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A METHODOLOGY TO ASSESS THE EFFECTS OF MAGNETOHYDRODYNAMIC
ELECTROMAGNETIC PULSE (MHD-EMP) ON POWER SYSTEMS

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ABSTRACT

This paper summarizes a method to evaluate the possible effects of magnetohydrodynamic-electromagnetic pulse (MHD-EMP) on power systems. This method is based on the approach adapted to study the impact of geomagnetic storms on power systems. The paper highlights the similarities and differences between the two phenomena. Also presented are areas of concern which are anticipated from MHD-EMP on the overall system operation.

INTRODUCTION

In the event of single or multiple high-altitude nuclear bursts, it is expected that a large geographic area will be illuminated by intense, transient electromagnetic fields. The first of these fields to be perceived on the ground will be an extremely fast transient having characteristic rise times in the nanoseconds, and known as high altitude electromagnetic pulse (HEMP). The second is perceived at much later times; i.e., seconds to hundreds of seconds after the burst, due to magnetic bubble formation and hydrodynamic motion of the heated atmosphere and debris remaining from the explosion. This pulse has been defined by the term magnetohydrodynamic-electromagnetic pulse (MHD-EMP). A comprehensive methodology for assessing the effect of MHD-EMP on power systems is the subject of this paper.

This paper defines the tools and techniques necessary to perform an analysis of the effects of MHD-EMP on a power system. No attempt has been made here to quantify power system performance in an MHD-EMP environment.

MHD-EMP ENVIRONMENTAL DESCRIPTION

Much of what is empirically known about the MHD-EMP environment is based upon magnetometer data acquired during actual nuclear events such as the Fishbowl test series conducted in the Pacific. The data obtained from the Starfish test (1962) has often been chosen as a benchmark case due to the large negative change, over time, in the ambient magnetic flux density as measured at Johnston Island. Figure 1 shows the magnetometer measurements at Johnston Island for Starfish and two other Fishbowl tests.

The Physics of MHD-EMP Generation

Two distinct physical mechanisms are thought to be responsible for generating the MHD-EMP environment [1]. The first results in the early portion of the MHD-EMP signal (less than ten seconds after the burst) while the second produces the response later than ten seconds. A nuclear burst

Figure 1. Measured Magnetometer Data at Johnston Island for Select Fishbowl Tests [2].

at high altitudes gives rise to a rapidly expanding ionized fireball, consisting of bomb debris and hot gas. This fireball tends to be diamagnetic, in the sense that the earth's magnetic field is excluded from the interior of the fireball. As the fireball expands and rises, it deforms the earth's geomagnetic field lines, creating a magnetic field disturbance of wide spread proportion. Directly under the burst point, a temporary layer of ionized air is created by atmospheric absorption of x-rays produced by the weapon. This region tends to shield the area under the burst for the "early" portion of the MHD-EMP signal. As time progresses, the hot ionized air under the burst begins to rise and move across the earth's geomagnetic field lines causing large atmospheric currents to flow. This motion may account for the second phase of the MHD-EMP signal. These atmospheric currents are imaged in the earth and result in changes in the earth's observed magnetic field flux density, as shown in Figure 1.

MASTER

Joe

Numerical simulations [2,3] of the Starfish event have been performed to compute the transient magnetic flux density at the surface of the earth. The magnetic bubble expansion, plasma pressure gradients, ion inertia and atmospheric conductivity were among the controlled variables for the simulations. In addition to the time dependence of the magnetic flux density, these simulations have shown that the magnetic flux density is also spatially dependent.

Determination of the MHD-EMP Electric Field

The environments of more direct interest to electric power system assessment are the time and spatially varying electric fields associated with the change in magnetic flux caused by the MHD-EMP event. It is the existence of these electric fields which directly effect the electric utility network.

The electric field of interest is the tangential field E caused by an induced current density J_s in the earth flowing in a medium of finite conductivity. This tangential electric field has the following form [4]:

$$E(t) = \frac{1}{\sqrt{(\pi \mu_0 \sigma)}} \int_0^t \frac{1}{\sqrt{(t-t')}} \frac{\partial B(t')}{\partial t'} dt' \quad (1)$$

The magnitude of the electric field is inversely proportional to the square root of the earth conductivity and also a function of the time rate of change of the magnetic flux density, both at a given spatial location.

