406 *Journal of Electrical Engineering & Technology Vol. 7, No. 3, pp. 406~410, 2012*
http://dx.doi.org/10.5370/JEET.2012.7.3.406

The Field of Power/Ground Planes influenced by the HPEM Source, and its Damage Reduction

Sungtek Kahng* and Hyeong-Seok Kim†

Abstract – This paper looks into the field inside the wide rectangular box structure that is excited by the High Power Electromagnetic(HPEM) source as a potential threat to electric grid and communication networks causing malfunction or destruction. The rectangular box is assumed power/ground planes and its internal field is calculated by the cavity model with the lightning strike excitation as an HPEM pulse. The accuracy of the calculation method employed here is validated through a 156mmX106mmX508μm parallel metallic plate case which is manufactured and tested, and is applied to the size of a building. With the help of the cavity model that takes into account loading, the level of the electric field is shown to decrease when a metal pillar is loaded between the power and ground planes.

Keywords: High power electromagnetic pulse(HPEM), Lightning, HEMP, Power/ground planes, Cavity model, Resonance suppression

1. Introduction

A civil standard on the electromagnetic effects of a high altitude nuclear burst was prepared by the technical committee 77 under the authority of International Electrotechnical Commission(IEC). In 1992, the member countries nodded their heads to form a subcommittee 77C to deal with the problem in a deeper level [1]. They have adopted basic theories and developed new ones to understand the radiated environment where the High Power Electromagnetic(HPEM) Threats and High Altitude Electromagnetic Pulse(HEMP)(Henceforth, HPEM/HEMP) create high power electromagnetic fields and waves and they propagate through the air and ground, and affect electric and electronic devices and systems physically and functionally. To predict the amount of influence and the influenced spots such as the Power Blackout in the US Northeast in 2003, the related modeling and mathematical methods are needed [1-3].

In the HPEM/HEMP modeling, there are generally the source model and environment and victim models. The source modeling is to express the current or electric field pulse shape imitating the realistic lightning strike or HEMP. This is an essential work in that it also provides a clue to the equivalent circuit used to make the experimental setup and source of excitation. M. Ianoz et al use the early time double exponential electric field pulse and model the radiated environment of the earth as well in [3]. The source as the obliquely incident plane wave excites the straight conducting line above the lossy ground and the Telegrapher equations are used for the analysis of the victim influenced by high power pulse [4]. Those are the studies about the high power electromagnetic effects of the victims in the open space, not the closed space.

While the conducting line above mimics the power line of the power grid, factories and office buildings can be thought of wide rectangular boxes and should also be dealt with on the HPEM/HEMP influence. Considering the material and geometry of a flat factory, it looks like a pair of power/ground planes(parallel plates) of a multi-layered PCB without loss of generality. The power/ground planes are a rectangular cavity that has resonance modes due to the boundary conditions of a dielectric sandwiched between the top and bottom PEC planes [5]. With this geometrical model, using the modal analysis method for this particular cavity problem, the field inside the wide rectangular box is characterized with a high power voltage source, in this paper. The internal electric field is calculated to show the resonance as the peak that causes very high impedance and power surge in the structure. The computation method here is validated by the case where its numerical result agrees with the measurement of 156mmX106mmX508μm power/ground planes that are easy to make(since it is too expensive to test a building model). Based upon this technique, the HPEM influence on a structure of 50mX50mX3m parallel plates is investigated. Besides, the high electric field due to the resonance is mitigated by introducing a metal pillar to the parallel plates, which is obtained by the cavity model modal analysis method combined with a scheme of [6]. Checking out the electric field, it is addressed what the magnitude and frequency points of resonance modes are and how they can be mitigated under the influence of lightning strike as an HPEM pulse.

