII is that the percentage of transmission substations with supervisory control is much greater than the percentage of distribution substations with supervisory control. This is significant when one considers that the

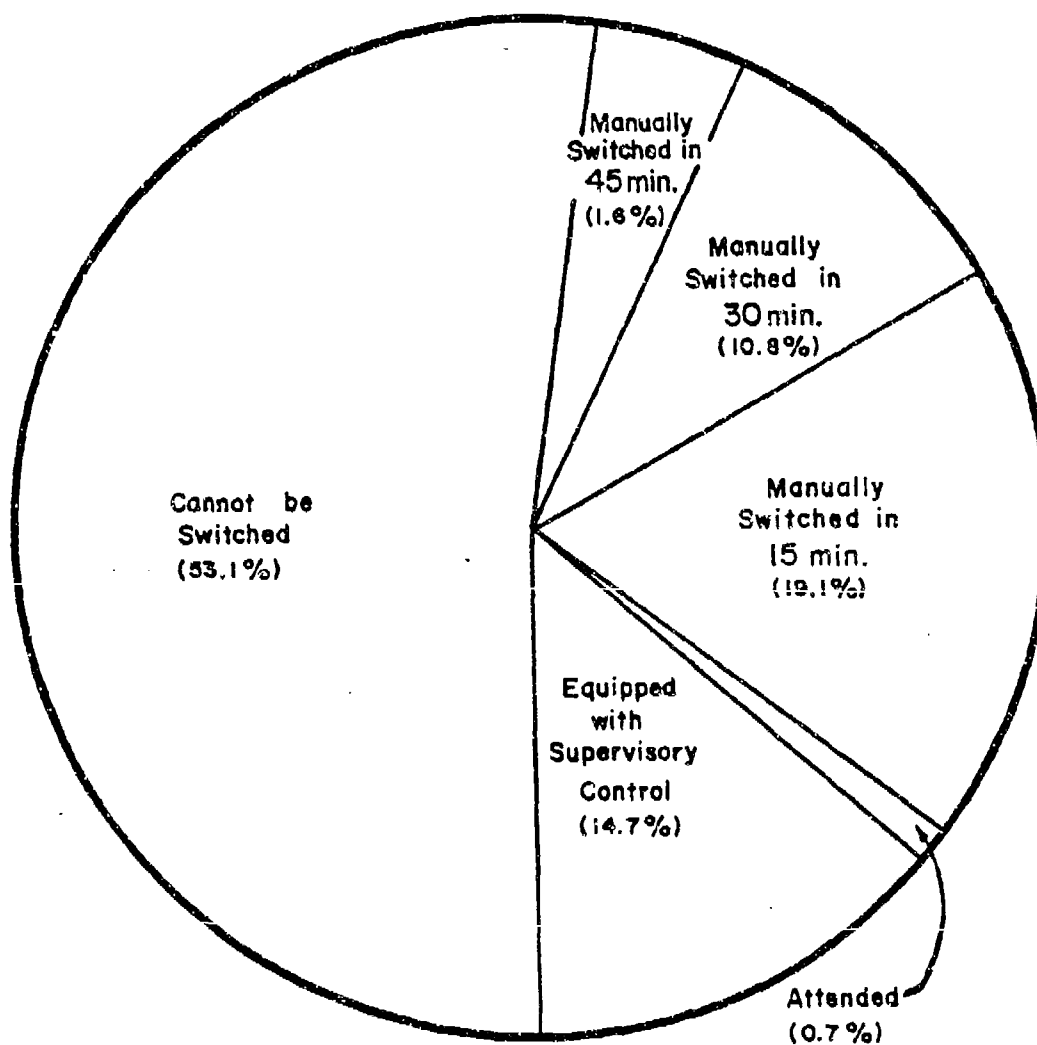


Figure 3 PERCENTAGES OF SUBSTATIONS THAT CAN BE SWITCHED BY VARIOUS REMOTE OR MANUAL MEASURES (based on eight utilities).

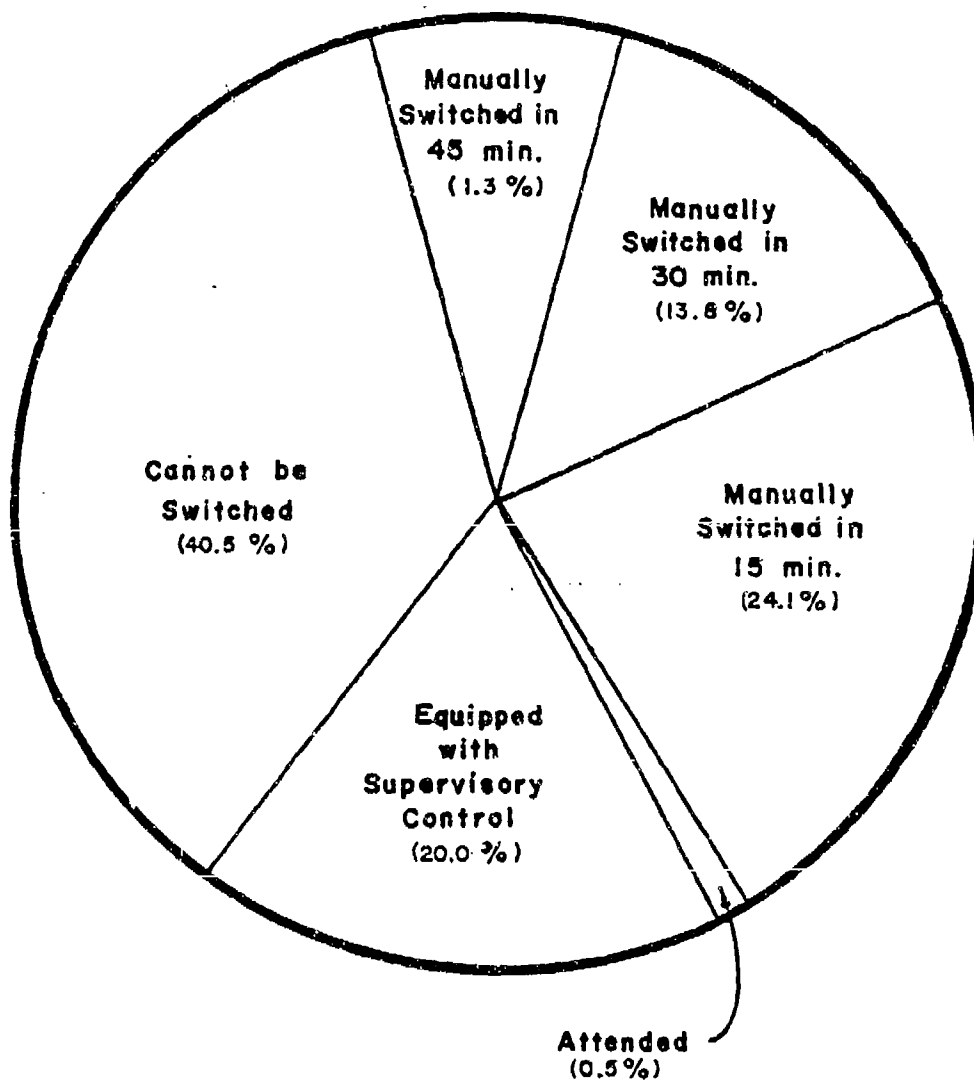


Figure 4 PERCENTAGES OF SUBSTATIONS THAT CAN BE SWITCHED BY VARIOUS REMOTE OR MANUAL MEASURES (based on seven utilities).

switching that one would like to perform would be in distribution rather than transmission substations. The reasons for this are twofold. First, the equipment in transmission substations has such a high BIL (basic impulse level) that it is not likely to be damaged by EMP and hence lead to system faults. This is not true of distribution substations that have lower BIL's and are vulnerable to EMP induced damage and are therefore a source of system faults. Second, if one wishes to trim load from the system to place it in a more secure state he would not wish to open breakers in transmission substations which would only weaken the transmission system. However, opening breakers in distribution substations would reduce load and could enhance the system stability if done properly.

This discussion points up a deficiency in the data collected in the interviews. Ideally, the number of transmission and distribution substations would have been separated throughout. That is, not only does one need the percentage of distribution substations with supervisory control but also the percentage of attended distribution substation and the percentage of distribution substations that can be switched manually in 15, 30 or 45 minutes. Similar data for transmission substations are interesting but are not vital to the study.

One can draw some conclusions on the number of distribution substations that can be switched in a 45 minute warning period in the following manner. The Moore Systems survey ¹³ covered a total of 76,400 substations (57,000 distribution and 18,600 transmission). Based on the results of the utility interviews it is likely that approximately 60% or 45,840 of these substations could be switched

either remotely or manually in 45 minutes. In the worst case, all of the transmission substations would be included in the 45,840 substations that could be switched. This would still leave 27,240 distribution substations or about 47% that could be switched as a lower limit. In reality, it would probably be possible to switch over 50% of the distribution substations since some of the 18,600 transmission substations would not be included in the 45,840 substations that could be switched.