COMPARISON OF MHD-EMP TO GEOMAGNETIC STORM ENVIRONMENTS

Since MHD-EMP environments can only be created by the detonation of a nuclear device at high altitudes over the earth's surface, it would facilitate our understanding of the environment if one could identify a phenomenon, naturally occurring, whose electric and magnetic environment has similar characteristics to the MHD-EMP event. A candidate environment for examination is that produced by geomagnetic storms.

The creation of auroral currents in the earth's atmosphere by solar storm activity gives rise to magnetic and electric fields at the surface of the earth. The characteristics of such an environment, and its consequential impact on power systems has been extensively explored by Albertson and others [5,6,7,8,9] in a series of technical papers and reports. The similarities and differences between geomagnetic storm and calculated MHD-EMP environments can be quantified as follows.

Spatial Dependence

In the case of geomagnetic storms in the northern hemisphere, the spatial dependence of the change in magnetic flux density is similar from storm to storm, due to the nature of the auroral currents in the ionosphere that are the causative factor. This allows for the spatial dependence to be divided into latitudinal regions and modelled approximately as an electric field of fixed polarization and spatially invariant intensity within each region. The spatial dependence of MHD-EMP environments is variable due to the variability of the burst point. The same event modelled at a different ground-zero in latitude will result in a different spatial pattern.

Intensity

Assuming identical earth conductivity models, the intensity of the MHD-EMP electric field strengths, measured in volts/km may be significantly greater than those produced by geomagnetic storms within certain geographic boundaries. This can best be understood by noting that the change (magnitude) of magnetic flux density for MHD-EMP can be greater than the most severe storm ever recorded and the time rate of change is also faster than that seen in the storm.

Duration

The duration of geomagnetic storm effects on electric power systems in a specific geographic region will be on the order of tens of minutes to hours, with degree of intensity varying unpredictably from low to severe during the storm period. The environment created by a single MHD-EMP event will effectively last no more than 400 seconds. Thus, even a finite number of MHD-EMP events will not continuously illuminate the power system for any length of time comparable to the storm.

Spectral Content

The spectral contents of the magnetic flux density and electric field for both phenomena are similar and contain only low frequency components (less than 1 Hz).

Despite differences between the two phenomena, there is sufficient similarity to invoke many of the methodologies and models developed for assessing geomagnetic storm effects on electric power systems as applicable to MHD-EMP assessments.

MHD-EMP COUPLING TO POWER SYSTEMS

In order to validate the assumption that the methods used for geomagnetic storms can be applied to MHD-EMP and to understand the effects on power systems of this phenomena, it is necessary to examine the spectral contents of the associated fields. The MHD-EMP spectral distribution [4] strongly suggest that a reasonable coupling model may be constructed where the electric field takes the form of quasi-dc excitation and the network topology for coupling is a distributed source dc resistive network.

Thus, for the MHD-EMP environment the power system network will be excited by and develop a response to a stimulus qualitatively identical to geomagnetic storm phenomena. Given this, the major aspects of the data base and models developed for understanding power system vulnerability during geomagnetic storms can also be used for the MHD-EMP event.

Example: Coupling of a field to a single conductor and coupling to overall power systems

The quasi-dc driving voltage source for a single conductor between two points (x_a, y_a) and (x_b, y_b) can be quantified given $E_t(x, y; t)$ as:

$$V_{ab}(t) = \sum_{\substack{x=x_a \\ y=y_a}}^{\substack{x=x_b \\ y=y_b}} E(x, y, t) \cdot \Delta l(x, y) \quad (2)$$

If the conductor is terminated to the earth at each end, the ground represents a return path and a quasi-direct current will flow in the conductor. It is important to note that the magnitude of the voltage difference, $V_{ab}(t)$ obtained from Equation (2) depends on the dot product of two vector quantities. In the case where the electric field is normal at all points to the conductor the value of $V_{ab}(t)$ is zero. Maximum coupling occurs when the electric field is parallel, at all points, to the conductor.

