Electromagnetic Effects on Transportation Systems

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Abstract

Unless properly accounted for in design, electromagnetic environments will have adverse effects on the operation and maintenance of intelligent transportation systems of the future. Electronic and electrical system protection design can be used to eliminate deleterious effects from lightning, electromagnetic interference, and electrostatic discharges. The evaluation of conventional lightning protection systems using advanced computational modeling in conjunction with rocket-triggered lightning tests suggests that currently used lightning protection system design rules are inadequate and that significant improvements in best practices used for electronic and electrical system protection designs are possible. A case study of lightning induced upset and failure of a railway signal and control system is sketched.

Introduction

The increasing reliance of modern transportation systems on increasingly sensitive electronic technologies is a trend that will continue well into the next century. The electronic-based technology elements include sophisticated computers, a broad range of sensors (video cameras, laser detectors, infrared sensors, microwave antennas, etc.), and hardwired and electromagnetically linked telecommunication systems. These elements will be subjected to potentially interfering effects from naturally occurring or manmade electromagnetic environments such as lightning from thunderstorms, air or land vehicle radio transmissions, or possibly intentional electrical disruption. These elements can be vulnerable to such electrical interference. Connectivity of regional systems to form large distributed transportation systems, encompassing states or regions of the country, will become more prevalent. Centralized information processing at control centers that operate air traffic, railway, and highway systems potentially will become more susceptible to interference from the increased area of coverage and from the trend to more sensitive electronic components.

Interruption of transportation system operations can have high safety and economic consequences. Because air traffic and railway system operations have been adversely impacted by lightning from thunderstorms, costly upgrades to existing systems are now underway. Future intelligent transportation systems can benefit from the lessons learned from recent evaluations of conventional lightning protection systems, and electronic and electrical system protection controls can be implemented early in the design phase of the system. An electronic and electrical protection retrofit or upgrade is usually much more expensive and less effective when compared with implementation of the protection in the design phase. Experience has shown that lightning protection system upgrades to fielded systems can cost up to 20% of the cost of the installed system compared with negligible costs if the protection is considered up front in the design phase.

Broad Spectrum Electromagnetic Effects

Robust protection of electronic and electrical systems from spurious electromagnetic environments requires consideration of all interfering sources that the system will encounter during its lifetime. For example, design and insertion of protection features for lightning will not necessarily provide protection against upset from electromagnetic sources such as transmitting radios or radar. Electromagnetic radiation susceptibility testing is routinely conducted in anechoic chambers and in mode-stirred chambers. A variety of analytical and computational techniques are available for theoretical assessments of electromagnetic radiation vulnerability of systems and components. These include PATRAN™ for structural/geometric modeling input, PV-Wave™ for output display and visualization and computational analysis codes such as THREDH and EIGER. Electrostatic discharge testing of systems and components is a well developed discipline that is detailed elsewhere. Only lightning effects on systems and components is covered in detail.

Lightning Effects and Protection

Perhaps the most pervasive requirement for electromagnetic protection in distributed transportation systems is for the effects of lightning from thunderstorms. Transportation systems are required to operate reliably both during and after thunderstorm activity. Over the past eight years, Sandia has conducted a rocket-triggered lightning test program to evaluate the performance of conventional lightning protection systems and to provide data to validate finite-difference, time-domain computer codes and simple analytical models used for the evaluation of such systems. Although these tests have been concentrated on earth-covered storage structures used for explosives and weapons, on maintenance-and-assembly buildings used for explosives assembly and disassembly operations, and on temporary lightning protection systems used in field operations, the results suggest that conventional lightning protection systems used in such situations are ineffective and that the electromagnetic environment associated with flashes attaching to such structures are best controlled in ways other than installation and maintenance of a conventional lightning protection system. Rudimentary details, as well as quantitative and qualitative information, is given to support these contentions.

