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ELECTROMAGNETIC COMPATIBILITY OF NUCLEAR POWER PLANTS

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ELECTROMAGNETIC COMPATIBILITY OF NUCLEAR POWER PLANTS

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ABSTRACT

Lately, there has been a mounting concern about the electromagnetic compatibility of nuclear power plant systems mainly because of the effects due to the nuclear electromagnetic pulse, and also because of the introduction of more-sophisticated and, therefore, more-susceptible solid-state devices into the plants. Questions have been raised about the adequacy of solid-state-device protection against plant electromagnetic-interference sources and transients due to the nuclear electromagnetic pulse.

In this paper, the author will briefly review the environment, and the coupling, susceptibility, and vulnerability assessment issues of commercial nuclear power plants.

1) INTRODUCTION AND BACKGROUND

Two factors have recently led to a re-evaluation of the adequacy of presently used protection methods in nuclear power plants against electromagnetic transients:

- a. The nuclear electromagnetic pulse. This pulse can induce strong transients that can disrupt the proper functioning of a plant and prevent a safe shutdown, for example.
- b. The introduction of sensitive solid state devices into the plants. These devices are more susceptible to transients and, therefore, may require additional protection.

There have been a few studies performed to scope the effects of nuclear electromagnetic pulses on nuclear power plants in the U.S. The earlier work by Oak Ridge National Laboratory [1-2] was a limited scope study. More recently, a more in depth study was conducted by Sandia National Laboratory and other contractors [3]. These studies are mostly based on paper analyses with some localized low level tests performed to provide empirical evidence for certain assumptions made in the course of performing the assessment. The analytical tools employed have, to a large extent, been previously developed during the nuclear electromagnetic pulse assessment programs of communication facilities. Large scale tests of such communication facilities were conducted in conjunction with the assessment methodology development and, therefore, to some extent, there has been some degree of experimental validation.

There have been no large scale nuclear electromagnetic pulse testing of a nuclear power plant and none are planned in the near future in the U.S. In the absence of such data, electromagnetic compatibility

analyses should be preferably cast in a format where uncertainties in the analyses can be accounted for and properly treated.

With nuclear plant designs becoming more dependent on highly sensitive solid state devices and instrumentation systems, including microprocessors, they are more vulnerable to spurious transient signals. Recently, an experimental study was performed to determine the electromagnetic interference (EMI) levels existing at various locations at two nuclear power plants [4]. In addition, the Lawrence Livermore National Laboratory is presently undertaking a study to evaluate the adequacy of solid state device protection against expected EMI levels.

Another source of concern for the protection of sensitive solid state devices is lightning. Some recent measurements suggest that the present lightning specs may not be adequate since such data indicate considerably more high frequency content than previously suspected. Problems resulting from direct lightning strikes and radiated fields need to be re-evaluated with this new technology in mind.

In the rest of this article, various technical areas that have to do with the electromagnetic compatibility of a nuclear power plant will be discussed. These include sections on the environment, functional analysis, coupling assessment, susceptibility assessment, and vulnerabilities assessment.

[1] ELECTROMAGNETIC ENVIRONMENT

Three different mechanisms contribute to the electromagnetic transient environment inside a nuclear power plant; namely the nuclear electromagnetic pulse, lightning, and the in-plant generated electromagnetic interference signals. These three sources of electrical energy are characterized by different amplitudes and frequency content.

Much has been written on the nuclear electromagnetic pulse environment [5, 6] and will not be repeated here. Suffice it to say that of these, the high high-altitude EMP (HEMP) and the magneto hydro dynamic electromagnetic pulse (MHD-EMP) are the most severe. HEMP produces strong radiated fields (10's of KV/m), covers large areas ($R = 100$'s to 1000 's km) and has a wide bandwidth (10's of MHz).

The MHD-EMP fields exhibit peak amplitudes in the V's/Km range and rise times of 10's of seconds. These fields are particularly effective in coupling to the long lines.

