2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI) | 978-1-6654-4228-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/USNC-URSI52151.2023.10237700

Estimation of High-Altitude Electromagnetic Pulse Coupling onto Power Generation Facility Equipment

DaHan Liao(1), Yilu Liu(2), Lawrence C. Markel(1), Benjamin W. McConnell(1), David P. Mignardot(2), Brian R. Poole(3), and Lisa Wang(3)

(1) Oak Ridge National Laboratory, Oak Ridge, TN
(2) University of Tennessee, Knoxville, TN
(3) Lawrence Livermore National Laboratory, Livermore, CA

***Abstract*—A systematic approach is presented to evaluate the effects of high-altitude electromagnetic pulse (HEMP) signals on the equipment located inside a power generation facility. The technique is based on a combination of practical measurement and simulation efforts in characterizing the radio wave propagation behavior and the device immunity profile. Of particular interest in this work is the estimation of the vulnerability level of equipment that is connected to long cables. As an example application, a detailed study is put forth for one common class of facility equipment, with its frequency- and time-domain HEMP coupling properties investigated as a function of terminal loading condition and cable attachment configuration. Overall, the proposed method can be generalized and applied to other electronic components and systems found in the facility environment.**

I. INTRODUCTION

As a response to increased U.S. government and commercial interest in energy infrastructure protection against electromagnetic threats, an investigation is carried out to study the effects of fast, high-intensity transients on the equipment located inside power generation facilities. The waveform of primary concern in this work is the early-time (E1) component that is produced by a nuclear explosion detonated high in the atmosphere; this so-called high-altitude electromagnetic pulse (HEMP) event has the potential to catastrophically impact the electrical infrastructure over a very wide area [1]. Although a building's physical structure can provide a certain level of shielding against external radiative electromagnetic attacks, the shielding effectiveness can vary drastically depending on the construction material, frequency, and location within the facility; a HEMP signal coupled into the facility, even if weakened, can still carry sufficient energy to cause significant disruption or damage, especially to low-voltage, semiconductor-based electronic systems. Of particular concern is when such equipment is attached to long cables or wires, as these conductors tend to act like antennas in picking up electromagnetic energy while also serving as conduits for propagating that energy to any connected component. A systematic approach is proposed in this work for analyzing E1 HEMP coupling onto the ports of facility equipment. The results can subsequently be used to assess system vulnerability and provide guidance in developing mitigation measures.

II. ANALYSIS FRAMEWORK

The technique for calculating the induced voltages and currents on the equipment ports follows a four-step procedure that combines measurement and simulation efforts. A brief outline of each step is presented below.

A. Step 1: Determination of Facility Interior HEMP Field Levels

Given that deriving the complete propagation characteristics of a full-scale power generation facility solely by electromagnetic simulations is intractable due to computational resource constraints, a semi-empirical approach is undertaken here that consists of complementing building shielding effectiveness measurements with wave simulation results for simple canonical models. Onsite measurements of ambient signals—such as those from cellular, broadcast radio, and television transmitters—are first conducted. By computing the ratio of exterior and interior field levels, a shielding effectiveness value can be obtained at locations of interest such as the control room, generator room, cable spreading room, etc. Although the reliance on ambient illuminators may limit the number of frequency points for which the coupling can be calculated empirically, this passive approach is more practical as compared to an active one that requires the irradiation of the plant with an onsite transmitter, as there are often operational and regulatory restrictions on the transmission of high-power signals, especially over a wide frequency band. To understand the propagation characteristics over the entire E1 HEMP frequency band, electromagnetic simulations of small-scale, canonical building structures are also performed; essentially, the simulation data complement the measurement data by filling in frequency gaps where no ambient sources may be present [2].

B. Step 2: Characterization of Equipment Port Impedances

Terminal loading conditions are an important factor in determining the amount of electromagnetic energy that cables and wires can pick up. As such, to evaluate the HEMP signal that eventually propagates into the equipment, the impedances seen at all the device ports must be characterized. In this study, port impedances are verified experimentally in the laboratory for various programmable logic controllers (PLCs) as described in [3], which proposes a measurement scheme based on the use of three different instruments—viz. LCR meter, impedance analyzer, and vector network analyzer—with each covering a separate frequency sub-band. To obtain the impedances over the complete E1 HEMP frequency range, the three measured data sets are integrated using interpolation and data-averaging techniques. Note that a special procedure must be developed to eliminate the influence of the measurement fixture; specifically, a non-uniform transmission line model is established to approximate and subsequently de-embed the impedance effects of the fixture. As each PLC can have a different circuit layout, the measurement data show that the port impedances can vary significantly depending on the device model and the manufacturer. As outlined in [3], a pulse current injection method is also proposed to simulate how the PLCs would react to fast transients caused by a HEMP event; however, the results therein assume that the excitation is provided by a standard waveform without building attenuation and cable coupling effects.

