Lightning Strike EMP Effect On Local Grids

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***Abstract*—Electric fields generated by lightning strikes are analysed and compared with effects of a high altitude nuclear weapon detonation electromagnetic pulse scenarios. The decay in amplitude of electric fields generated by a intermediate level lightning strike is calculated over distance and further analysed in a full real world simulation of a severe lightning strike event within close proximity of a isolated residential grid. Factors influencing the immunity of the grid to electromagnetic pulses are simulated and discussed as well as induced voltages on conductors.**

***Index Terms*—Electromagnetic interference, Electromagnetic Pulse, Lighting strikes, High-altitude electromagnetic pulse**

I. INTRODUCTION

Accelerating dependency worldwide on uninterrupted electrical and electronic system operation highlights the importance of good electromagnetic compatibility practice. Hardening systems against continuous or intermittent high impact events is of paramount importance. Simulations can be a powerful tool, especially with computational electromagnetic software closing the void between real and virtual. Technological advancements continue to improve rapidly in the fields of electrical and electronic systems. With the adoption of these technologies a dependency on reliability becomes imperative. Electromagnetic compatibility (EMC) engineers are facing great challenges to maintain operability as systems become more complex and interdependent. Due to insufficient immunity to conducted and radiated emissions, effects vary from temporary device malfunction to permanent system damage as well as infrastructure outages which, in many cases, have enormous implications in terms of productivity [1], [2], financial [3]–[5] and even loss of life [6].

Electromagnetic interference (EMI) sources include natural occurrences such as lightning [7], [8] or geomagnetic storms [9], [10]. Many studies have been done on the effect of a Electromagnetic Pulse (EMP) as a source of intentional electromagnetic interference (IEMI) in the form of a High-Altitude Electromagnetic Pulse (HEMP) attack as well as lighting strikes [11], [12]. In the United States the number of power outages caused by lightning strikes is estimated to be around 30 %. The financial figure attached to this estimate is USD1bil, which includes damage to equipment, loss of production and life [5].

In case of HEMP, the consequences would be devastating to nearly all key infrastructure resulting in a long duration complete blackout. In 2016 the Electric Power Research Institute (EPRI) initiated a research project to provide unclassified and technically based research into various aspects of IEMI in the form of a HEMP attack. The project delved into aspects such as threat characterization, mitigation and hardening, impacts as well as vulnerability investigations [12]. The aim of the 2016 EPRI study was mainly effects on electrical transmission infrastructure as well as other key state assets.

In this paper an analysis is done on the impact of Lightning Electromagnetic Pulse (LEMP) on common infrastructure, such as buildings, and electrical systems encapsulated inside. The scope of this paper includes a discussion of the effects of HEMP and difference onset waves as well as simulations of lightning strike a certain distance from the point of interest. In the case of lighting, analysis is performed on the factor distance from the source affecting the electric field strengths generated by a strike. Calculations show the expected vertical electric field and the decay in field strength as a factor of radial distance from the lightning strike source. Taking the calculated field strengths into account, which prove to reach high levels in close proximity to a strike, the electric fields which penetrate a building are simulated and surge voltages present on conductors inside a building are analysed.

II. FIELDS STRENGTHS ASSOCIATED WITH HEMP AND LIGHTNING STRIKES

The field strength and rise time of the emissions sources are required to gauge the extent of risk. Nuclear detonations in the altitude range of 40 km to 500 km pose a great threat as an intense EMP is produced in the form of three waves in time [12]. The three waves classified as E1, E2 and E3 due to the distinct differences and onset times of early-, intermediate- and late time onset. The initial E1 wave has a rise time of approximately 5 ns and amplitude of up to 50 kV/m or higher depending on various factors. The secondary (E2 - occurring a few micro-seconds after E1) and tertiary (E3 - occurring a few seconds later) wave is produced at a slower rise time and lower amplitude which is significantly less devastating. The respective waves are produced due to a variety of effects of interaction with the earth's magnetic field [13]. An expression of the mathematical approximate of the E1 pulse is described as Eq. 1 [13]:

$$E(t) = E_0 k(e^{-\alpha t} - e^{-\beta t}) \tag{1}$$

Etopia project research is funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 812753.

where, E_0 = 50 kV/m, $\alpha = 4 \times 10^7 s^{-1}$, $\beta = 6 \times 10^8 s^{-1}$ and $k = 1.3$