For other periods of warning one can also derive a worst case value for percentage of distribution substations that can be switched to move vulnerable equipment off line. Using the same procedure and assuming a 30 minute warning period, calculations show that one would be able to switch at least 44.7% of the distribution substations. For a 15 minute warning this value would drop to 26.5%. For a shorter warning period only distribution substations with supervisory control could be switched. This would be only 11.8% of the distribution substations.

D. Qualitative Comments from Utility Representatives

Some of the comments made by electric utility representatives during the utility interviews are as significant as the quantitative data gathered because they demonstrate the level of EMP awareness in the industry. Basically, one can discern two basic reactions. One group of utility people had grave doubts about performing switching operations to move vulnerable equipment off line and hence limit EMP-induced faults. These engineers felt that the EMP threat would be confined to relay and control circuits. They were unaware that numer-

ous faults on the distribution system are likely. They doubted the feasibility of performing switching operations that would shed load without the wholesale loss of generation due to overspeed protection. These engineers also felt that their automatic load shedding equipment would allow them to "ride out" any problems from the EMP. It should be noted that these attitudes prevailed in the largest, most sophisticated systems that had a high degree of automation, large-complex generating plants and automatic load shedding equipment.

It should not be implied that all of the utility personnel were as negative as the reactions above would indicate. The next section of this chapter will be dedicated to summarizing the views of the majority of the utility personnel. These comments are largely based on the interviews with Julian Hayden of the Public Service Company of Colorado and Kenneth Wolters of the Wisconsin Electric Power Co.

Impact on Generation

The majority of the utility personnel interviewed agreed that a strategy of switching vulnerable equipment off line would have a profound impact on the generation in the nation's electric power systems. All of the engineers interviewed agreed that the first priority would be to maintain the maximum number of units on-line during both the pre-attack reactions and the EMP threat.

Most of the engineers interviewed agreed that the switching to isolate vulnerable equipment could create a problem with respect to system stability. The primary reason for this is the fact that as one performs switching operations he will drop load from the substations.

This reduction in load will cause the system frequency to rise and could possibly cause many generating units to trip out due to overspeed protection unless the necessary adjustments are made with respect to valve control on the boilers of individual units.

Several of the utility personnel interviewed outlined a procedure for moving to a more secure state. This procedure basically entailed reduction of generator output prior to load shedding. The procedure would require that communications channels exist between the system dispatching center, the generating plants and personnel at substations. These communications lines would consist of ordinary telephone lines, wireless communications and communications over carrier channels. The goal of reducing generation prior to reducing load (as a result of performing switching in distribution substations to isolate vulnerable equipment) is to avoid problems with overspeed protection. The system reaction to the reduction of generator output without an accompanied reduction of load will be a reduction in system frequency. The power system is more tolerant to underfrequency than it is to overfrequency. Once the frequency sags, the switching operations can be performed in substations to isolate vulnerable equipment and to drop load. After load is dropped and system frequency is restored, a new round of generation cutback followed by frequency sag and load reduction can be initiated.

In this manner two things can be accomplished: 1) vulnerable equipment in the distribution system is isolated, 2) the system is moved into a more secure or stable state as rotor angle differences become smaller due to lower system load. The ultimate state

produced by these procedures would be a system with the generation and transmission system intact but with essentially all loads disconnected so that the generators are running at auxiliary power levels. Auxiliary power is used to run various pumps, fans, fuel preparation equipments, etc. in the power plants. In reality, this point cannot be reached because of the inability to perform switching operations in 100% of the distribution substations.

Obviously, the reduction of load and moving equipment vulnerable to the effects of EMP off line will not completely protect the electric power system during an attack since it is still subject to the effects of heat and overpressure from the detonation of nuclear weapons. These effects will damage generation, transmission and distribution equipment. In the quiescent state described above, the system will be better able to survive these effects as well as the EMP-induced faults on distribution equipment not moved off line by the proposed switching operations. Hopefully, the faults caused by heat, overpressure and EMP will be removed by the system relaying without such a profound loss of load as to cause a widespread loss of synchronism and subsequent trip out of the bulk of the nation's generation capacity.

Depending upon whether the nation's power systems remain in synchronism or not, the post-attack recovery could be from one of two states. The worst case would be from a completely shut down system. In this case, one would be recovering from a nation-wide blackout similar to the 1965 Northeast blackout and the 1977 New York blackout with the following complications:

- 1) Lack of help from neighboring utilities who are busy experiencing the same problems.
- 2) Loss of some system facilities, permanently damaged by heat and overpressure.
- 3) Poor communications due to possible damage to the telephone system.
- 4) Impending threat of radio-active fall out.

The best state from which to recover would be one in which the generation had remained in synchronism, in spite of faults caused by heat, overpressure and EMP-induced effects on vulnerable equipment that had not been isolated by the proposed switching operations. The generation would be operating at a relatively low percentage of its rating due to the pre-attack measures.

Attempting to keep the entire nation in synchronism during the combined effects of overpressure, heat and EMP may not be realistic. It may be more practical to sever tie lines between companies and even allow the systems of individual companies to break into islands. Comparisons between these two divergent philosophies require very complex analysis. Utility personnel are generally in favor of maintaining synchronism, if at all possible. Maintaining synchronism seems to be something of an all or nothing philosophy.

Post Attack Recovery

Contrary to the experiences during the 1977 New York blackout, most utility personnel interviewed felt that they could re-start generators, that were tripped out, in 4-12 hours from a completely dead system. The time varied depending on the size and complexity of the system. The larger, more complex systems with sophisticated

generating units will require longer to re-start and bring back up to near full load.

Generating units can generally be classified into four subsets:

- 1) Conventional or fossil-fueled thermal units (82%)*
- 2) Combustion turbine units (part of total for conventional fossil)
- 3) Nuclear units (1%)
- 4) Hydroelectric units (17%)

* 1970 percentages based on generating capacities.

The preponderance of generation in the United States is of the conventional thermal type. The percentages of each type of unit in the United States are given in parentheses above. The best types of units for dead start are combustion turbines and hydroelectric units. Combustion units are normally installed as peaking capacity and are frequently used as a source of auxiliary power for plant re-start. The output of combustion turbines is available almost instantaneously. Hydroelectric units are also an excellent source of power for re-start. These units can be brought up to rated load very rapidly. However, combustion turbines and hydroelectric units can serve only a small percentage of the total load. Nuclear units can be brought up to rated load in about three hours, as long as the reactor has remained active (even without electric power being generated). Operating a nuclear unit during an attack may be dangerous. A policy decision based on considerable study needs to be made.

Conventional or fossil-fuel thermal units can be broken down into several types. There are single (one turbine) units, both with and without re-heat, common header units, tandem-compounded units and

cross-compounded units. These are listed roughly in the order of increasing complexity and difficulty in reducing to auxiliary power level, as well as re-start, if they trip out due to overspeed. The time required to re-start and load these units back to their rated capacity varies from 6 to 12 hours.

Additional Comments

Some additional comments made by utility personnel are appropriate to discuss here. First, loss of reactor control due to EMP was brought up by one utility representative. Barnes and Marable¹⁴ have looked at this problem and concluded that unshielded cables may experience transients as high as 88kV while coaxial cables or cables in conduit do not have significant transients voltages. This could cause faults in control cables. The utility representative interviewed suggested that they might consider shutting down their nuclear units upon notice of an attack. Second, officials of one large utility expressed doubts that it would be possible to bring one of their large units down from near rated load to auxiliary load level and stop there. They pointed out that most of their units are large and quite sophisticated and thus their ability to take the proposed actions is questionable.

Vulnerable Equipment

Utility personnel were more concerned that transformers would be damaged than any other item of equipment. They pointed out that faults internal to transformers (as opposed to bushing flashovers) are generally permanent and cause damage that is not field repairable. At least one utility representative expressed a fear that the thousands

and thousands of transformers on the distribution system could be damaged by EMP, thus eroding any benefit obtained by isolating a relative few transformers in distribution substations. This fear is not justified based on an IITRI study. ⁷

Other items of equipment that utility personnel saw as being vulnerable to EMP effects included supervisory control equipment, oil-filled cables, relays, power line carrier equipment, equipment with solid state devices, microwave equipment, and communications equipment. Only one utility representative expressed concern about direct damage to generators from EMP-induced voltage surges. Several of those interviewed expressed a concern about large, EHV transformers, particularly those at generating stations.

Perhaps the comments made by utility personnel with respect to vulnerable equipment are more interesting as a yardstick to measure the awareness of the utility industry on this subject as opposed to authoritative information on power system vulnerability.

