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Lightning Simulation with Current Injection in a Nuclear Power Station

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ABSTRACT

This paper describes a recent lightning current injection experiment performed in a Swiss nuclear power station. The main purpose of this experiment was to verify the theoretical analysis of the lightning protection system (LPS) and the methods to predict lightning-induced voltages in the instrumentation and control system.

Induced voltages at both ends of a number of control cables were measured with different lightning injection points and current waveforms. An optical trigger system was used together with digital oscilloscopes. With this set-up, a precise time correlation between injected current and induced voltages was achieved and it was possible to successfully discriminate current-induced signals from background noise and interference caused by the plant control system which was operating during experiments. To measure induced differential-mode and common-mode voltages at floating potential under EMI-free conditions, the cable terminals under test were linked with battery powered optically isolated preamplifiers.

The characteristics of the injected current waveforms obtained with the experimental setup are discussed with regard to the induced voltages measured at the cable ends. A simple model is proposed to simulate the transient response of the current injection system including the spiderlike current return path.

1. Introduction

A lightning protection system (LPS) of a nuclear power station should be designed to ensure reliable operation of the plant even in the event of a direct lightning strike. Nuclear power plants have very extensive instrumentation and control systems which are based on solid state and microprocessor technology. Such systems usually employ a huge number of signal and control cables between different sections and buildings of the plant.

A direct lightning stroke on a power station causes a distributed surge current in the LPS. This current splits into branches of the LPS and passes through down-conductors and building steelwork into the grounding mesh of the station. Subsequently, the current propagates via grounding mesh to ground. If the LPS measures are insufficient, the traveling current wave induces excessive interference voltages in the instrumentation and control cables which may adversely effect vital control and protection functions of the power plant.

Due to the large extent of the plant installations and due to the complexity of the various coupling mechanisms, a purely theoretical method of predicting lightning-induced interference voltages in a nuclear power plant, even with greatly simplified assumptions, is very difficult and not reliable enough. Therefore, an experimental check of the LPS measures using artificial lightning currents and the determination of the lightning-induced interference voltage levels on safety related instrumentation and control circuits is mandatory for all Swiss nuclear power stations.

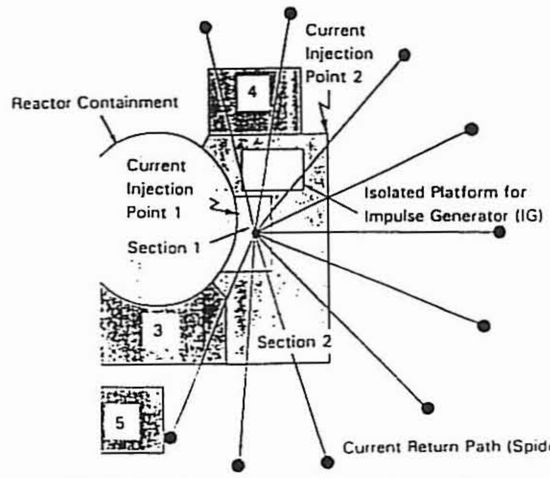
Several on-site experiments to study the characteristics of lightning-induced interference voltages in nuclear power stations and telecommunication buildings have been described in the literature (e.g. /1/,/2/,/3/,/4/,/5/,/6/).

The lightning simulation experiment described here has been carried out in a nuclear power generating station in Switzerland after a major upgrade of the emergency control system. The plant consists of two 1120 megawatt PWR units with an electrical output of 350 megawatt per unit. During the experiment, the reactor of the unit under test was shut down, however, the control system was operating (testing phase). This created a considerable background noise level on some control circuits to be investigated. To overcome these inherent on-site noise problems, optical links have been used for both EMI-free signal acquisition and triggering.

2. Experimental Setup

There are several methods and experimental arrangements for injecting artificial lightning current impulses into large objects /4/. In the most simple configuration, a current impulse generator (IG) is located outside the object on ground level and a connection from the output terminal of the generator to the injection point (i.e. roof) is made via a single wire or h.v. cable. Due to the high inductance of the rather large loop of the current injection circuit, it is generally not possible with this arrangement to achieve fast rising current impulses with high di/dt.