† Corresponding Author: School of Electrical and Electronics Eng., Chung-Ang Univ., Korea. (kimcaf2@cau.ac.kr)
* Dept. of Information and Telecommunication Eng., University of Incheon, Korea. (s-kahng@incheon.ac.kr)
Received: April 30, 2011; Accepted: December 13, 2011

2. Modeling and analysis method

If an electromagnetic burst occurs due to a lightning strike or high altitude nuclear explosion, the objects in the air and on the ground will be victimized. Depending on the energy level and its spectrum, the upset and damage will be determined and go very adverse, different with respect to the victim's electromagnetic and metallurgical properties. There are a variety of kinds of victims to the HPEM, which are categorized by the shielding capability, the size, the coating material and dispersion characteristics, the shape, etc. Whether a victim is directly exposed to the high power electromagnetic radiation or indirectly influenced. The indirect exposure is that the victim is placed in the closed space. Though it is inside an enclosure, there exists a slit or an aperture along the edge of the closed geometry. Now we imagine a factory building that has dielectric walls and steel frames and supports between the top and bottom metal planes, as illustrated in Fig. 1

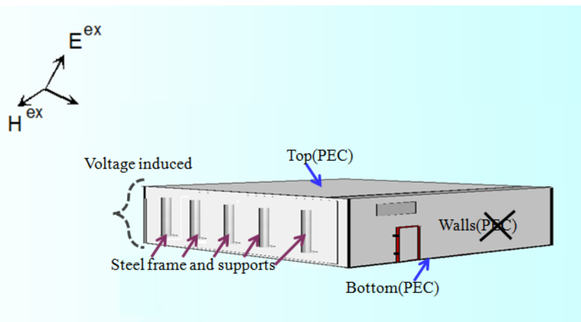


Fig. 1. A factory building as a wide rectangular box under the influence of the high power electromagnetic plane wave incidence.

The roof and the bottom of the structure are a thin PEC. The size in the horizontal direction is much greater than the height. So this structure can be modeled as the pair of power/ground planes [5, 6]. The incident electromagnetic wave induces the electric field over the gap between the top and bottom planes and this becomes the voltage source that causes the electromagnetic penetration(EMP) into the enclosure.

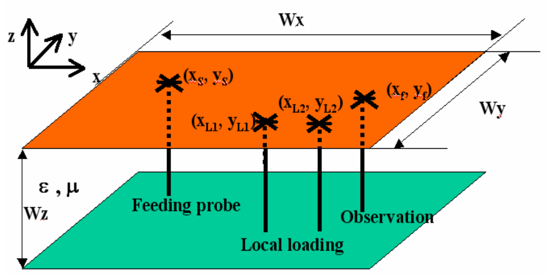


Fig. 2. Cavity model for the wide rectangular box

The penetrated electromagnetic energy will bounce back and forth, and generate hot spots in the boundaries of PEC top and bottom planes and PMC walls. Fig. 2 is the cavity model for solving the EMP problem of the wide rectangular box whose size is Wx×Wy×Wz. In the figure, the feeding point (X_S, Y_S) and the observation point (X_f, Y_f) are where the voltage excitation is made and the resultant electric field is observed, respectively. The feeding and observation points are often called ports 1 and 2. To consider loads which will come later, lumped elements will be placed at (X_{Lu}, Y_{Lu}). This boundary condition(2 horizontal PECs and 4 vertical PMCs) problem is solved by the modal analysis method using the double sum to evaluate the field and impedance of the rectangular power/ground planes accurately [5].

$$E_{Ld}(f, X_f, Y_f) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{\gamma_{mn}\cdot c_{mn}(X_s, Y_s)\cdot c_{mn}(X_f, Y_f)\cdot W_z/(W_x W_y)}{\varepsilon\omega/Q + j(\varepsilon\omega - \frac{k_{xm}^2 + k_{yn}^2}{\omega\mu})} \tag{1}$$

where

$$c_{mn}(X_i, Y_i) = cos(k_{xm}X_i)\cdot\cos(k_{yn}Y_i) \cdot sinc(k_{xm}P_{xi}/2)\cdot sinc(k_{yn}P_{yi}/2)$$
$$\text{with } k_{xm} = m\pi/W_x,\ k_{yn} = n\pi/W_y,\ \omega = 2\pi f$$
$$Q = [\tan\delta + \sqrt{2/\omega\mu_0\kappa W_z^2}\,]^{-1} \tag{2}$$

γ_{mn} is 1 and 4 for (m =0, n =0) and ($m\neq0$, $n\neq0$) each. When ($m\neq0$, n=0) or (m=0,$n\neq0$), γ_{mn} takes 2. $tan\delta$, ε , μ, f, P_i and j denote loss-tangent, permittivity, permeability, frequency, port's width and $\sqrt{-1}$, respectively. When we need to take into consideration the loading effect of lumped elements, Eq. (1) of [6] is employed, which is not repeated in this paper.