Utility Views on Feasibility

The eight utility representatives interviewed were asked whether or not they felt the proposed protective actions were feasible. Of the eight replies, five were positive and two were negative. One of the reactions was quite non-committal. One of the negative replies was from the American Electric Power Service Corp. and it is generally felt that this reply was based on only their system (which can't be switched remotely or manually in 45 minutes to any extent) rather than the nation's power systems as a whole. The view of the second company was that their generating plants were large and complex and hence they would not be able to reduce the load on them to auxiliary levels without causing them to trip out.

III. FEASIBILITY OF ISOLATING EQUIPMENT VULNERABLE TO EMP

In Chapter II the conclusion was reached that approximately 50% of the distribution substations could be isolated by performing either remote or manual switching operations. This single number only reveals part of the answer as to whether it is feasible to isolate equipment that is vulnerable to EMP induced surges. In order to adequately assess the importance of this quantitative result, one must also look at the topology of substations, the impact of the proposed actions on the entire power system, the impact of the proposed actions on the pre-attack response of the general population, and the ability to depend on utility personnel to take the proposed actions. Each of these four items will be discussed in this Chapter.

A. Ability to Switch Vulnerable Equipment Off-Line

The mere ability to perform switching in 50% of the distribution substations is not sufficient to state that vulnerable equipment is being isolated. For instance, consider Fig. 5 which shows some of the typical simple layouts used in substations.¹⁵ Notice that the only circuit breakers present are on the low-voltage side of the transformers. The high-side protection is often provided by a high-voltage fuse for economic reasons. Any supervisory control would normally be applied to the low-voltage circuit breakers. The transformers can be completely isolated only by operating both the disconnect switches on the high-voltage side of the transformers and the low-voltage circuit breakers. These high-voltage switches are not always remotely controlled. Thus, if only the circuit breakers

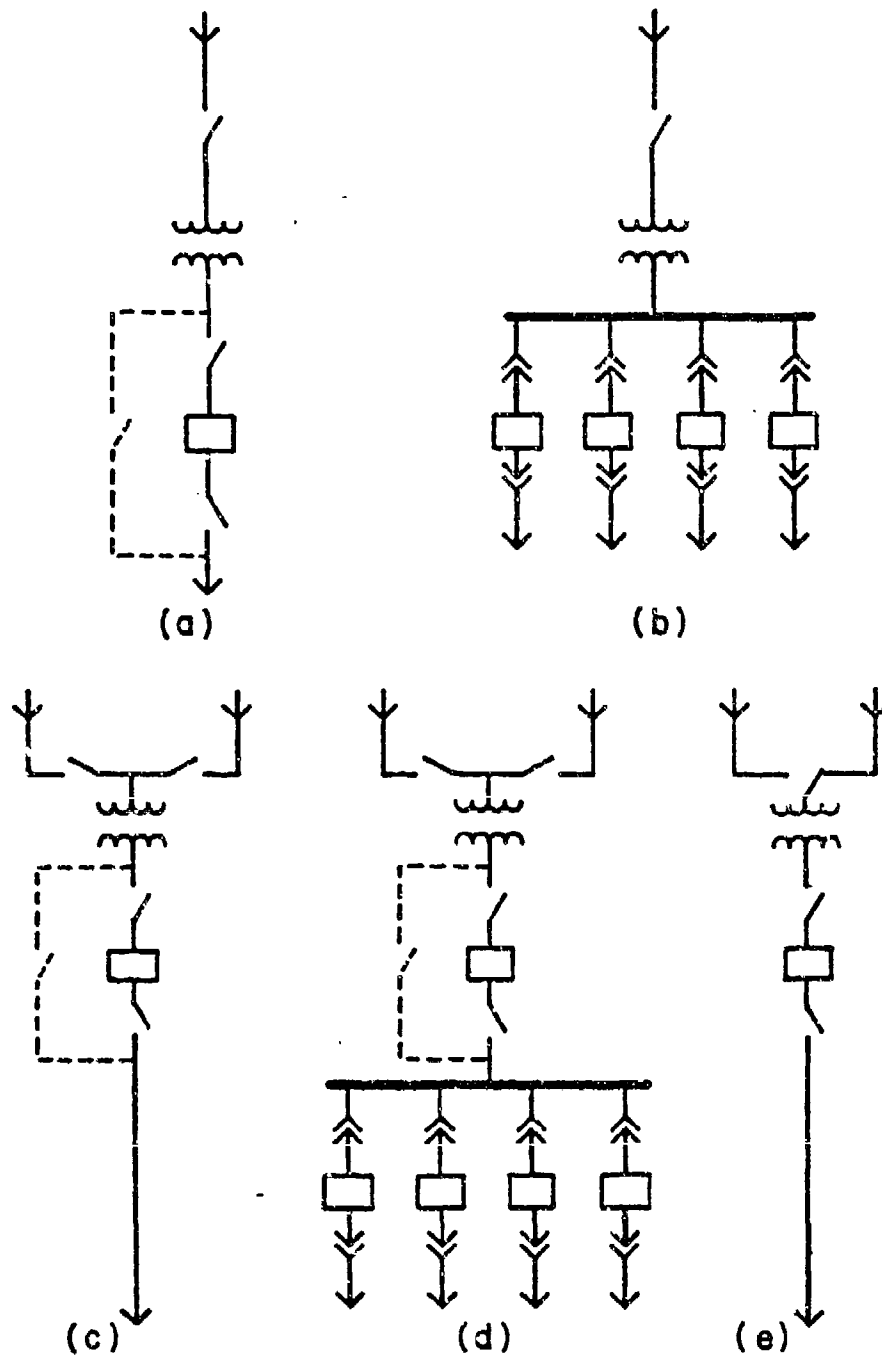


Figure 5 VARIOUS SUBSTATION CONFIGURATIONS WITHOUT HIGH-SIDE CIRCUIT BREAKERS, WITHOUT ALTERNATE SUBTRANSMISSION SUPPLIES (a and b) OR WITH ALTERNATE SUBTRANSMISSION SUPPLIES (c, d, and e).

were tripped, the transformers would still be connected to the transmission system and would still be subject to EMF-induced voltage stresses from the transmission system.

It should be pointed out that some utilities can control breakers or disconnect switches on both the high- and low-voltage sides of their circuit breakers. Fig. 6 shows some typical substation layouts with circuit breakers on both sides of the transformer.¹⁵ The trend seems to be that the larger utilities(except AEP) have the ability to perform switching on both the high- and low-voltage sides of the transformer. In the light of the relatively small percentage of distribution substations with supervisory control, this is probably not a very significant factor. In cases where dispatched personnel are performing the switching, they could trip the low voltage circuit breaker and then, when the only current through the isolation switch is the transformer exciting current, it can be opened even if it has no load break rating.

B. Impact of Proposed Actions on Power Systems

One of the major impacts of the proposed actions on the nation's power systems was reviewed when comments of the utility personnel were reviewed. This was the impact on the generating equipment of the power systems. The number one concern of the utility personnel interviewed was that the wholesale shedding of loads would lead to the trip out of generators due to overspeed protection. This effect was discussed rather thoroughly in Chapter II, but it is not the only effect that is possible.

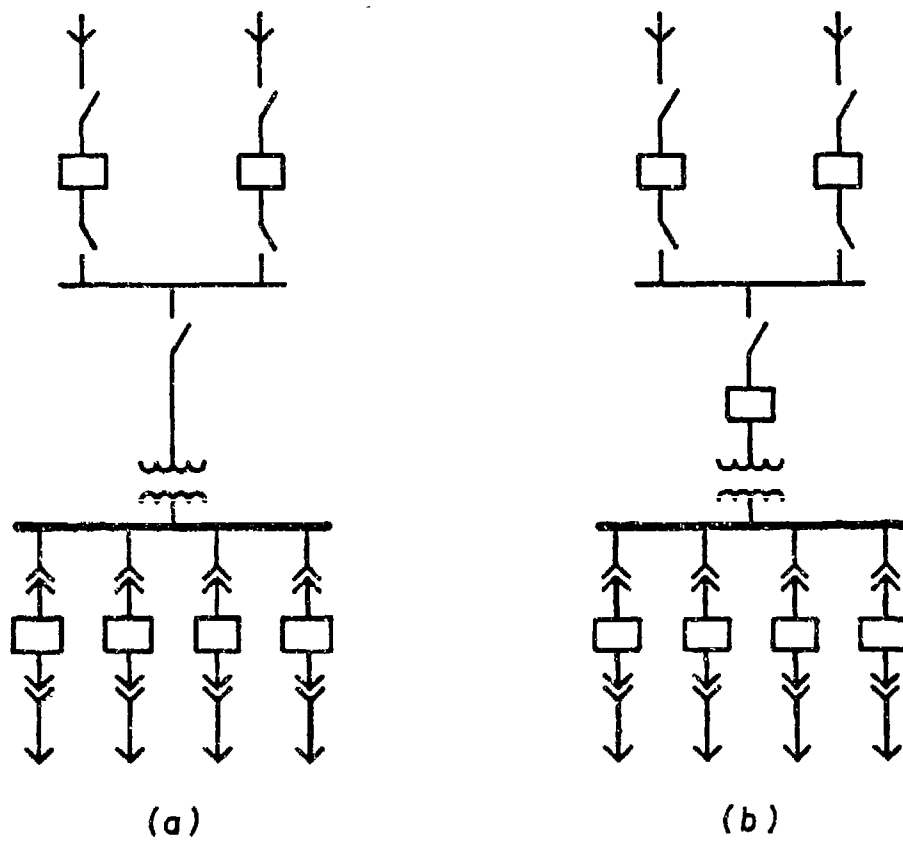


Figure 6 TYPICAL SUBSTATION LAYOUTS WITH HIGH-SIDE
CIRCUIT BREAKERS AND ALTERNATE SUBTRANS-
MISSION CIRCUITS.