In order to simulate lightning currents with high di/dt and to obtain a realistic approximation of the current distribution in the LPS and in the grounding system, an experimental setup with spiderlike current return path was used for the present investigation. The impulse current source was installed on the roof of a large building complex adjacent to the reactor containment. An overview of the situation is given in Figure 1.



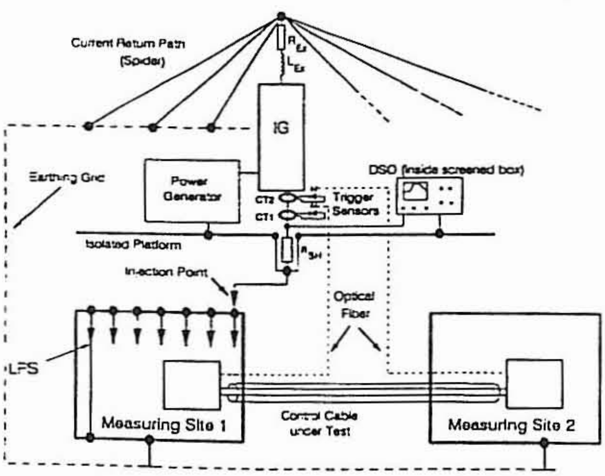
Figur 1 Lightning simulation experiment in a nuclear power station. Top view of the experimental setup.

2.1 Current Return Path

With the installation of a distributed, spiderlike current return path, the present experimental setup could fulfil two requirements: (a) low inductance of the main current path to inject steep current impulses, and (b) realistic current distribution in the earthing system in the surroundings of the test object. The return path consisted of ten radially arranged steel wires, 2.5 mm in diameter, which were connected on one end to an electrically isolated collection point located 5 m above the roof level of the highest part of the building (section 1 in Fig. 1). The other end of each wire was directly connected with the grounding grid. These grounding points of the wires were located in a half circle of about 50 m radius.

2.2 Impulse Current Generator (IG)

A low inductance (10 μH) Marx generator, rated 800 kV, 40 kJ, 125 nF (10 stages in series), was set up as an impulse current source on the roof of the building in section 2 (see Fig. 1). The impulse generator including its control and charging unit, current measuring system and a power generator were placed on an electrically isolated platform (4 m by 8 m) covered with a metal sheet. The IG ground terminal (platform) was connected with either of the two current injection points (see Fig. 1). To minimize additional circuit inductance, a fine metal mesh of 1 m width was used for the connection between platform and injection points. The output terminal of the IG was connected with the central collection point of the current return path via an external resistor R_{Ex} and additional inductance L_{Ex}, as shown in Fig. 2. Different values for R_{Ex} and L_{Ex} have been inserted in the circuit to adjust the current waveforms (see Table 1).



Figur 2 Experimental setup for lightning surge simulation and simultaneous measurement of current induced interference voltages at both ends of cables.

2.3 Measuring Equipment and Trigger System

The injected current was measured with a 18 mΩ- coaxial shunt. The measuring signal of the shunt was recorded on a 8 bit, 100 MS/s digital storage oscilloscope (DSO) with 40 MHz analogue bandwith (YOKOGAWA, Model DL 1200A) which was operated inside a shielded cabinet.

Two wideband current transformers, CT_1 and CT_2 in Fig. 2, in the main current path of the impulse generator were used as current sensors generating a trigger signal which was strictly correlated in time with the corresponding current injection. The output of these current transformers excited fast LED's whose light impulses were transmitted through optical fibres, up to 300 m in length, to the measuring sites. In the present experiment, the time delay caused by the optical trigger link was less than one μs and was therefore negligibly small compared with the time range of the induced interference signals to be observed (typical duration: 50 to 100 μs).

An essential step in the experimental set-up was made with the application of optically isolated wideband links between measuring instruments and the cable terminals under test. Battery powered optically isolated amplifier systems (OIAS) with optical fibres up to 100 m in length were used throughout the experiment: problems due to signal pick-up in long measuring loops or other electrical disturbances of the measuring system could be avoided. Moreover, all measurements could be carried out at floating potential with high sensitivity.