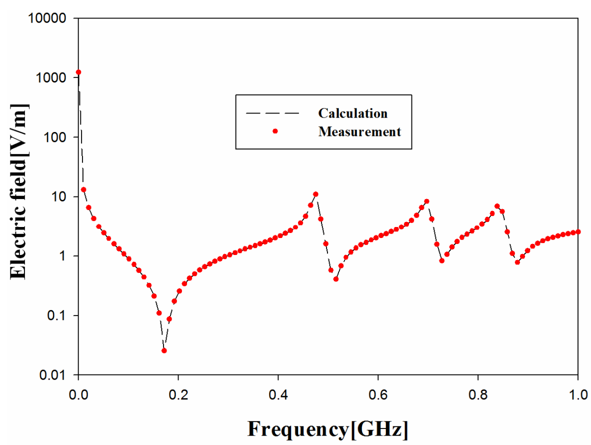


Fig. 3. Calculated and measured results of an example of power/ground planes.

3. Validation of the modeling technique

Firstly, the accuracy of the calculation method [6, 8, 9] adopted in this paper here is tested by being compared to the measurement of a simple power/ground plane structure.

Eq. (1) is evaluated with the 160000 mode numbers(with the truncation number for both m and n set to 400). The geometry of interest takes the size of 156mm×106mm× 508μm for experimental purpose with $X_S = X_f$ and $Y_S = Y_f$ at the origin of the coordinates. The excitation voltage is 1V. As shown in the figure, the calculation scheme turns out robust to result in reliable accuracy, agreeing with the counterpart. Also, it is noticed that the resonance modes appear as the peaks in the frequency response of the electric field and hot spots(danger zones) over the structure, which cause the ground-bounce damaging electronic equipment inside the wide rectangular box and the radiated emission back to the external region as well. The following figure is the electric field distribution in the cavity at its TE_{10} resonance mode(470MHz) to show why the resonance needs to be circumvented.

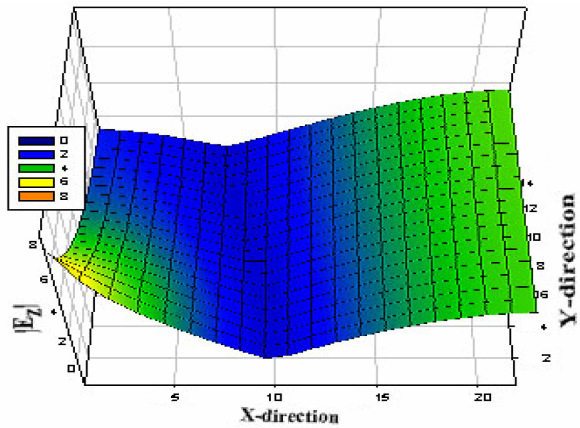
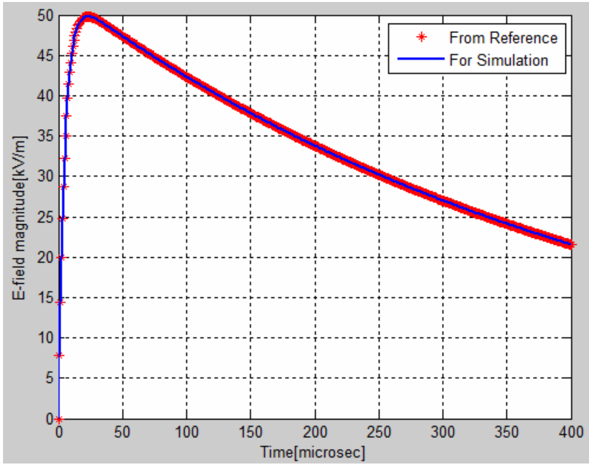
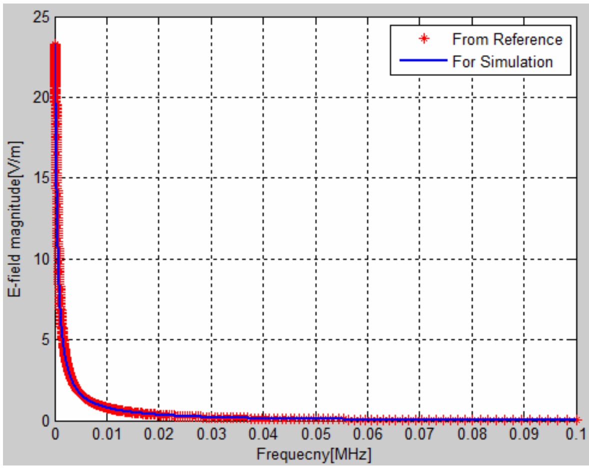


Fig. 4. Electric field distribution in the cavity at its TE_{10} resonance mode.