Another effect caused by the shedding of loads is the increase of system voltage at the ends of long lines. This voltage rise is caused by drawing leading current (to supply the distributed line capacitance) through the distributed line inductance. For long lines (over 150 miles long), this effect can cause a voltage rise in the range of 10-15%. This rise in power system voltage can be dangerous and could lead to system faults, even in the absence of any transient effects. While system faults from this overvoltage are possible, they are not likely. What is more likely is the operation of lightning arresters due to excessive system voltage. This is an extremely grave problem since the operation of a lightning arrester on system voltage generally repeats on successive peaks of system voltage until the arrester fails due to thermal build up.

Another problem associated with the shedding of load is the problem of cold start up. Many loads on a power system are automatically cycled on and off (heating, air conditioning, refrigeration, freezers). When a system is shut down for a long period of time, all of these loads are ready to cycle on as soon as power is available. In some cases, the surge of load current due to this lack of diversity in the loads causes overload devices to trip out when the system is re-energized.

An allied problem is that of re-energizing secondary network systems. Secondary network systems are complex circuit arrangements used to serve the business districts of large cities with a very high degree of reliability. The system consists of a number of primary feeders that each supply a series of transformers.

The secondaries of the transformers on all of the feeders are interconnected by a grid of secondary cables. This arrangement is shown in Fig. 7.¹⁶

The secondary network system has proven to be a problem on re-start after black outs. If the disconnection and reconnection is done at the individual transformers, it is clear that the first transformer that is closed, tries to pick up all of the load. Even if the system is re-energized by connecting all the transformers to a given primary feeder and then closing in that feeder, the current drawn by the load through the one feeder could cause overloads and trip outs. Ideally, one would like to close in all of the transformers and then simultaneously energize all of the feeders. This requires a great deal of time consuming switching and communications from various locations in the field but it can be done.

These effects are important but are not as important as the loss of generation due to overspeed protection. The manner in which this problem could be avoided by reducing generation prior to load shedding, was reviewed in Chapter II.

C. Impact of the Proposed Actions on the Population

The loss of electrical service to a large area of the country will have profound effects on the nation's population. This was brought out during the large scale black outs in the Northeast in 1965 and in New York in 1977. The list of problems created by a blackout is very long and includes such items as people trapped in elevators, loss of traffic signals, loss of power for subways, elevated trains and electrified railways. Other problems are loss

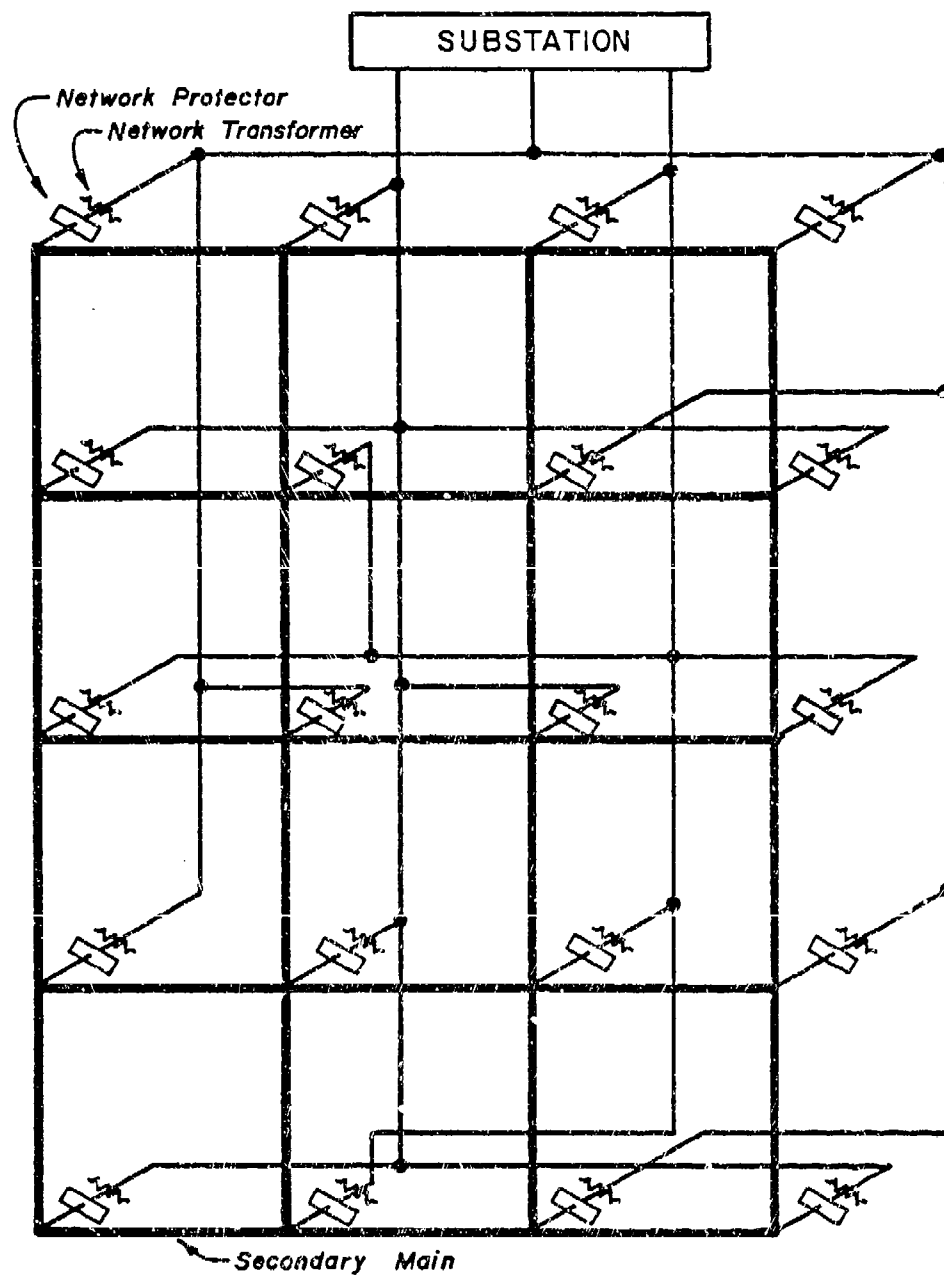


Figure 7 TYPICAL SECONDARY NETWORK SYSTEM

of power for industry and space conditioning, light for normal daily life, electrical power for food preparation and storage, etc. Because the proposed outage will have a duration of only a few hours, the major problems would be those related to transportation and the ability to move the population to relative safety within the assumed warning periods. This would present a clear conflict between protecting the power system and protecting lives. Thus, it is assumed that the proposed switching actions would be implemented only after crisis relocation has been implemented.

The above problem is not an easy one to address in a nation that values human life above material property. Certainly, one could rationalize that the preservation of the nation's electric power systems would be one of the vital factors in the nation's ability to recover from an attack.

D. Ability to Depend on Utility Personnel to Perform Manual Switching

Because the percentage of distribution substations equipped with supervisory control equipment is not large, there will be a strong dependence on utility personnel to perform manual switching. The possibility that these personnel will not perform these tasks during the threat of a nuclear attack must be considered a possibility. Certainly, one could try to extrapolate the performance of utility personnel during large-scale natural disasters to the pre-attack period.

The problems with extrapolating the behavior of utility personnel during natural disasters to a nuclear attack are many-fold.

Some of the differences are as follows:

1. People have a better understanding of the effects of floods, hurricanes, tornadoes, etc. than they do of nuclear warfare.
2. The geographical area covered by the destruction of property and the loss of lives are both more limited in natural disasters.
3. The utility personnel are generally asked to perform repair functions after a natural disaster as opposed to reacting during an alert period.
4. The utility personnel generally are aware that their families are "safe" after a natural disaster.

These items will now be discussed individually.

Natural disasters occur with a frequency such that many utility personnel have seen the effects of natural disasters that are common to their geographical area. Thus, the fear of the unknown is not a large factor. Few laymen realize the limited area coverage of the heat and overpressure from a nuclear detonation. Thus, even personnel that are in non-target areas may be very concerned with their own and/or their families' safety.