At each of the two measuring sites, a 100 MHz OIAS (SONY-TEKTRONIX, Model A6903S) and a 10 Bit, 100 MHz digital storage oscilloscope (LE CROY, Model 9430) with a PC-system was installed for data acquisition and storage. The two measuring sites near the cable terminals were typically several hundred meters apart from each other, i.e. Site 1 near the racks of the control and instrumentation system and Site 2 close to the corresponding transducer or actuation device (relay, valve etc.).

3. Waveforms of Injected Currents

The design of the LPS of a nuclear power station in Switzerland has to comply with lightning current parameters which are specified by the Swiss nuclear safety department (HSK). The Swiss regulation defines three different lightning current waveforms which are representative for first negative strokes, subsequent negative strokes and positive flashes, denoted here with "middle", "steep" and "slow", respectively. The values of the HSK-parameters are given in Table 1 together with the waveforms and amplitudes used for the experimental verification of the LPS measures in the present investigation.

Type	Parameters for Design (HSK-Values)	Parameters of present Experiment	R_{Ex} [Ω]	L_{Ex} [mH]
Middle	1 / 1000 μs 100 kA	1.8 / 15 μs 4 kA	150	---
Steep	0.25 / 50 μs 50 kA	0.7 / 50 μs 1.1 kA	600	---
Slow	40 / 200 μs 300 kA	17 / 53 μs 2.2 kA	150	6.0

Table 1 Lightning current parameters (front time, time to half-value, peak amplitude) for design and experimental verification of LPS measures in a nuclear power plant.

Due to the limited energy stored in the capacitors of the IG, it is impossible to generate long wave tails for the middle and slow waveform. However, it is mainly the steepness of the lightning current front and the current amplitude which determine the interference voltages in the instrumentation and control circuits.

For this reason, the current waveforms and the amplitudes (Table 1) obtained with the present setup were acceptable to investigate effects of natural lightning strikes as long as the sensitivity for unambiguous determination of the induced interference signals was high enough.

With the present experiment, the peak currents were mainly limited by the maximum charging voltage of the IG. To save life time of the capacitors, the generator was only charged to about 90% of the rated voltage (73 kV per stage).

In the case of the steep waveform, an external resistor of 600 Ω was inserted in the circuit to obtain high di/dt values in the current front. This resulted in a significant reduction of the current amplitude. Due to reflections in the current return path, high frequency oscillations were superimposed on the steep current waveform (for discussion, see Sec. 4.2). To simulate a lightning current with longer risetime (type: slow), an external inductance L_{Ex} of about 6 mH was utilized which lead to an impulse shape with a bipolar swinging wave tail. Figures 3 and 4 show measured current waveforms of the present simulation experiment.

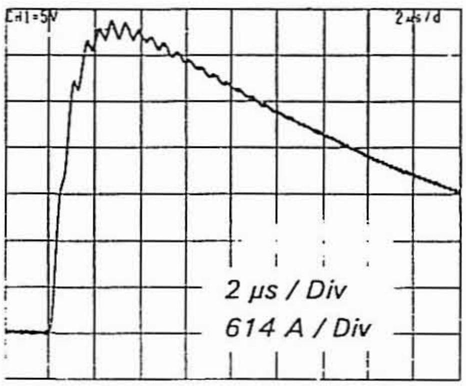


Figure 3 Injected current measured with a coaxial shunt. Waveform type: middle, injection point 1.

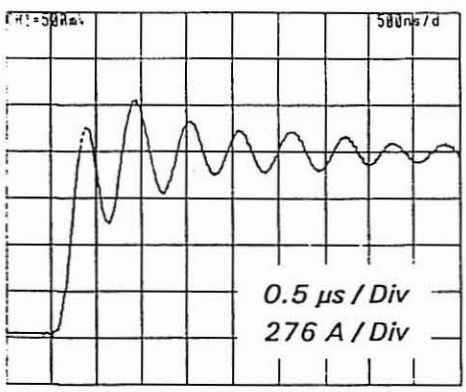


Figure 4 Injected current measured with a coaxial shunt. Waveform type: steep, injection point 2.