In case of lighting strikes, the effects are less severe but not negligible. The peak electric field generated in case of lighting is similar in magnitude and rise time to the E2 pulse produced by a HEMP event. The expression used to calculate the vertical electric fields, E_v, is taken from [14] and described as Eq. 2.

$$E_v(z,r,t) = \frac{1}{2\pi\varepsilon_0 c\sqrt{r^2+z^2-2zr\cos\theta}} i(t-\tau_1) + \frac{1}{2\pi\varepsilon_0 c\sqrt{r^2+z^2+2zr\cos\theta}} i(t-\tau_2) \quad (2)$$

where, $\tau_1 = \frac{\sqrt{r^2+z^2-2zr\cos\theta}}{c}$ and $\tau_2 = \frac{\sqrt{r^2+z^2+2zr\cos\theta}}{c}$, r is the radial distance from the source of strike, ε_0 is the permittivity of free space, c is the speed of light, θ is the angle from the point of observation from the strike point, z is the height above ground of the observation point.

The equation to describe an intermediate level lightning base strike current is obtained from MIL-STD 464C also used by [15] and shown in Eq. 3.

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (3)$$

where, $I_0 = 11.3\,\text{kA}$ is the lighting base current amplitude of an intermediate level strike, $\alpha = 3 \times 10^4$ and $\beta = 10^7$. Using the formula from Eq. 2 and 3, the decay of the electric field over a distance from 50 m to 5000 m is calculated shown in Fig. 1 as ”Calc. E_v ”. this is validated against findings indicated as markers from Barbosa [16] in red, Izade [17] in black and Zhou [14] in green. The result shows a significantly high electric field strength in close proximity to the lightning strike location which rapidly decays with distance away from the source.

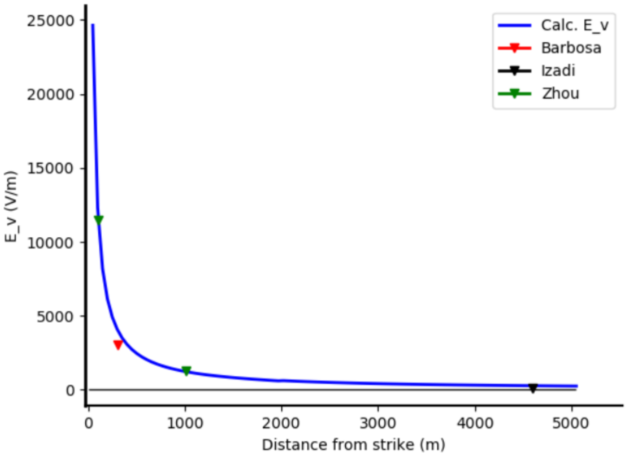

Fig. 1: Calculated vertical electric field over distance from point of lighting strike

It should be noted that obstacles between the lighting strike point and the point of observation can have a large effect on the propagation of electric fields [18]. For the scenario discussed in this paper a lighting strike is considered close (less than 100 m) to the observation point (or building) and unobstructed by any media which would provide effects of shielding. The standard model of HEMP electric field strengths radiated towards a target achieves 50 kV/m. MIL-STD 464C classify a severe lightning strike base current at 200 kA ±10%. The calculations for an intermediate level strike performed in Section II achieved field strengths of up to 25 kV/m for intermediate base currents up to 11.3 kA at a distance of 50 m. So it is fair to say for an intense strike base current of up to 220 kA the electric field can exceed these levels. In fact, it is stated in MIL-STD 464C that electric field strengths of up to 3 MV/m are achievable at close distance for a intense lightning strike. It is therefore possible under the right conditions that a lightning strike may achieve equivalent or greater field strengths in comparison to a HEMP. Although the rise time of the Electro-Magnetic (EM) field generated by lightning is in the order of μS and HEMP in the order of a few nS. Higher frequencies tend to have larger effect depending on sensitivity of equipment.

III. SIMULATION OF LIGHTNING STRIKE ELECTRIC FIELDS AND SURGE VOLTAGES IN CABLES

A model of a common building is simulated with Altair FEKO in this section with a size footprint of 13.2 m x 8 m x 2.5 m shown in Fig. 2. The walls of the building are constructed from brick, 180 mm thick, with ceramic roof tiles and glass windows. A cable bundle consisting of 3 unshielded 5 mm conductors are included in the simulation in the path shown in Fig. 4.