C. Step 3: Extraction of Spectral Response for Equipment With Cable Attachment

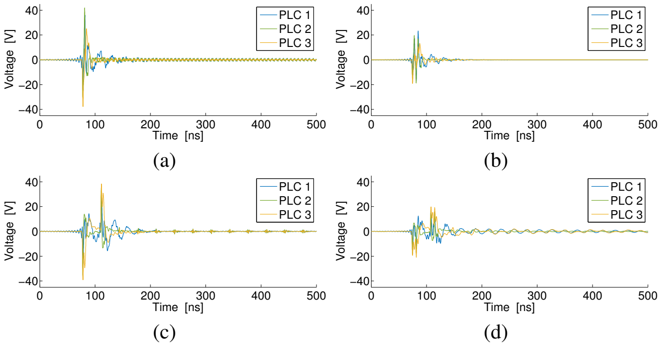
Next, frequency-domain full-wave simulations are performed to characterize the spectral response of cables loaded with the measured PLC port impedances from the previous step; as such, in effect, the equipment only appears at the cable terminals—in the electromagnetic models—as frequency-dependent loads. The cable geometries are created and simulated in a method-of-moments solver as implemented by a commercial software package [4]. For each model, a cable of length L is situated at a height h above a perfectly conducting ground plane; the terminal voltage and current responses are characterized as a function of frequency, cable length, and height for each PLC, with the excitation provided by a plane wave of unity amplitude. As the exact polarization of the wave irradiating the equipment and cable attachment in a real facility setting is not known, a worst-case scenario assumption is taken to simplify the analysis; that is, for example, in the case of a two-wire model, the incident electric field vector is set to be parallel to the geometrical plane containing the wires to establish maximum coupling.

D. Step 4: Derivation of Total System Response in Frequency and Time Domains

In the final step of the analysis procedure, the semi-empirical building attenuation profile is applied to determine the response of the equipment when it is placed in a facility environment. Accordingly, for instance, the total (electric) system response $S_E(f)$ at the equipment terminal, in the frequency domain, is given as

$$S_E(f) = E_1(f)T_E(f)P_E(f) \tag{1}$$

where $E_1(f)$ is the standard E1 HEMP spectrum [2], $T_E(f)$ is the transfer function deduced in Step 1, and $P_E(f)$ is the plane-wave impulse response from Step 3. In view that the procedure in Step 1 only allows the amplitude component of the transfer function to be measured but a phase term is also needed to obtain a physical (causal) response, to resolve this inconsistency, the phase term in this work is derived from the equivalent circuits modeling the attenuation profile as presented in [2]. With the frequency-domain responses determined, the time-domain waveforms can be calculated from (1) with an FFT operation. Note that a windowing function may be employed to suppress "ringing" artifacts caused by frequency truncation.



(a) (b)

(c) (d)

Fig. 1. Induced voltage responses on the power port of three different PLCs: (a) L = 1 m, h = 1 cm; (b) L = 1 m, h = 1 m; (c) L = 10 m, h = 1 cm; (d) L = 10 m, h = 1 m.

III. RESULTS

The four-step procedure is applied to electromagnetic coupling analysis for three different PLCs with a power cable attachment. The voltage responses at the power port of the devices are shown in Fig. 1, with the facility transfer function assumed as that for the control room [2]. It is seen that the waveform structure of the responses can be very different depending on the PLC model, as each has its own distinctive impedance characteristics, but, in terms of the maximum voltage induced, the responses have similar amplitudes. Interestingly, although longer cables tend to lead to longer reverberations, increasing the cable length does not always seem to significantly increase coupling—at least for the two cases considered: L = 1 m and L = 10 m; however, more studies are needed to fully understand the impact of cable length and type. In general, the coupled waveforms have faster variations and risetimes than the incident E1 pulse mostly due to the high-pass filtering behavior of the facility transfer function. Also, for the two cable heights studied (h = 1 cm and h = 1 m), note that placing the cable closer to the ground plane can lead to higher coupling; this is caused by the higher magnetic field intensity in the vicinity of the ground plane as a consequence of the metallic boundary condition effect. Similar analysis as above can be performed for the other ports of the device—for example, the I/O data and communications ports, but the results are not explicitly included here.

REFERENCES

[1] E. Savage, J. Gilbert, W. Radasky, *The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid*, Meta-R-320, 2010.

[2] D.H. Liao, Z. Li, Y. Liu, L.C. Markel, B.W. McConnell, B. Poole, L. Wang, *Estimation of High-Altitude Electromagnetic Pulse Signal Leakage into Power Generation Facilities: Simulations and Measurements*, ORNL/TM-2022/2779, 2022.

[3] W. Qiu, L. Zhang, H. Yin, K. Sun, L.C. Markel, D.H. Liao, Z. Li, B.W. McConnell, Y. Liu, "Port Impedance Measurement and Current Injection Response Analysis for PLCs," *IEEE Trans. Industry Applications*, vol. 58, 2022.

[4] Altair Engineering Inc., Feko, https://www.altair.com/feko/.