Rocket-Triggered Lightning Testing of Weapon Storage Structures

In the summer of 1991, rocket-triggered lightning tests were conducted on an earth-covered weapon storage structure at Ft. McClellan, AL. Detailed results of the tests are given in References 1 and 2. The basic design of the structure is shown in Figure 1. The structure included double-layered rebar in the ceiling and walls, rebar in the floor, a conventional lightning protection system with air terminals, interconnections, a ground ring electrode with ground rods, and grounded and surge protected AC power and signal lines. During the tests, a total of nine lightning flashes with thirty-eight return strokes

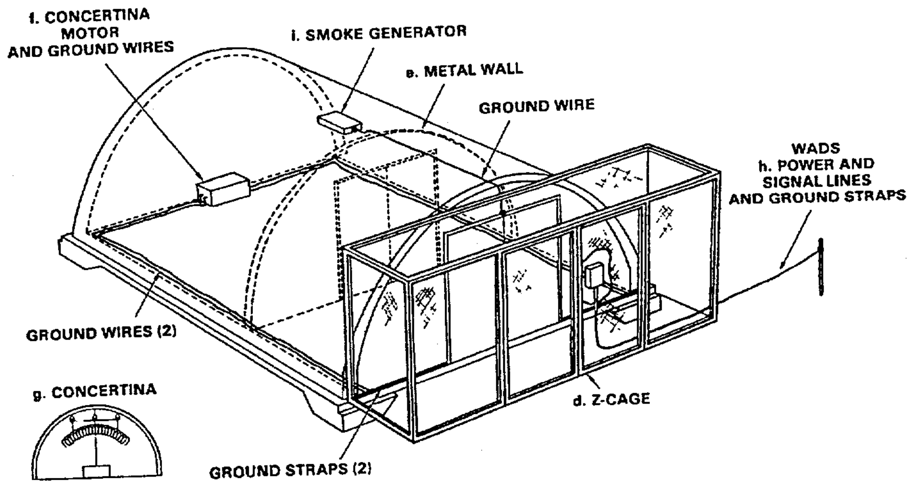

Figure 1. Basic Design Structure

were triggered to the structure. The average peak current of the return strokes was 12.2 kiloamperes with an average 0.3 microsecond risetime. Open-circuit voltages between exposed pieces of metal, short-circuit currents flowing on conductors connecting the metal pieces, the interior electric fields, and the internal magnetic fields were measured. In addition, current flowing at selected locations in the rebar and in elements of the lightning protection were measured. The results of the tests were surprising, in that they suggested that the only function of the air terminals and lightning protection system was to conduct the current from the lightning flash to the rebar, the lowest inductance return path to earth, which subsequently conducted the current to earth through the concrete and through large diameter conduits connecting power to the structure. Surprisingly, the testing showed that typically less than five percent of the lightning current flowed in the lightning protection system. Testing showed that the maximum voltage between exposed pieces of metal was 20 kilovolts with 1.9 kiloamperes short-circuit current when the results were extrapolated to an extreme one percentile (200 kiloampere) lightning strike. Subsequent interpolation of the data showed that the ground impedance played only a trival role in establishing the internal electromagnetic fields, voltages and currents. Interconnection of the wall and floor rebar, as well as grounding of metal penetrations to the rebar, were the dominant factors limiting the internal electromagnetic fields, voltages, and currents.

Rocket-Triggered Lightning Testing of Maintenance-and-Assembly Building

The results from the storage structure testing were surprising in that they suggested that the lightning protection system and maintenance of ground impedances of the lightning protection system played almost no role in determining the electromagnetic fields, voltages, and currents inside the structure, but that instead the topology and properties of the incomplete Faraday cage formed by the interconnected rebar determined the electrical response. Because of the differences between earth-covered structures and more conventional building construction, a decision was made to construct a building with a metal roof, rebar reinforced walls, and a rebar reinforced floor as shown in Figure 2. The building had

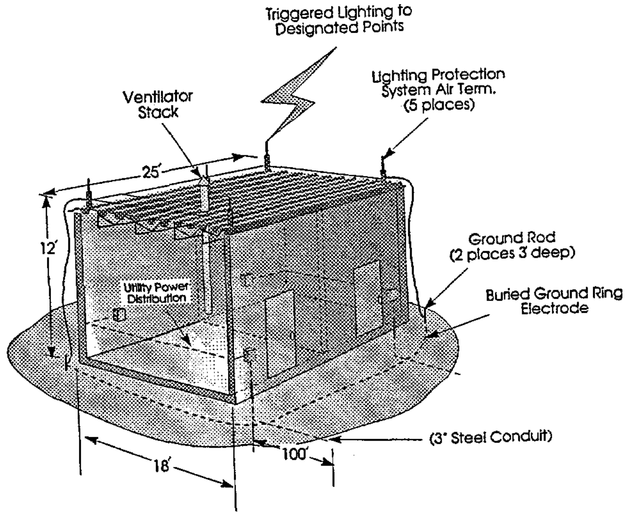

Figure 2.