This same procedure has to be repeated for all the conductors in the transmission and distribution grids. The current in each branch of the overall grid is not solely the result of the electric field directly exciting that circuit, but rather must be obtained by a network solution. In addition to this, the time and spatial dependence of the electric field have to be included, making the problem of solving for the overall impact of MHD-EMP on the power system a complex one.

MHD-EMP ASSESSMENT METHODOLOGY

For a single high-altitude nuclear burst, the MHD-EMP environment will always be preceded by an HEMP environment. The two distinct environments, as perceived by the power system, are separated in time. The system under investigation will sense and react to the existence of HEMP for seconds until the formation of the MHD-EMP environment. In power systems analysis, where devices operate in the order of 60-Hz cycle times and short-term stability is a concern, an elapsed time of second(s) between the two environments is a significant separation. The power system may change state due to the existence of HEMP, but many of the transient operations occurring within this change of state will essentially be completed within an elapsed time of seconds. The power system can be considered to be in a new state which serves as the initial condition for MHD-EMP assessment. This separation by "state," within the framework of an overall assessment technique, may also be required due to the vast differences in the natures of the environments and the corresponding power system modeling techniques. Initial investigation indicates that it may be practically impossible to employ a single set of models within a unified assessment code to simulate both HEMP and MHD-EMP effects.

The methodology process begins with the translation of the MHD-EMP environment, as seen by a power system grid, into the corresponding initial system response. This objective is achieved by the sequential accomplishment of the following four tasks.

1. Determine MHD-EMP Environment

A data base is established to quantify the MHD-EMP environment as a tangential electric field $E(x,y,t)$.

One way to define the environment is to approximate the time dependent electric field as a product of three independent terms:

$$E(x,y,t) = e(x,y) \bar{e}(x,y) f(t) \quad (3)$$

In this approximation the time and spatial behavior of the electric field environment is separated. The term $e(x,y)$ represents the spatially dependent time invariant magnitude of the field. The term $\bar{e}(x,y)$ is a unit vector describing the spatially dependent time invariant direction of the field. The

function $f(t)$ describes the time dependent, spatially independent behavior of the field. Using such an approximation, both small geographic and large geographic systems can be considered.

In order to more accurately represent the field it might be necessary to separate the definition of the electric field environment into a "sum of products" expression of the form:

$$E(x,y,t) = e_1(x,y) \bar{e}_1(x,y) f_1(t) + e_2(x,y) \bar{e}_2(x,y) f_2(t) \quad (4)$$

2. Establish Power Systems Grid Data

In this task, a data base is established for the power system grid exposed to the tangential electric field. The data base includes the following information:

- State of the electric power system in terms of 60 Hz electric connection.
- Spatial orientation and circuit length for applicable transmission, subtransmission and distribution networks.
- DC resistance per unit length for the conductors contained within the above networks.
- Location, winding resistance and winding connection for all power transformer and shunt reactor banks contained within the grid.
- Location and terminating dc resistance for all power ground points contained within the grid.
- Location of all power system components, such as series capacitors which serve to block the flow of dc current.

3. Determine Power System Response Network Models

In this task, the previously compiled data bases are processed into a set of equivalent dc power system response networks. The number and complexity of these networks will be determined by the dc open-circuit nodes in the power system grid.

Each network consists of lumped resistive branch elements and distributed dc voltage sources. The network is then solved to compute the time varying dc branch currents.

4. Determine DC Branch Currents

This portion of the methodology concludes with the establishment of a data base containing the time varying magnitude of all dc branch currents. The currents are assumed to flow simultaneously with the 60-Hz current in applicable conductors and windings.

Having established this data base, the different analyses needed to study the impact of MHD-EMP on power systems can proceed. The complete set of tasks constituting the MHD-EMP assessment methodology process consists of the following subsets:

- Power Transformer Analysis
- System State Analysis
- DC Transmission Analysis
- Generator Analysis

- Instrument Transformer Analysis
- Instrumentation and Protective Relay System Analysis
- Utility Communications System Analysis
- Fuse Coordination Analysis

The specific assessment performed for one subset may modify, or cause additional iterations of another subset. For example, the mis-operation of a protective relay scheme due to the presence of power frequency harmonic generation by power transformer increased excitation may result in breaker operation. The circuit switching creates a new set of conditions whose impact can be assessed in terms of change in system load flow and transient stability. The following describes the subsets in more detail.