The geographical coverage of natural disasters is generally quite limited. Thus, there is a feeling that outside help will be forthcoming. This offers hope and encouragement to those involved in the disaster. Whether it is justified or not, it is likely that personnel will feel that damage from a nuclear attack will be universal. Thus, a feeling of hopelessness may prevail before an attack.

Generally, utility personnel are asked to perform repairs after a natural disaster, rather than during an alert period. This is distinctly different from the proposed actions during the alert period. After a flood, tornado, etc., the direct danger from the threat is over and people are more likely to leave shelter and perform their jobs. The personnel being dispatched to manually switch substations may be very hesitant about leaving shelter prior to an attack. Poor understanding of the targets, area coverage of blast effects, number of expected weapons, etc. will contribute to this hesitancy.

The point that was emphasized the most by utility personnel when discussing the reactions of their line crews, dispatchers, etc., during a disaster, was the knowledge that the families of the personnel were safe. Once the repair crews know that their families are safe they would generally work around the clock to get the system back in service. This could be a problem with regard to dispatching personnel to perform manual switching. Their ability to perform effectively might be contingent on their confidence that their families were not threatened by the attack.

In spite of these problems, the utility officials who were informally questioned felt that they could depend on their employees to continue to act effectively during a pre-attack period. This is really not an engineering problem. Perhaps it should be explored by a psychologist. However, the answers to some of these questions do have an important impact on the ability to protect vulnerable equipment via the proposed remote and manual switching operations.

IV. IMPACT OF NEW ARRESTER DESIGNS

A. Turn-up of Arrester Characteristics for Fast Rise Time Pulses

Perhaps some justification is needed for indicating that EMP constitutes a threat to electric utility power systems. The electric power system is protected from lightning and the EMP produces a lightning-like disturbance on the power system. The primary means of protecting an electric power system from lightning are the use of static or shield wires and the application of lightning or surge arresters. Neither of these means of protection are completely effective in protecting the system from the effects of EMP.

The use of shield wires to intercept lightning strokes and to divert the current to ground is not effective for EMP-induced voltage stresses. The phenomena are entirely different and the effect of the shield wire is totally different in each case. In the case of lightning, the shield wire by virtue of its greater height above ground provides a more attractive target for the lightning stroke than the phase conductors which are located at a lesser height. This is not a deterministic phenomenon but one can calculate the areas where lightning is more likely to hit the shield wire, phase conductor or ground. This is illustrated in Fig. 8 where the length $2x$ is the width of the swath where strokes have greatest probability of striking the shield wire, and $x' - x$ is the width of the swath on each side of the line where strokes to the phase conductor are most probable. In the region beyond x' from the centerline of the tower, the strokes would most probably be directly to the earth. If the

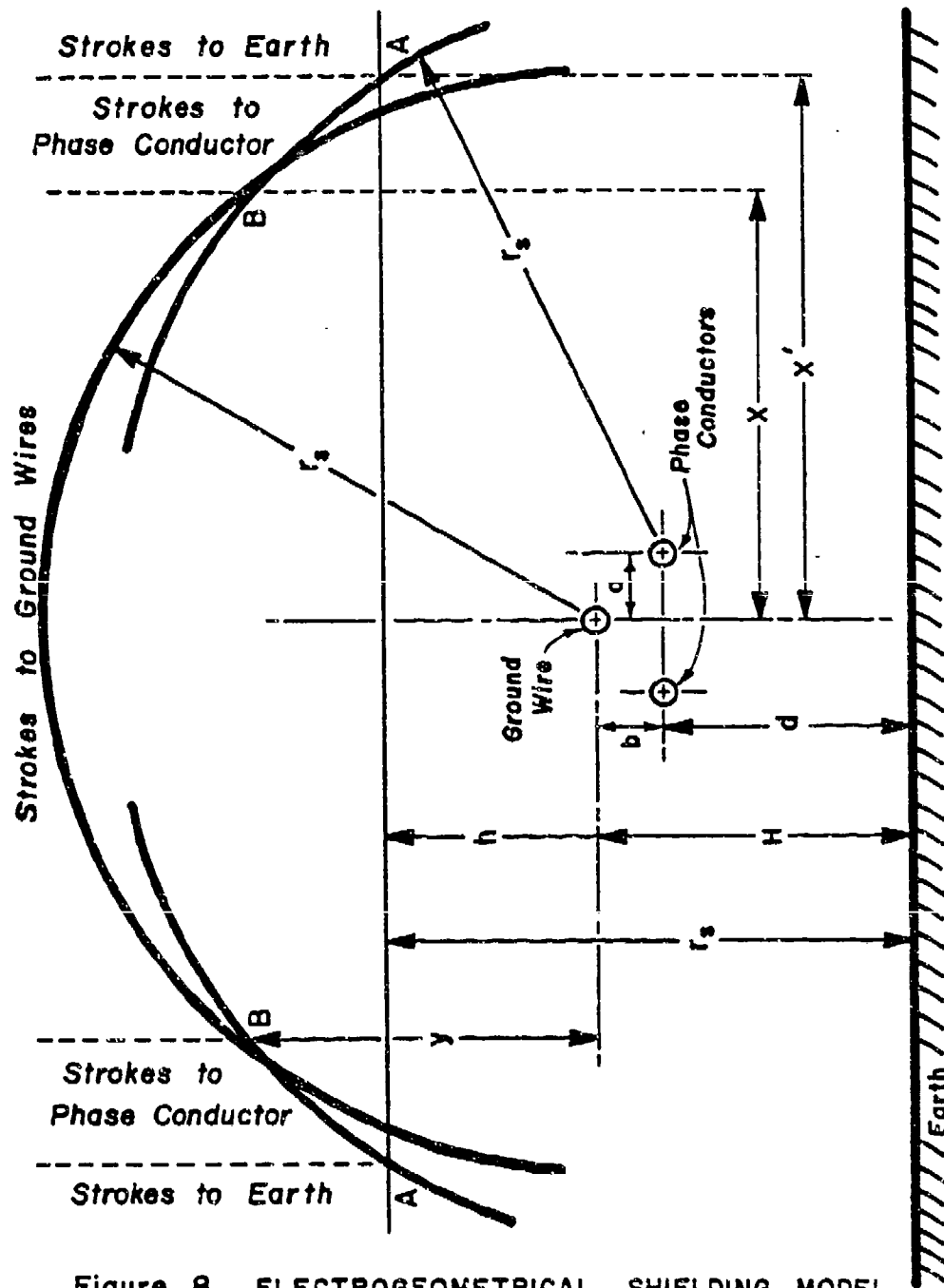


Figure 8 ELECTROGEOMETRICAL SHIELDING MODEL

stroke is to earth, the phase conductor will not normally be threatened. If the stroke is to the phase conductor, the shielding has failed and a flashover occurs to ground except for very low current surges on extra-high voltage lines. If the stroke is to the shield wire, certain voltages appear across the phase to ground insulation which depend primarily on the tower footing resistance. Suffice it to say that only very high current surges to the shield wire cause a flash-over and the line to trip out.

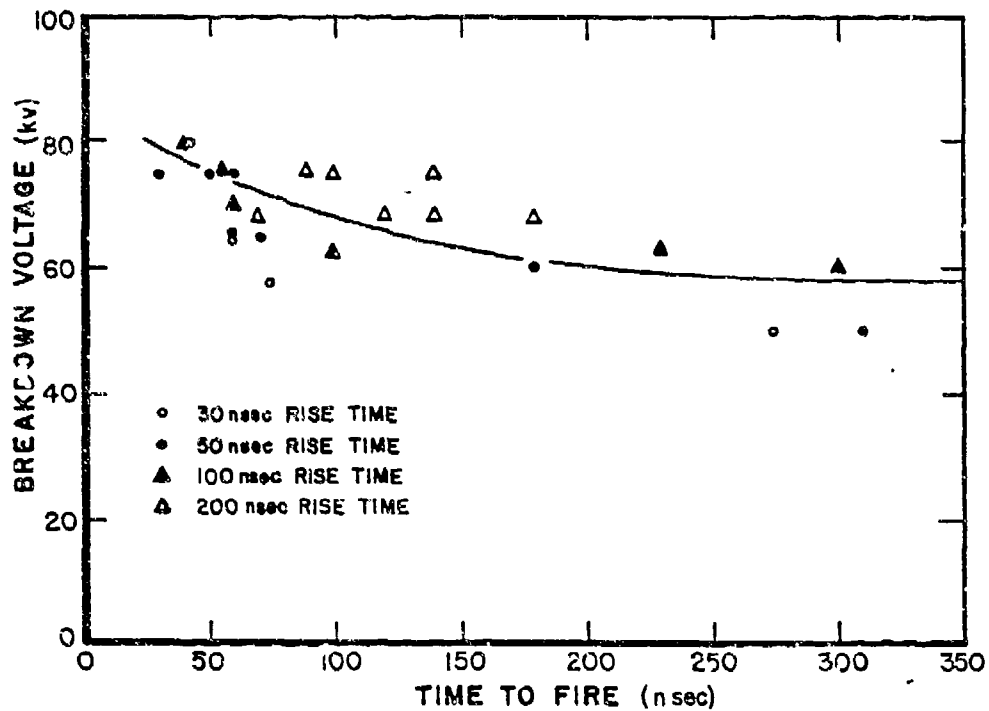
On the other hand, when EMP induces voltages on a transmission line of the same design, the shield wire does not protect the phase conductors in the same way. The induced voltage is essentially a common mode effect; all conductors whether phase or shield have the same induced voltage. The only shielding produced by the shield wire to the EMP is the result of current flow in the multi-grounded neutral. This current flow produces a component of voltage in the phase conductors of opposite polarity to the direct EMP induced voltage, through electromagnetic coupling. The net effect of this phenomena is to reduce the voltage on the phase conductor by about 20%. This is in contrast to the lightning case where the protection is essentially complete.