a conventional lightning protection system with air terminals,down conductors, and a ground ring electrode with ground rods. The major unusual feature included in this building was an approximately 100-kilovolt dielectric breakdown barrier between the wall rebar and the floor rebar with connection points every sixteen inches which could be used to short out the dielectric barrier. The purpose of the barrier was to force as much current as possible to flow in the conventional lightning protection system to evaluate its effectiveness under the best possible conditions. The results of the 1994 testing of this building are detailed in Reference 3. In summary, even if the floor rebar was disconnected from the wall rebar, only about 40% of the initial return stroke current flowed in the conventional lightning protection system for several microseconds. Once arcs were established through the dielectric barrier or elsewhere in the first microsecond or so, virtually all of the remaining 100 microseconds of return stroke current flowed in metallic building structural elements. If the wall rebar was disconnected from the floor rebar, floor-to-ceiling voltages of approximately 200 kilovolts were measured. Almost all of the return stroke current flowed away from the building through two large diameter conduits intended to simulate part of an AC-power distribution network. If the floor rebar was connected to the wall rebar, floor-to-ceiling voltages of approximately 35 kilovolts were measured – comparable to voltages measured in the earth covered structures. Once again, both with and without the wall rebar connected to the floor rebar, the interior electromagnetic fields, voltages, and currents were basically unaffected by the presence or absence of a conventional lightning protection system.

In the 1995 testing of the structure, the two large diameter conduits were excavated and removed so that no metallic path went from the building to a large distance. The purpose of this change was to eliminate the major parallel path to the lightning protection system ground ring electrode and ground rods to force as much current as possible into the lightning protection system. The results of these tests are detailed in Reference 4. Although more current flowed in the lightning protection system, over 30% of the current flowed in building structural elements, with or without connection of the floor rebar to the wall rebar. The interior floor-to-ceiling voltage remained at approximately 200 kilovolts if the wall rebar was disconnected from the floor rebar. The voltage had a strong resistive component, proportional to the return stroke current, in addition to the inductive component, proportional to the derivative of the return stroke current. Even in this very artificial case unlikely to occur in practice where all piping, wiring, and conduits were removed from the building, arcing occurred immediately through dielectric barriers and established current paths through metallic building structural elements When the floor rebar was connected to the wall rebar, the interior floor-to-ceiling voltage dropped to approximately 40 kilovolts, again similar to the earth covered storage structure results. Once again, the lightning protection system did not provide a reliable path to intercept and divert current away from the structure through the ground ring electrodes and ground rods. Instead, breakdown paths conducted a significant fraction of the return stroke current through the building structural elements, generating very large common mode voltages within the building, unless the building structural elements formed a rudimentary Faraday cage.

Rocket-Triggered Lightning Tests of Temporary Lightning Protection Systems

During the summer of 1993, rocket-triggered lightning tests were conducted on a temporary lightning protection system consisting of 5- and 10-meter air terminals with various grounding systems. The grounding, consisting of one or more ground rods is typical of grounding provided for remote data collection and signaling systems such as railway signaling and control wayside stations. The electromagnetic fields at 10 meters and 20 meters distance from the system were measured and compared with models for the current distribution. The results of the testing are detailed in References 5 and 6. The most interesting practical result from the testing was that for grounding systems of one to four 1.0-meter ground rods and for peak return stroke currents greater than about 5 kiloamperes, surface arcs 20 or more meters in length formed on the ground as shown in Figure 3. Measurements showed that if one of the arcs contacted a well-grounded metallic object, up to 10% of the return stroke current could flow in that path. In the design of a lightning protection system, the data show that one cannot assume that the lightning return stroke current will stay confined to the lightning protection element, but that it will arc to adjacent metallic objects, such as cabling.