Power Transformer Analysis

Simultaneous ac and dc excitation of a power transformer can result in the following phenomena:

- Possible insulation deterioration, damage, or gas evolution due to internal localized heating.
- Harmonic generation due to transformer core half-cycle saturation.
- Increased transformer VAR requirements.

Tests on full-size, single-phase, core-form transformers, as well as analytical studies [6] have shown that the equivalent exciting current can be approximated by:

$$I_{eq} = I_{ac} + K I_{dc} \quad (5)$$

where

I_{dc} = dc current per phase
 K = proportionality constant
 I_{ac} = ac magnetizing current

A value of 2.8 for K has been found to fit data for current magnitudes induced by geomagnetic storms [6]. Additional research should be performed to validate the approximation and the value of K for MHD current levels.

Equation (5) has been derived for two-winding transformers. However, it can also be applied to autotransformers, if an equivalent value for I_{dc} is first calculated to account for the unequal value of current in the series and common windings [8].

To assess the possibility of insulation damage due to overexcitation, for any transformer, the value of I_{eq} as obtained above is located on the transformer magnetization curve and the corresponding value of per unit excitation is obtained. Transformer damage threshold curves are normally presented as an inverse time, per-unit, excitation relationship. The interpretation is that, for a given per-unit excitation, a time duration of more than the corresponding time will probably result in thermal degradation of the insulation. It is important to understand that this comparison does not indicate the amount of damage but merely the threshold of damage. More detailed investigation is required to obtain the quantitative risk.

Another aspect of simultaneous excitation of power transformers is the local generation of 60-Hz harmonics in the exciting current. Spectral content

of the current waveform has been measured for various lower levels of dc current combined with normal ac excitation. Given the fact that the harmonic response is a complex function of transformer design and construction, the existing limited amount of test data cannot be expanded to achieve accurate generalization for all types and designs. More research is needed before a comprehensive data base on the different common types of transformers is completed.

As a pre-requisite to system analysis such as load flow and stability, the increased VAR requirements caused by transformer overexcitation must be developed into a data base. This data base can be established in two ways [8]. The more precise approach for a given transformer design is founded on the harmonic content of the exciting current as follows:

$$Q = V \sum_{i=1}^n I_i^2 \quad (6)$$

where:

Q = reactive power
 V = RMS value of the applied sinusoidal voltage
 I_i = RMS value of the i th harmonic component of the exciting current
 n = highest order harmonic value

As an alternate approach, the reactive power could be approximated from the following:

$$Q = V (I_{exc} + K I_{dc}) \quad (7)$$

where:

Q = reactive power
 V = RMS value of the applied sinusoidal voltage
 I_{exc} = normal RMS exciting current at normal operating voltage with no dc current per phase
 K = proportionality factor, same as in Equation (5)
 I_{dc} = dc current per phase

System State Analysis

It is expected that system reactive power requirements will increase due to power transformer increased excitation. The location and magnitude of these increased VAR demand loads is established per the transformer analysis above. The impact of the system change in "state" is assessed from the following aspects:

- System Load Flow
- System Short-Term Stability
- System Switching Surge

For each assessment several base-case steady state conditions for the power system may be specified. The additional reactive power demand would then be integrated into the system model to quantify response. The base-case steady state condition for the above studies is "as modified" by any HEMP effects prior to the start of the MHD-EMP analysis.

The required load flow models are identical to those contained in typical existing load flow digital programs. However, the increased reactive

power requirements should be represented at the transformers. Also the existing system loads represented as constant MVA in typical load flow studies should be modified to become voltage dependent to reflect the effect of the dip in voltage due to the increased reactive requirement by the transformer. At each affected bus, a percentage of the load would be changed from constant MVA to constant impedance, varying as the square of the bus voltage. This percentage would be set dependent on the level of the dc circulating current.