4. Analysis and Circuit Model

To assess the limits of the present lightning simulation experiment, an attempt was made to analyze and model the observed behavior of the current injection circuit.

4.1 Circuit Parameters

The inductance of each wire in the current return path (spider) was calculated to be 108 µH with a resistance of 184 Ω. The approximate length of the wires was 65 m.

The total resistance R_s of 10 wires in parallel becomes 18.4 Ω, however, the total inductance L_s of the spiderlike arranged wires is larger than 10.8 µH due to the mutual coupling near the collection point (see Fig. 1). A value of several tens of micro Henry is assumed for L_s.

The inductance of the LPS in the building is estimated to be in the same range as the spiderlike current return path, since the current concentrates near the injection point. All other inductances in the circuit, in particular that of the connection IG to injection point are assumed to be negligible small compared with the total circuit inductance L_{tot} of approximately 100...150µH. This is supported by the fact that changing the injection point had nearly no influence on the current waveforms.

A good estimate of the total circuit inductance L_{tot} can be obtained from the time constant $\tau_f = (L_{tot}/R_d)$ or from the front time T_f of the measured current impulse if the damping resistor R_d of the circuit is known. For the waveform in Fig. 3 (type: middle) we have $R_d = (150\,\Omega + 18.4\,\Omega)$ and the total inductance is estimated to be:

$$L_{tot} = (\tau_f \cdot R_d) = (T_f / 2.5) \cdot R_d = 121\,\mu H .$$

For the high frequency range covered with the steep current waveform (Fig. 4), the stray capacitance C_p of the isolated platform (Fig. 2) cannot be neglected. This platform covered an area of 32 m^2, the distance to the roof was 0.5 m. Using a parallel plane arrangement, a value for C_p of 283 pF is calculated assuming image charges 0.5 m below the roof level. This value for C_p is comparable with the capacitance of an isolated circular plate of the same surface area which was calculated to be 226 pF.

4.2 Modeling of the Current Injection Circuit

Based on the analysis above, a simplified equivalent circuit was utilized for computer simulation. The model and the values of the circuit elements are given in Figure 5. The inductance of the building structure including the LPS has two parts: (a) L_b of the building wall, and (b) L_p modeling the LPS near the current injection point (roof) which is affected by capacitive coupling effects (C_p). There are two transmission line elements in the model to include travelling wave effects in the spiderlike current return path and in the LPS of the building with propagation times T_s and T_b of 180 ns and 50 ns, respectively. Considering the size of the objects, the characteristic surge impedance of these transmission lines are assumed to be in the range of 20 - 50 Ω /5/. Within this impedance range, the influence upon the current waveform is only very small.

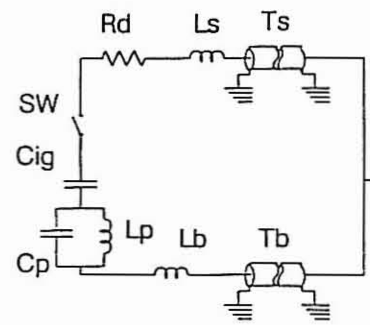


Figure 5 Circuit for simulation of injected currents.
L_s: 90 µH, L_p: 40 µH, L_b: 30 µH, C_p: 280 pF, C_{ig}: 125 nF, IG charged to 730 kV, R_d: see text.

Figures 6 and 7 show calculated currents in L_p (position of the measuring shunt) for the middle and steep waveform. The same R_d-values were used in the simulation as in the experiment (see Table 1). In general, the calculated currents are in good agreement with the experimental waveforms (Figs. 3 and 4). This supports the validity of the model proposed here.

The superimposed high frequency oscillations in Fig. 7 are somewhat smaller than in the measured case (Fig. 4), while in Fig. 6 oscillations are larger in amplitude and longer in duration compared with the measurements (Fig. 3). These small differences are supposed to originate mainly from distributed coupling between the platform and the building structure and from the losses in the LPS and grounding grid which are not taken into account in the present model.