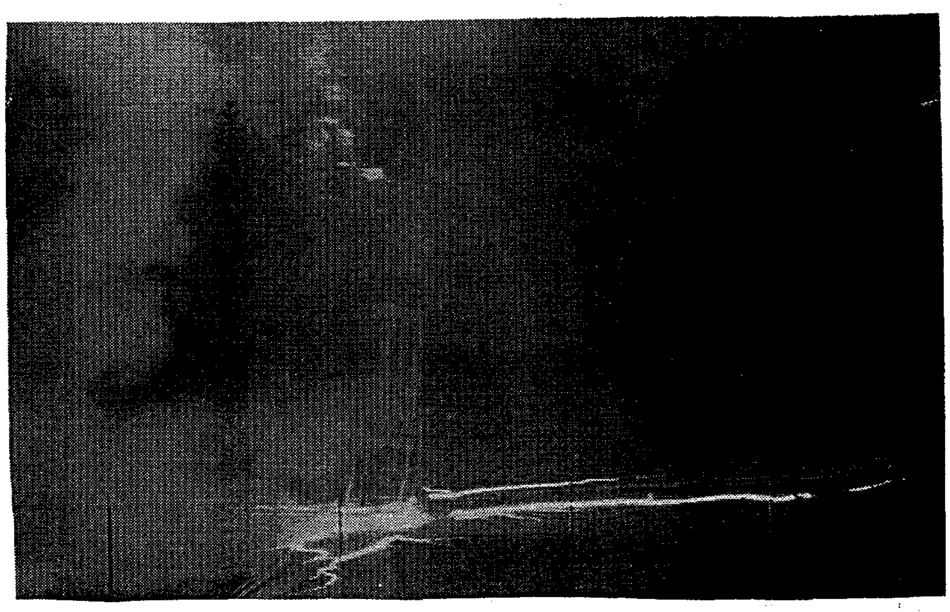

Figure 3.

Case Study of Lightning Effects on Modern Railway Wayside Signal and Control Systems

An example of how the knowledge gained from these tests affected evaluation of an electronic upgrade for a railway wayside signal and control system is now given. A recent upgrade from an electrical to an electronic signal and control system for wayside stations for a railway was found to be very sensitive to lightning attaching to the tracks or signal or AC wiring connected to the wayside stations. The upgrade included digital interfaces for signal and control, a stand-alone computer system, and a baseband radio communication system to eliminate point-to-point signal and control wiring. Field experience showed that lockups between the various subsystems occurred that were associated with thunderstorm activity. These lockups did not usually involve damage to the electronic equipment, but were extremely costly because the rail traffic was stopped until repair crews could come to the often remote site and complete the repairs. The repairs were completed so rapidly that identification of the lockup modes could not easily be accomplished after the event. When lightning strikes attached directly to the building or very nearby wiring, damage would often result to the equipment, but this happened sufficiently infrequently that the cost was considered acceptable. The lockups occurred sufficiently frequently, even from lightning attaching to tracks and wiring at substantial distance, that the cost was not considered acceptable.

A cursory examination of the wayside signal and control system showed that the rudimentary surge protection components and their associated high-inductance grounding system, complete with a single or dual ground rod system and often without even a rudimentary Faraday cage, could not easily be changed to prevent damage to the electronics from a direct lightning flash. Additionally, the review showed that the surge protection system could not be upgraded easily, mainly due to the lack of a Faraday cage, to prevent upsets from remote lightning. The approach to testing was to attempt to duplicate the lockups that occurred by injecting current pulses similar to those expected from remote lightning so that hardware/software responsibility for the lockups could be assigned to the appropriate subsystem subcontractor and corrected by hardware/software fixes. Testing revealed three different lockup modes involving hardware and software from all the major subcontractors. Several minor changes to grounding systems were suggested to improve their performance, but these changes were not expected to improve the performance of the system by more than 50%.

The root cause of the problem with this system was that the older electrical systems with slow acting surge protection were robust enough that lightning upset and damage was a minor problem, but when these systems were converted to modern electronics and telecommunications, lightning effects were not considered in the design. These problems could have been addressed trivially in the design and testing phase of the project.

Conclusions

Unless electromagnetic environments are considered seriously and, if necessary, mitigated early in the design phase of highly distributed intelligent transportation systems, the safety and reliability of these systems may be affected adversely, and costly and embarrassing upgrades may be required. Both testing techniques and computational tools are currently available to assess the effects of the environments of electromagnetic radiation, electrostatic discharge, and lightning on these systems.

Acknowledgment

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