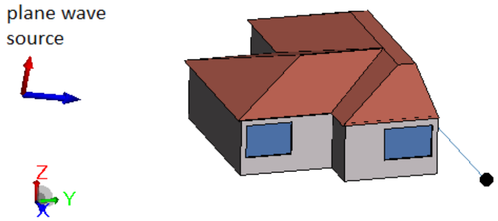

Fig. 2: Isometric view of simulated building including cable bundle

To reduce the computation requirements of the simulation the model was converted into two-dimensional faces which are configured to the relevant medium and specified with a thickness as thin dielectric sheets. E.g. The brick walls are a two-dimensional shapes configured as brick with a defined thickness, in this case, of 180 mm. This removes all dielectric volumetric regions in the model which reduces the amount of mesh elements as well as to avoid the use of Surface Equivalence Principle (SEP) which may result in invalid results for relatively low frequency simulations, as in this case when using Method of Moments (MoM). The model is solved in less than 6 min on a personal computer with core i7 8th generation Intel CPU with 16 GB of RAM. A lightning strike electric field time domain waveform can be represented Using the same mathematical expression as used for an EMP from

Eq. 1. Due to the slower rise and fall times the values for α and β of 11.3×10^3 and 6.5×10^5 were used. The rise time of the electric field between 10 % and 90 % is now approximately 5 μs similar to the front wave current pulse rise time defined in Mil-STD 464C for an intense strike. The lighting strike electric field is represented by a plane wave source as shown in Fig. 2 and a time domain waveform with a double exponential mathematical expression shown in Fig. 3. The amplitude is extrapolated from the calculated maximum shown in Fig. 1 at a base strike current of 11.3 kA to a severe base strike current of 220 kA.

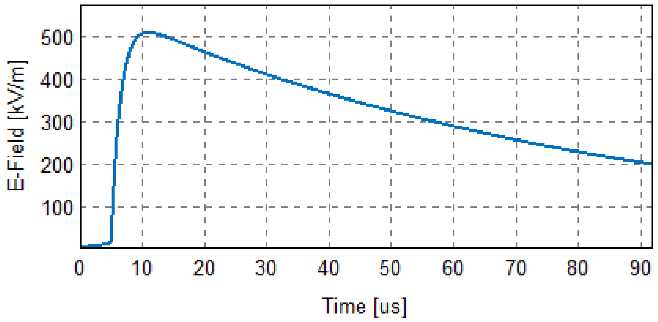

Fig. 3: Excitation waveform

A cable consisting of three conductors labeled Live, Neutral and Earth is arranged to form a standard grid connection for a residential home. The cable path runs for approximately 40 m from a grid connection to a connection inside the building. A spice circuit diagram shown in Fig. 5 represents the cable, connectors and components or the grid connection. The grid connection and impedance is determined by components L1, R1 and C1. The values are typical for a Line Impedance Stabilization Network (LISN) and obtained from MIL-STD 461E. Voltage probes are placed on Live and Neutral conductors to Earth as well as Live to Neutral on both ends of the cable to measure the voltage induced in the cables due to a lighting strike close proximity (50 m) to the building. The grid connection point is taken as reference point A and the connection inside the structure labeled as ”lounge” as point B, shown in Fig. 4.

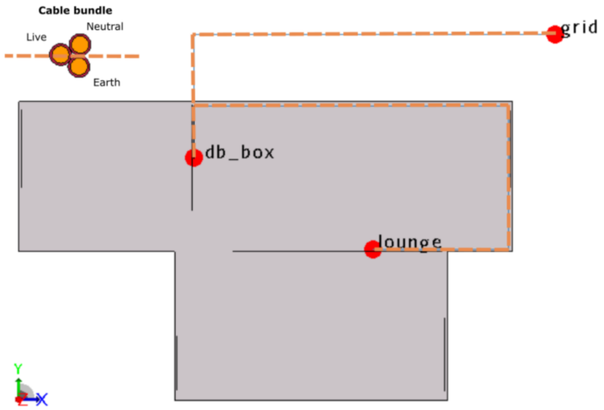

Fig. 4: Cable bundle path inside and outside building

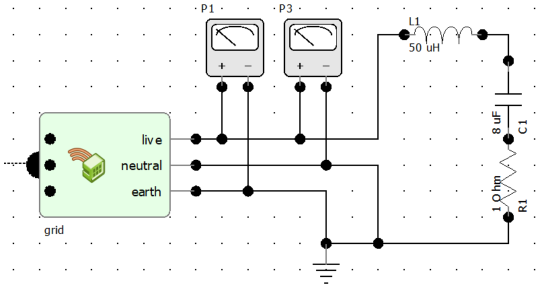

Fig. 5: Grid connection and impedance spice circuit components.