As seen above, lightning surges that are not sufficiently high to cause flashover of line insulation can be present on the phase conductors, either due to direct strokes of low current magnitude or due to induced effects of strokes to the static wire or to earth. When these surges enter substations the protection of equipment in the substation is accomplished by the proper application of surge

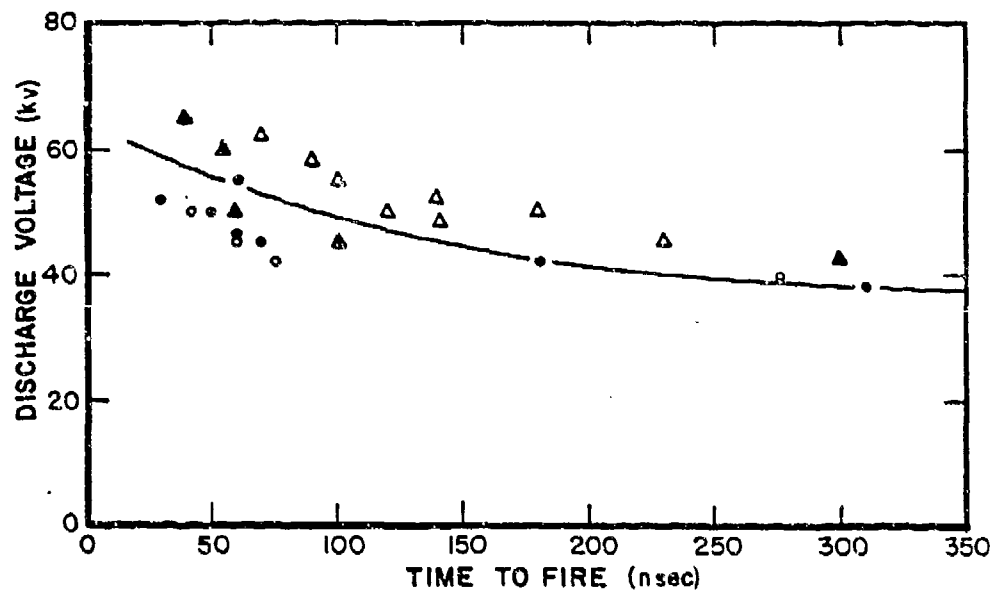
arresters. This is relatively easy to accomplish because the characteristics of both the lightning arresters and the vulnerable insulation are well known for lightning-type surges ($1.2 \times 50 \mu s$ surges). The major difference between the lightning-type surges transmitted into the substation and the surges from EMP is the relative rise times. The standard lightning pulse has a rise time of $1.2 \mu s$. The standard EMP-induced waveform has a rise time of 10 nanoseconds. The behavior of lightning arresters for these two types of surges is markedly different.

Marable, Barnes and Nelson⁸ presented some interesting test results for the breakdown and discharge voltages for a 9kV and a 15kV lightning arrester. Figs. 9 and 10 reproduce figures from their report. Fig. 9 a and b, respectively, show the breakdown and discharge voltages for a 15kV Kearney arrester. Fig. 10 shows the breakdown voltage for a 9kV arrester. The significant features of these curves is the turn up of the breakdown voltage for fast rise time pulses. Because the insulation breakdown voltage does not increase as fast as the breakdown voltage of the lightning arrester, the system insulation is not adequately protected. This has been verified in tests performed by Emberson.¹⁷

The breakdown voltages for arresters are presented in Table IX.



(a) Breakdown Voltage



(b) Discharge Voltage

Figure 9 BREAKDOWN AND DISCHARGE VOLTAGES FOR THE 15 KV KEARNEY ARRESTER.

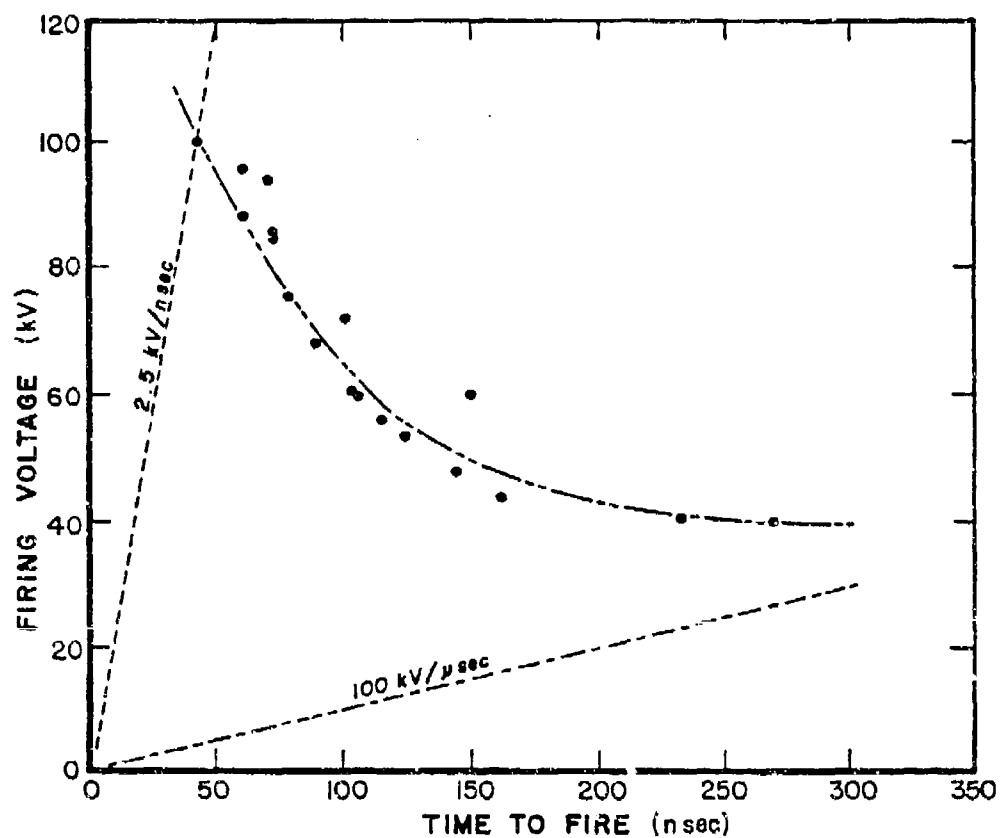


Figure 10 BREAKDOWN VOLTAGE FOR A 9KV ARRESTER.

TABLE IX

Arrester Breakdown and Discharge Voltages Versus Pulse Rate of Rise

Arrester Rating	Pulse Rate of Rise kV/nsec	Breakdown Voltage kV	Discharge Voltage kV
15 kV	0.28	60	40
	0.38	75	50
	2	75	50
	2.33	80	55
9 kV	2.5	100	
120-volts	5	7	

It is important that one compare these results to values for lightning-type surges. For slowly rising EMP surges with a pulse rate of rise of 2kV/ns, the sparkover voltage is about twice that due to lightning. Based on an extrapolation for a pulse rate of rise of 20 kV/ns the sparkover voltage could be as much as ten times that due to lightning.

The primary cause for the turn up of lightning arrester sparkover or breakdown voltage is the presence of an air gap in the conventional lightning arrester design. This gap prevents the flow of current for normal power system voltages. Only when the total voltage across this gap increases enough to cause the gap to flash-over does the arrester begin to conduct. Thus, the sparkover of the lightning arrester has many of the characteristics of an ordinary air gap.

Alston presents a set of interesting curves in Reference 13 which explain, to a great extent, the reason that lightning arresters that have a series air gap will not protect various items of the power system for very fast rise time pulses. Fig. 11 reproduces these curves. Notice that the upturn for the rod gap crosses over the curve for the transformer insulation for short periods of time. The air gap of the lightning arrester could give it a sparkover characteristic similar to the rod gap so that it would not be able to protect the transformer for fast rise time waveforms.

New arrester designs, described below have the capability of overcoming this problem at least in part.