In addition to the quantification of the new steady-state load flow caused by the MHD-EMP environment, the effects on system stability as it moves from state to state must also be considered. The load flow defines the initial steady-state conditions. The stability program contains dynamic models of generation, load, reactive power compensation and HVDC transmission. The program output would quantify the dynamic response of the system, such as generator swing angles as a function of time. In addition, the effects of load shedding schemes and line tripping are considered.

A switching operation might take place during the MHD-EMP event. The effects of long-line energization, single and three-pole reclosing, and other switching phenomena are investigated in the presence of the MHD-EMP quasi-dc currents.

The combination of load flow, stability and switching surge studies, caused by and in the presence of an MHD-EMP environment, lead to an understanding of complete system operational response and final system state after the nuclear event.

DC Transmission Analysis

Based on previous analyses [7] for geomagnetic storms, the impact of MHD-EMP on dc terminals is investigated. This impact might result in damage to harmonic filters, commutation failure, and saturation of the converter transformer. These could lead to the loss of dc transmission capability with subsequent effects on system stability.

Turbine Generator Analysis

The overexcitation of generator step-up transformers and the other electrically close transformers in the system might cause harmonic current flow in the generator stator windings. Stator second harmonic (negative sequence) current, in particular, could produce heating problems in the machines. Negative sequence currents might also occur due to phase current imbalance caused by unequal excitation of the transformer bank.

Instrument Transformer Analysis

Knowledge of the steady state and transient performance of instrument transformers exposed to an MHD-EMP environment is of critical importance for instrumentation and protective relay system assessment. Simultaneous ac and dc excitation results in transformer operation closer to or in the saturation state. Partial or full saturation causes the secondary voltage or current waveform to deviate from the primary waveform. For transient fault conditions, a dc offset in the fault current of the same polarity as the dc branch current can substantially reduce the time to saturation.

Based on the magnitude and time history of the dc branch current exciting the current transformer, in conjunction with ac excitation, the percent ratio and phase angle errors are calculated. Secondary waveform harmonic content is determined as a function of self-generated harmonics and harmonics caused by nearby power transformers. An analysis is made of the possible magnitude of CT remanent flux and reduced time to saturation under fault conditions. The effect of dc on capacitive coupled voltage transformers (CCVT) is also determined.

Instrumentation and Relay System Analysis

This analysis includes the results of the instrument transformer analysis. For instrumentation, the assessment consists of the quantification of measurement error introduced by the modified secondary characteristics of the instrument transformers. Protective relay schemes are investigated in the context of relay security and operational dependability.

Utility Communication Systems Analysis

Utility communication systems can include a wide variety of methods. The information transfer may be voice, analog or digital in form corresponding to the telemetry, control and/or protective system functions required. For MHD-EMP assessment, communications can be considered as two general categories:

- Radio communication systems including point-to-point microwave and base station/mobile radio equipment.
- Wire based communication systems which can take the form of (1) power line carrier, (2) shield wire, (3) utility owned twisted pair and coaxial circuits, and (4) leased telephone lines.

In the case of wire communications, the MHD-EMP environment is identical to that previously discussed for the power system grid. Based on the information gathered in the previous task and the specified electric field environment, an equivalent dc network is simulated and resolved for the individual dc branch currents. This approach is qualitatively identical to that used in the power system response network. Given the time dependent magnitude of the dc branch currents, the increase in channel noise and/or threshold of circuit upset is assessed. For assessment of radio communication links only, additional environmental definition concerning signal propagation in, and through the atmosphere is required. The propagation of the above types of radio communication system through the atmospheric environment is analyzed to determine the probability of and the duration of loss of a communication channel.

Fuse Coordination Analysis

For lower-voltage distribution systems, fuses are used abundantly and the simultaneous presence of ac and dc current due to the MHD-EMP phenomena might cause them to misoperate. To perform this analysis the data base containing the dc branch currents is combined with that containing the steady state ac currents flowing in the distribution system, to form a third data base of equivalent RMS currents to which the fuses are subjected. This, in addition, to a fourth data base containing the location, type

and characteristic of the fuses quantifies the status of the fuses.