In Fig. 6, The electric field contour plot is shown at a level of z =1 m. The shielding provided by the structure is clear. Especially near the walls perpendicular to the source. At a time step of 10 μs, near the peak of the electric field waveform, the maximum electric field external to the building is 533 V/m while the minimum point inside the building is 477 V/m.

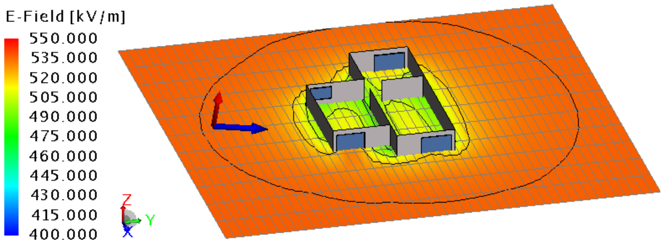

Fig. 6: Simulated field strength in and around the building

In Fig. 7 the peak induced voltages measured on the voltage probes for live to neutral voltages at the ”grid” as well as the ”lounge” measurement points are shown. The wave front is strikes at around 5 μs and the peak voltages measure are 425 V and 255 V for point A and point B respectively.

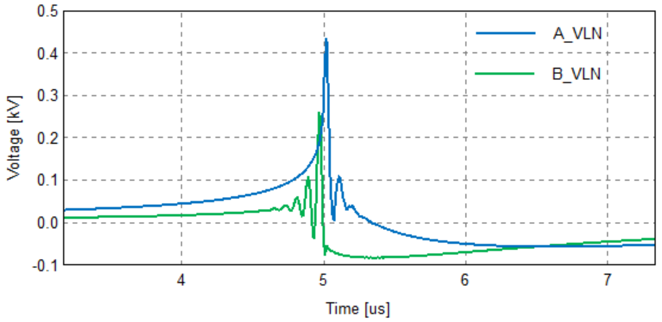

Fig. 7: Induced line to neutral voltages for point A and B

In this scenario, factors which have a large influence on the induced voltages on the grid include electric field amplitude, rise time, cable length and impedance of the grid. Grid impedance depends on many factors and can widely vary. Altering the grid impedance in the model shows voltages induced on the cables at grid and lounge in Fig. 8.

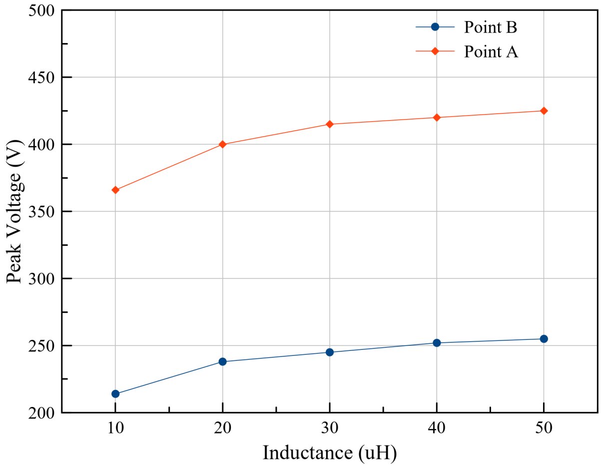

Fig. 8: Peak surge voltage vs inductance of the simulated grid

The effect of inserting C_y capacitors has been analysed. This tends to nearly eliminate the coupled voltages on the cables. Adding a capacitor between Live and Earth at point A reduces the voltage peaks across the entire simulated grid. At Point A the voltage surge peak is below 1 V. The voltage surge peak at point B is reduced from 255 V. Adding C_y at both point A and point B reduces the peak surge voltages at both points to below 1 V, effectively eliminating the voltage surge in this scenario.

CONCLUSION

A specific case showing the effect of a severe lightning strike on a local grid is analysed in this paper as well as discussions and comparison with effects of . The electric field strength of lightning strikes may be comparable to those caused by HEMP but the rise times of the fields are significantly lower. The electric field decay over distance caused by a lightning strike is calculated for intermediate level strike base current from 50 m to 5000 m. Using the same approach for a simulation of a severe close proximity strike shows voltages induced on conductors in a building of up to 425 V. Complex cable and building layouts can be simulated with relatively low computation power if the correct techniques are adhered to. It is shown that the impedance of the grid effects the amplitude of the induced voltage on the conductors. Furthermore adding C_y can effectively act as protection and diminish the induced voltage on the conductors.

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