B. Comparison of Conventional and New Lightning Arrester Characteristics.

Conventional lightning arrester characteristics used on transmission and distribution systems fall into two categories: expulsion type and valve type. Expulsion-type arresters are primarily a tube with a material coating on the inside that is consumed by the arc when the arrester sparks over. As the material is removed by gases expelled, the arc is cooled and stretched so that the power follow current can be interrupted. On the other hand, valve-type arresters consist of an air gap in series with a block of semi-conducting material. The air gap prevents conduction at normal power frequency voltages. The block of semiconductor is normally made of silicon carbide and it is vital to the interruption of power follow current. A valve type arrester made of silicon carbide without a series air gap would have problems with thermal runaway. That is, the current

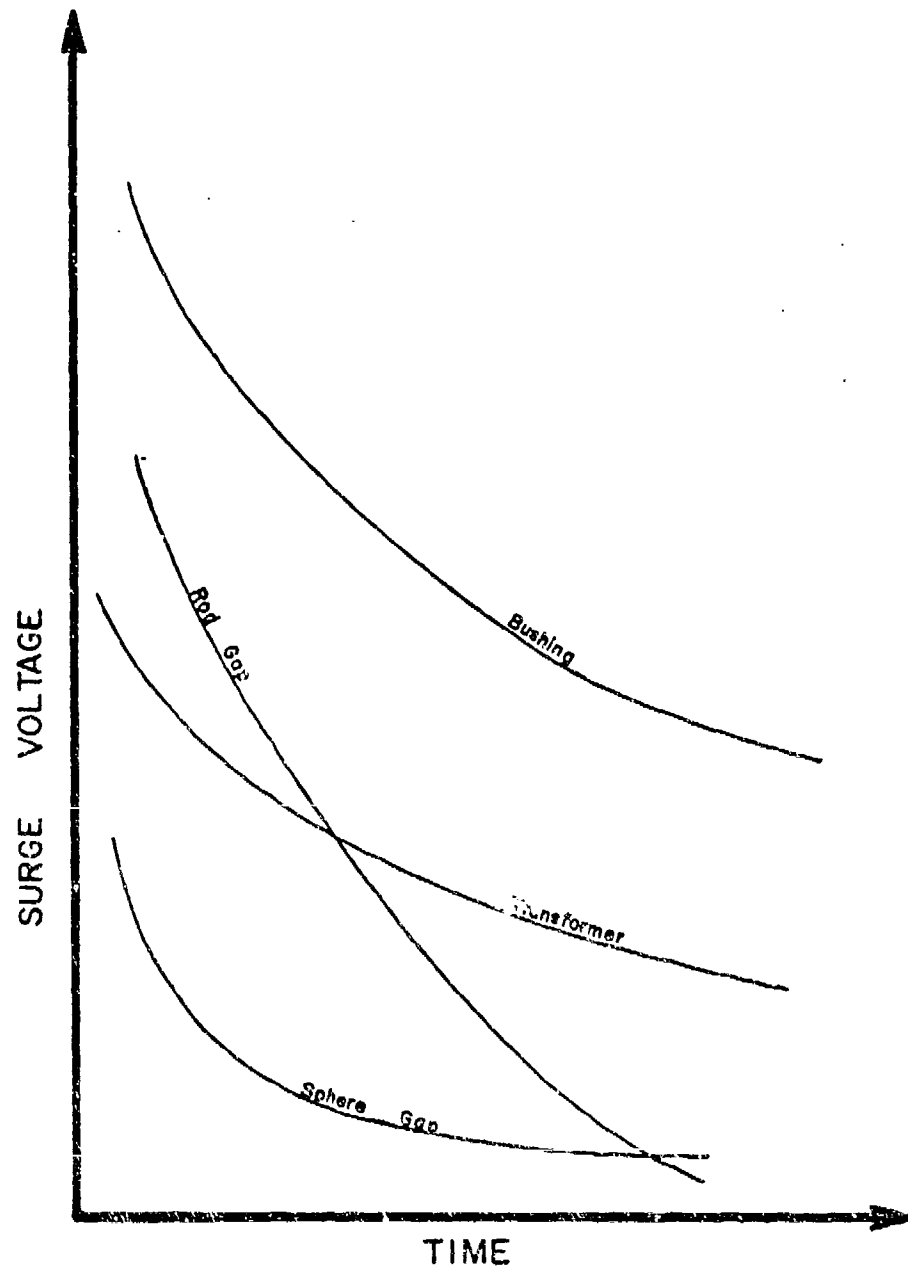


Figure 11 IMPULSE CHARACTERISTICS

flow caused by the power frequency voltage would cause heating of the semiconducting block which would lower the resistance, causing more current flow and heating, etc.

The latest breakthrough in lightning arrester design is a valve-type of arrester without an air gap that uses a different semiconducting material, zinc oxide. This semiconducting material has properties that allow it to avoid the thermal runaway problem described above. Walsh¹⁹ describes research being carried out to develop this arrester in the United States. Fig. 12 from this paper shows the discharge voltage versus time to crest for a block of zinc oxide material, a block of silicon carbide and a conventional silicon carbide arrester. Clearly, the ZnO block is inherently superior to the SiC block for fast rise time waves. When the SiC block is combined with an air gap to form an arrester, the performance for short time pulses is degraded substantially. Notice that this curve is only extended down to 0.1μ s. At 10 ns rise time the anticipated difference in discharge voltage between the ZnO arrester and the SiC arrester is much greater.

Obviously, the ZnO arrester would be far superior to the conventional SiC design with its series air gap for protecting equipment from EMP-induced voltages. While this arrester design seems to be in the research stage in the United States, a paper by Kobayaski et al,²⁰ indicates that ZnO arresters rated 42 to 140 kV have been installed on actual power systems of several electric power companies in Japan for about 2 years. This would indicate that the use of the newer arresters may not be far from reality.

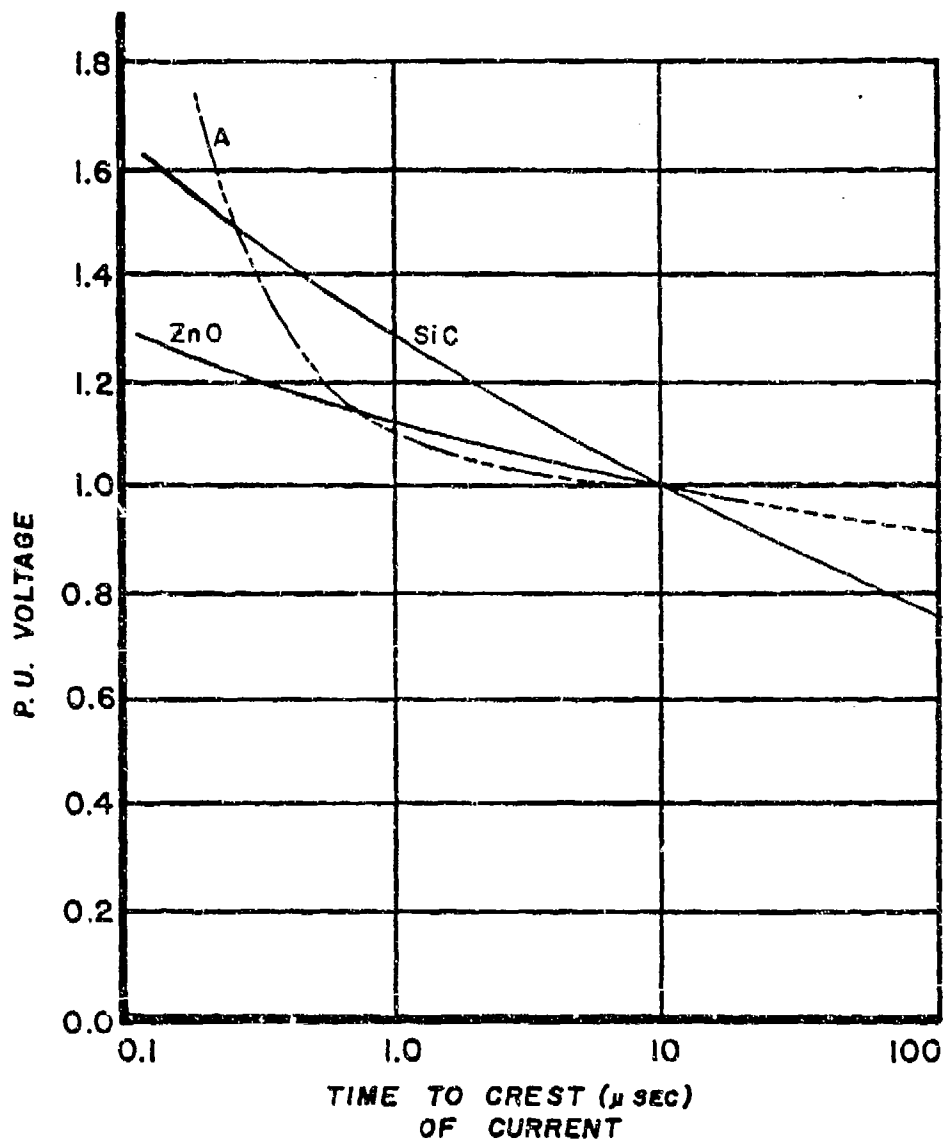


Figure 12 DISCHARGE VOLTAGE vs CURRENT WAVE CREST TIME (μ sec) FOR 10 KA DISCHARGE. THE PER UNIT VOLTAGE IS BASED ON DISCHARGE VOLTAGE ASSOCIATED WITH 10 μ sec. TO CREST ON CURRENT WAVE.