NETWORK MODELS

The geographic extent of the power system grid, subject to evaluation by the MHD-EMP assessment methodology, is explicitly dependent on the corresponding geographic profile of the surface tangential transient electric field $E(x,y;t)$. Previous simulations [2] indicate that the affected area may be several million square kilometers.

No dc current will flow in a branch of the power system grid that contains a dc open circuit due to:

- Open switches, circuit breakers, and fuses.
- Existence of power transformers whose simulation models incorporate a dc open circuit.
- Series capacitors and other electrical equipment whose dc models are open circuits.

Any MHD-EMP power system assessment entails the solution of many dc coupling response networks. Each network may represent transmission, subtransmission or distribution segments of the power system grid. Previous geomagnetic storm assessments [7] have concentrated on circuits with operating voltages at or above 69 kV. Maximum electric field gradients were simulated at 6.2 volts/km. For MHD-EMP environments it is expected that certain areas of the power system grid can experience electric field gradients several times greater than 10 V/km. Hence, lines of shorter lengths normally associated with lower operating voltage levels may develop significant dc currents.

The component models which constitute the MHD-EMP response network are strict dc equivalents for each type of equipment. This has both advantages and drawbacks. One advantage is that the models needed for the analysis are simple and frequency independent. The major drawback is that these equivalents are not normally contained in the system data base of most utilities because of their infrequent applications in other studies.

ANALYSIS CODES

A number of computer programs are needed for the assessment of the impact of MHD-EMP on power systems. These are described below.

Quasi-DC Branch Currents Calculation Code

The calculation of circulating induced currents due to the MHD-EMP environment requires only a distributed source, dc system representation. The mathematical solution is straightforward, but the code must be able to represent a large network in a single analysis.

One candidate for this analysis is the Electro-magnetic Transients Program (EMTP) [10,11]. This program has become an industry standard and does not require any modification to existing code to perform the simulation. Data base I/O requirements for EMTP would be enhanced by the development of pre-processor and post-processor modules. The pre-processor should contain graphic digitizing capability, since many parameters of the MHD-EMP environment and power system grid data bases are graphic in format.

The EMTP post-processor would create data format compatibility and automatic calculation of system harmonics and reactive power data bases required by subsequent analysis codes.

System Load Flow and Stability Codes

A number of load flow/dynamic simulation programs are in common use within the power system analysis community. The applicability of these programs to the MHD-EMP analysis depends on: 1) increased reactive power requirement, 2) the ease of implementing voltage-dependent loads, 3) the size of the system they can handle, and 4) the transferability of data.

Switching Surge and Harmonic Analysis

The effects of long line energization, single and three-pole reclosing and other switching operations in the MHD-EMP environment can be investigated by the use of the EMTP program. This program has been used by Mohan [12] and others to perform similar studies for geomagnetic storm environments. The harmonic analysis can be made with a Fourier analysis program on the results of an EMTP simulation where both the ac and dc sources are modelled.

CONCLUSIONS AND RECOMMENDATIONS

In the areas of MHD-EMP environmental definition, power system coupling response, methodology development and system analysis, the following conclusions are reached:

1. A high altitude nuclear weapon burst will produce both HEMP and MHD-EMP transient electromagnetic environments which require separate system response models and assessment methodologies.
2. For power system analysis, the MHD-EMP environment can be defined as a spatial and time dependent, surface tangential, transient electric field.
3. The nature of the MHD-EMP environment exhibits sufficient similarity to the geomagnetic storm environment such that a parallel system response and assessment methodology can be defined.
4. The system response network contains dc resistive models and time varying dc distributed voltage sources. The initial response of interest is quantified as the time varying dc induced currents flowing simultaneously with normal 60 Hz currents.

This investigation of the MHD-EMP phenomena has revealed the following areas of additional research required to perform detailed and accurate risk assessment:

1. Detailed development of an MHD-EMP environmental definition directly suitable for power systems analysis.
2. Additional investigation of power and instrument transformer response to simultaneous ac and dc excitation.

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