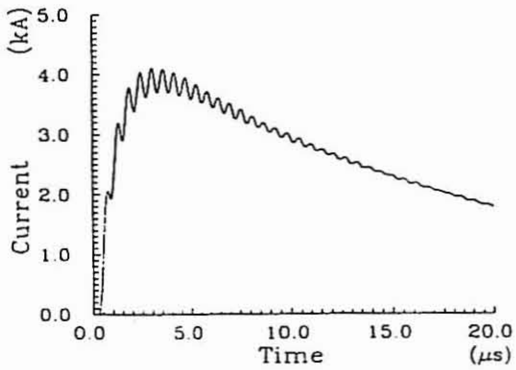


Figure 6 Simulated current for middle waveform (cf. Fig. 3).

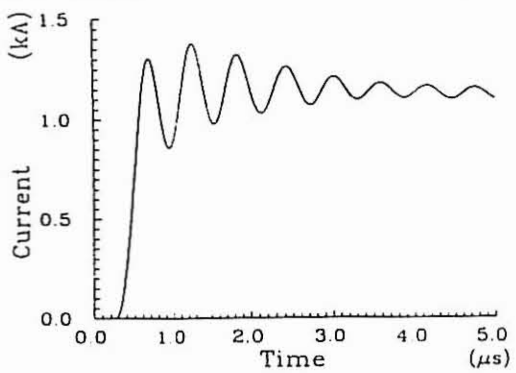


Figure 7 Simulated current for steep waveform (cf. Fig. 4).

5. Interference Voltage Measurements

Due to the operation of the control and instrumentation system of the plant, a high background noise level was present during the measurements. Some interference sources could be identified to be 50 Hz power supplies, AC-AC or DC-DC converters and impulsive noise originating from status messages and control sequences. Figures 8 and 9 show a typical situation with signals measured at Site 1 between two clamps (differential mode) of a control system rack.

The background noise in this particular case (Fig. 8) consists of a triangular signal of about 4 kHz with high frequency noise spikes superimposed on it. This noise pattern is caused by a DC-DC converter which is present in that particular circuit.

Although the lightning current induced interference voltage (circle in upper trace of Fig. 9) is much smaller than the background noise, the induced signal can readily be detected and identified by making use of the time correlation with the trigger signal (lower trace in Fig. 9). A more detailed view of the induced interference voltage is possible by expansion of the signal trace on the DSO. It is obvious, that a conventional event trigger method would have never worked under these conditions.

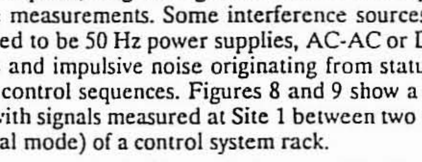


Figure 8 Background noise produced by the instrumentation and control system (differential-mode signal).

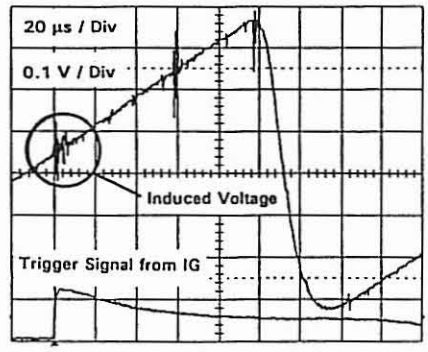


Figure 9 Detection of induced signal (upper trace) caused by current injection (4 kA, risetime 1.8 μs, otherwise same condition as Fig. 8). Lower trace: trigger signal.

It should be noted, that the recorded wave shape of the trigger signal (see lower trace in Fig. 9) is not representative for the shape of the injected current due to nonlinear effects in the electro-optical transducers of the trigger circuit.

6. Concluding Remarks

Due to the complicated structure and extensive installation in a nuclear power plant, an experimental verification of the lightning protection measures is highly desirable. The present investigation confirms that carefully designed current injection circuits can deliver appropriate current waveshapes and realistic current distributions in the LPS and in the grounding grid.

An optimization of the current injection circuit is possible by using a simplified model. Good agreement between simulated and measured currents was obtained which supports the validity of the proposed model for the injection circuit.

By applying optical links for both, signal and trigger channel, the sensitivity and noise immunity required for unambiguous detection of low level common-mode and differential-mode interference voltages, caused by artificially injected lightning currents, could be reached even in a harsh noise environment.

Acknowledgement

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