In order to assess the impact of these new arresters on EMP vulnerability one should examine the manner in which they will be integrated into existing and new power systems. It is highly unlikely that the advantages of the ZnO arresters over the SiC arresters will be sufficiently great for lightning or switching surges to justify a program of replacement of units in the field. It is more likely that the newer design will be used initially in applications where an expensive but vulnerable piece of equipment is involved. In time, as the new arrester design proves its worth in the field, a greater percentage of new installations will be of the ZnO type. Eventually, ZnO arresters may become the industry standard and as conventional arresters in the field are retired they will be replaced by ZnO arresters. This process may take a couple of decades but is characteristic of the cautious approach the electric utility industry uses in adopting new technology and their reluctance to scrap outdated but useable units in the field.

Based on the above discussion it would appear that in the long run, these new arresters could have a very positive impact on the ability of the nation's power systems to withstand the effects of EMP-induced voltages. However, it will be several years before enough of the new arresters are in the field to have a significant effect.

V. CONCLUSIONS AND RECOMMENDATIONS

The basic reason this study has been conducted was to explore the feasibility of electric power system operators isolating circuit breakers and transformers from transmission lines through remote switching by supervisory control panels, and manual switching at the substations in order to avoid power failures caused by EMP. In the process of conducting the study it was found necessary to assess the impact of the proposed switching actions on the power system, the degree to which utility personnel could be depended upon during a crisis and the effects of new lightning arrester designs on EMP protection. All of these primary and secondary tasks were performed.

A. Conclusions

The major quantitative conclusion drawn from the data collected was that about 50% of the distribution substations in the nation could be switched within a 45 minute warning period. The corresponding percentages for 30 and 15 minute warning periods are 44.7% and 26.5%, respectively. For a warning period shorter than 15 minutes, only substations with supervisory control could be switched. This is only 11.8% of the distribution substations. The percentage of substations would appear to be significant for all but the two shortest warning periods. Data from the literature would indicate that the percentage of distribution substations with supervisory control will grow significantly in the coming years (19.2% by 1982 according to Reference 13). Reference 21 predicts a 6% annual growth of installed capacity of supervisory control equipment.

The impact on the electric power system of the proposed actions would be acceptable if the cut backs in system generation were to precede the shedding of load, such that problems with overspeed relays were avoided. Because the percentage of substations that could be switched is only about 50%, the problems anticipated with controlling large units when they are operated at auxiliary level will not materialize.

Because the system cannot be totally disconnected even with a 45 minute warning, perhaps it is premature to talk about the priority of preserving the system or equipment versus continuity of service. However, it is clear that the ultimate goal is to be able to re-establish the production of electric power after the attack. Thus, if continuity of service must be sacrificed in the short run to achieve this long term goal, this is the obvious choice. This also means that one should consider the possibility of breaking the transmission grid prior to an attack. A decision on this item is beyond the scope of this study.

The impact of the proposed actions on the general population were reviewed in an extremely superficial manner. This is an area that requires much greater research effort than could be devoted to it in this study. However, it is safe to say that the important functions that would be interrupted by a partial blackout are traffic control, transportation systems, lighting and communications. Thus, it is clear that the proposed switching actions would not be implemented until after crisis relocation was complete.

The extent to which one could depend on utility personnel to perform the proposed actions during a nuclear attack, was explored in the utility interviews. Basically, utility executives had great confidence in their line crews, etc. based on experiences with natural disasters. Important differences exist between natural disasters and a nuclear attack, which may make extrapolations of this nature inaccurate.

New lightning arrester designs using zinc oxide semiconductors without air gaps lead to characteristics that are far superior to existing arrester characteristics for EMP-type surges. However, the likelihood is that it will be many years before arresters of this design represent a significant percentage of the arresters in the field, even though arresters of this design are being field tested in Japan. Perhaps federal aid could speed this change over to arresters with better EMP characteristics.

B. Recommendations

As is the case with many studies of this nature, several areas were revealed that required further study. An important and difficult question is the extent to which one could depend on dispatched personnel to perform switching during a warning of an impending nuclear attack.

A key question that also needs to be answered is the vehicle by which the warning will be transmitted to the utilities. It was emphasized by several utility personnel that the proposed actions were radical and were only acceptable as a once-in-a-lifetime measure. They said that operating personnel would hesitate to take these

actions until the message to switch vulnerable equipment off line had been confirmed. This could cut into the potential warning period considerably.

Clearly, a tremendous pre-planning effort is required before the proposed switching actions could be implemented by the electric power industry. Communications problems, studies of system reactions due to the switching, the advisability of maintaining tie lines, and other problems need to be studied in detail.

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APPENDIX A

SELECTED ANNOTATED BIBLIOGRAPHY

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-----, Summary Note on Report TR-61-B: EMP Protective Systems
by the Defense Civil Preparedness Agency, Lawrence Livermore
Laboratory, Livermore, CA, January 1977. This PEM is a summary
note, intended to acquaint the protection engineer with available
documentation that may be highly relevant to the solution of his
problems, to summarize the information contained herein, and to
specify sources from which documents may be obtained.

-----, Summary Note on Report TR-61-C: EMP Protection for AM Radio
Broadcast Stations by the Defense Civil Preparedness Agency, Lawrence
Livermore Laboratory, Livermore, CA, January 1977. The EMP threat is
described in the report, and compared/contrasted in some detail to
the lightning threat. While direct strike voltage and current
levels of lightning and the maximum induced levels from EMP may both
be very high, the spectra are sufficiently different that a system
protected from lightning might suffer EMP damage due to the higher
frequency energy content of EMP.

Fishbine, B. H., et al., Self-Consistency and Radiation Enhanced Ground Conductivity in the Surface Burst Code SCX, Science Applications Corporation, La Jolla, CA, November 1975. A description of the numerical techniques used to include the self-consistent effect in the two-dimensional ground burst EMP code, SCX, is given. The effect of this phenomenon on the fields predicted by SCX is discussed and illustrated.

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Graves, B. D., et al., Electromagnetic Field Penetration through Apertures, Dikewood Corporation, Albuquerque, July 1975. A numerical method is presented for determining the electromagnetic field diffracted by an aperture in an infinite conducting plate.

Gray, Robert F., Nuclear Electromagnetic Pulse Simulation by Point Source Injection Techniques for Shielded and Unshielded Penetrations, Harry Diamond Laboratories, Adelphi, MD, December 1975. The overall objective of the program reported herein is to develop current injection technology for threat and lower-level system EMP assessment.

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Hays, J. B., "Protecting Communication Systems from EMP Effects of Nuclear Explosions," IEEE Spectrum, May 1964, pp. 115-124. Electromagnetic pulses created by nuclear blasts propagate electric and magnetic fields that can damage today's complex and sensitive electronic equipment. The suggested protective measures draw heavily on lightning protection experience.

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-----, Generalized Boundary Condition in SEMP, Mission Research Corporation, Santa Barbara, October 27, 1975. This report describes a technique designed to model some structures which are not easily handled with a spatial mesh and conventional boundary conditions.

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APPENDIX B

QUESTIONNAIRE USED IN COMPANY INTERVIEWS

1. How many substations are there on your system?
2. How many of these substations have supervisory control?
3. How many substations without supervisory control are attended?
4. How many unattended substations could be reached in time to disconnect equipment in 15, 30 or 45 minutes?
5. What would be the impact on generating plants of the widespread disconnection of loads?
6. How difficult and lengthy would start-up be after disconnection?
7. Do you consider this plan of EMP feasible?
8. What types of lightning arresters are applied in your system?
Where are they located?
9. If your system has supervisory control, what company manufactures the equipment?
10. What do you consider to be the most vulnerable equipment on your system to fast rise-short duration transients?

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Unclassified; E.K. Stanek, Emergency Electric Power
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Work Order DCPA 01-76-C-0290

The feasibility of isolating vulnerable equipment of
the electric power system from sources of electromagnetic
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dispatched personnel to perform remote and manual
switching, respectively, is evaluated.

The conclusion drawn from data collected in a series
of utility interviews is that it is possible to isolate a
significant portion of the vulnerable equipment in the
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The report also contains information on the
development of a new lightning arrester that has better
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