Most EMI transients are due to such sources as switching of inductive loads (i.e., relays, etc.).

battery charger/inverter system(s), welding equipment, communication equipment, etc. Recent measurements [4] have indicated that the dominant frequency of such transients is typically less than 1 MHz with peak-to-peak current amplitudes typically less than 1 A (dominant frequencies as high as 4.8 MHz and peak-to-peak currents as high as 4-2A were measured however). The measurements were obtained at two plants. The first is representative of BWRs presently being built. The plant was shutdown and all equipment was energized from off-site power during the measurements. The second is representative of PWRs. The plant was in normal operation during the measurements. In Fig. 1, a typical scatter diagram showing peak-to-peak current amplitude vs. frequency for one of the plants is shown. Free-field probes were also used to monitor the magnetic fields. The measurements indicated peak field amplitudes less than .05 A/m and in the 10's of kHz range.

Figure 1 - Scatter diagrams for one of the nuclear power plants where EMI data were obtained.

The characteristics of the lightning return stroke currents and the radiated fields have recently been measured [7,8]. First stroke peak currents as high as 418 kA were observed with the 50% level varying from 15 to 45 kA and the 95% level varying from 70 to 130 kA depending on geographical location. The radiated fields from lightning were measured at the ground in New Mexico. Pulses significantly faster than a microsecond in rise characteristics (< 100 ns) were observed. The leader EM fields exhibited rise times (10 to 90) from less than 30 ns to 100 ns with pulse widths from 70 to 500 ns. The return stroke EM fields exhibited rise times of the order of 50 ns with pulse widths of the order of 1 μ s. At comparable distances, the amplitude of the return stroke fields are larger than those due to the leader, but the time rate of change are about the same.

III) FUNCTIONAL ANALYSIS

This consists of the study as to how the parts (circuits, subsystems, components, etc.) of a system work together to perform their overall function. Any reliability or vulnerability assessment of which electromagnetic compatibility is only a subset should, in principle, be performed with some specific goal in mind. For example, one may want to guarantee the safe shutdown of a plant in the event of a high-altitude burst. In this case, all the subsets

of the system that have to function in a certain sequence to complete the desired mission have to be identified. There are several techniques used to perform such tasks of which fault tree analyses are the most commonly used [9].

IV) COUPLING

As in the case of any communication facility, the electromagnetic energy can reach sensitive devices by coupling to the long lines (aerial or buried) which, in turn, conduct the energy inside the facility and by coupling directly to the internal cabling inside the facility by diffusing through the walls. Several techniques are available for performing a coupling assessment of a nuclear power plant.

- 1 - High-level testing of the facility with a large scale simulator with independent injection of the penetrations.
- 2 - Local illumination of the plant to determine shielding effectiveness of the building and to validate assumptions in the analytical treatment.
- 3 - Current injection tests to determine energy distribution via cabling.
- 4 - Analyses to supplement the tests.

No tests as in 1 above have been performed. A program has just been completed which included a combination of approaches as in items 2, 3 and 4 [3]. Analytical methods have been developed to treat coupling to aerial or buried cables. These have been validated with scale model tests and also with full-scale partial illumination tests in the past. The building shielding effectiveness is typically very difficult to estimate as a function of frequency. Short of full-scale tests, partial illumination with monopole antennas from various directions are necessary. The evaluation of the induced currents inside the plant, due to the diffused fields, is typically very hard to perform analytically; often, the penetration currents dominate and the impact of the diffused fields from nuclear electromagnetic pulses or lightning is negligible. The energy on the penetration cable is attenuated due to re-radiation and due to cable distribution before it reaches sensitive components. If cables are shielded, commonly used cable shielding calculations or tests have to be performed to determine the induced energy at the center conductor.

A typical high-altitude electromagnetic pulse induces upwards to 15 kA on a single above ground line and 1 kA on a single buried cable. For example, buried conductors may be placed inside plastic conduits which contain a large number of cables. Several conduits typically run parallel to each other. The 1 kA peak current quoted above should be reduced due to the presence of nearby conduits and then shared by the various cables in the conduits. A substantial body of empirical recipes have been developed to estimate the magnitude of the current on individual cables. Once this cable penetrates the building, it is attenuated due to ohmic losses, multimoding and cross coupling (typically 5-6 dB/100'). At a distribution board, such as a bus board, the incoming current tends to divide among the conductors attached to the bus (the bounds have been determined empirically to be $1/N$ and $1/N^{1/2}$, where N is the number of conductors). From the knowledge of these short circuit currents, the source impedance of the cable and the load impedance, the induced voltages across the loads

can be determined. The assessment exercise described in Ref. [9] has shown that most induced voltages are less than 10 volts, a few between 10 and 100 volts, and a couple as high as a few hundred volts at critical equipment. These are shown in Fig. 2 with the nominal operational levels of the equipment involved. Observe that, in most cases, the predicted voltages are much less than the nominal operating levels.

Figure 2 - Predicted induced voltages at critical equipment due to a nominal high-altitude burst.

V) SUSCEPTIBILITY ASSESSMENT

EM induced transients cause both permanent and temporary equipment malfunction. Of the two, permanent damage is the easier to quantify. Upset cannot be evaluated by analysis alone and usually tests need to be performed. To the best knowledge of the author, no upset assessment of nuclear power plants have been performed. The problems encountered presently will be compounded when more sophisticated electronics are introduced.

VI) VULNERABILITY ANALYSIS

A vulnerability assessment, the last step in a vulnerability analysis, is the process of quantifying the vulnerability of the equipment, systems and/or plant. To perform this, one must fold together the outputs of the functional analysis, and coupling and susceptibility assessment. Because of the limitation of available "good" data on nuclear power plants (particularly in the coupling arena) and the random uncertainties inherent in device susceptibility, the vulnerability analysis is subject to uncertainties. Furthermore, a system analysis is required that takes into account the interrelationships between subsystems.

Since the vulnerability assessment of systems is dependent on the interrelationships between the operation of the components within the system and the vulnerability of the individual components, for all but the simplest systems, the system analysis will need to rely on approaches such as event/fault trees.

In order to illustrate the role uncertainties play in the analysis, the various options available for measuring the vulnerability of a system will be discussed. Basically, there are two analyses approaches: one is exact (the stresses due to the electromagnetic energy and the thresholds are known exactly) and the other is analysis with uncertainty (systematic uncertainties due to analytical and experimental errors in all stages of assessment). In each approach, the inherent random uncertainties (i.e., device thresholds) are either taken into consideration or else a straightforward deterministic behavior is used. For the case of exact analysis with deterministic EM response/subsystem threshold characteristic, the usual measure used is the damage (or upset) safety margin defined as the ratio, expressed in decibels, of the damage threshold to the response. To the best knowledge of the author, this is the approach used by the few assessments of nuclear power plants that have been performed. This approach is acceptable for a zeroth-order "quick-look" type analysis. However, it is deficient if used to make hard decisions about necessity of hardening the plant. The introduction of random uncertainties (EM responses and component/subsystem thresholds) necessitates a probabilistic approach whereby the probability of failure is evaluated instead of a simple yes/no answer as in the deterministic case. Going one step further and introducing systematic uncertainties in the analyses and experiments data used in the vulnerability analysis necessitates the evaluation of confidence levels associated with the probabilities. Such approaches are covered extensively in the literature [see Ref. 10-16].

VII) SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The evaluation of the electromagnetic compatibility of nuclear power plants, particularly in light of nuclear electromagnetic pulses and the on-going introduction of sophisticated and sensitive solid upset state devices, is still in its infancy. The most sophisticated approaches used so far have simply been zeroth-order "quick-look" analyses. These approaches are inadequate if hardening and associated trade-off analyses are contemplated.

In the environment area, EM transients (due to high-altitude electromagnetic pulse or to internally generated interference) have been considered. Transients due to MHD-EMP (which couple very efficiently to long lines) have not been evaluated and those due to lightning have not been measured.

In coupling assessment, reliance has been placed on techniques developed for the assessment of communication facilities over the last decade or so. Only limited partial tests have been conducted or one nuclear plant to determine building shielding and current distribution. These tests have to be expanded over a larger number of plants to develop recipes of coupling levels by generic classes. Indiscriminate testing will be expensive and counter productive. What is needed is a combination of analyses and well designed low-level partial tests.

Although a large body of literature exists on a more realistic probabilistic vulnerability analyses, it has not been used. Going a step further beyond zeroth-order analyses will require casting the vulnerability assessment measures in such a framework.

The "strength-order" exercises alluded to above have concentrated on turnout. These have to be expanded to include upset which may very likely turnout to be the more troublesome.

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