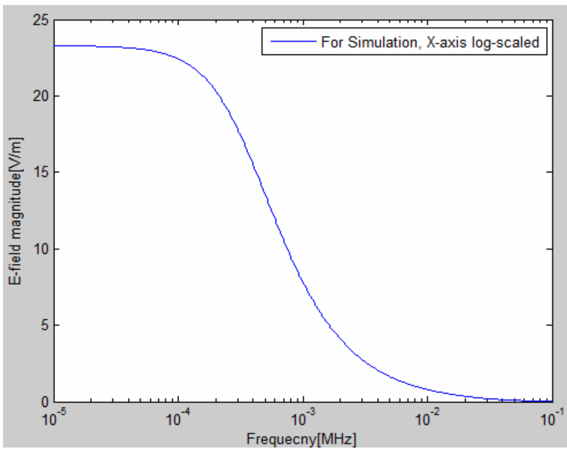
For plotting, the field is calculated with the observation point moving around the discretizing mesh plane. The bottom left corner is the voltage excitation point where the strongest electric field is observed. The self-term(the feed and observation points are the same) will be checked first in practice. As for the TE_{10} mode, the right-most edge is another maximum electric field spot, namely, hot spot. This hot spot is equivalent to the magnetic surface current on the wall and plays a role of the source of the radiated emission. Now, we move on to deal with the high power electromagnetic pulse injected to an enlarged case. The size of the wide rectangular box is set 50m×50m×3m to mimic a real 1 story building. This cavity has steel(μ_r=5000) supports whose population equals a fraction 1/100~1/10 of the plane size. We consider Concrete as the dielectric(ε_r=3). Regarding the injected voltage of an HPEM pulse, we consider the lightning and implement the excitation voltage model given by the IEC 61312 lightning standard saying the peak 50 kV, rise time ~10μs, etc.



(a)



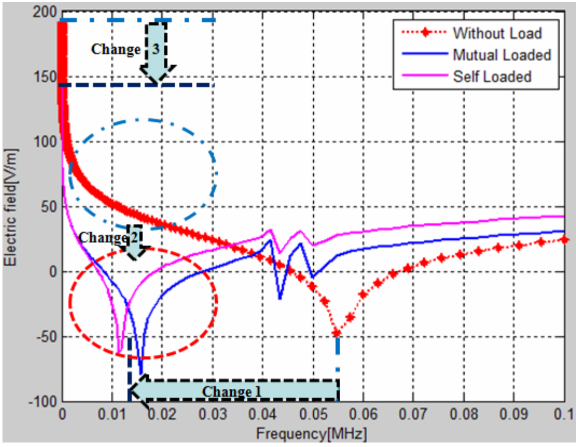
(b)



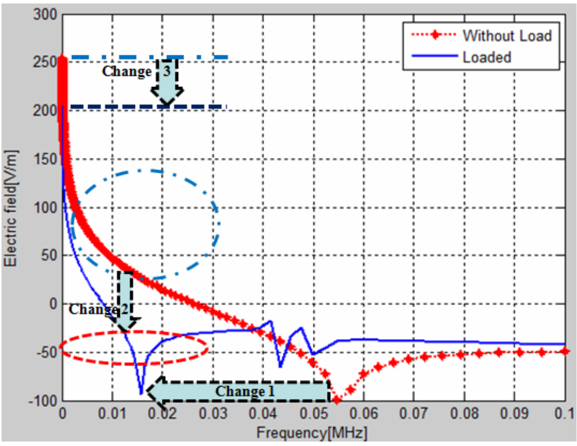
(c)

Fig. 5. Excitation voltage vs. IEC standard(ref.): (a) Time-domain; (b) Frequency-domain, linear scaled x-axis; (c) Frequency-domain, log-scaled x-axis

As shown in Fig. 5, the excitation model is correct according to the standard IEC 61312 and its frequency domain version is used for the following simulation.



(a)



(b)

Fig. 6. Electric field in the cavity model of a factory building: (a) with the excitation voltage of 1V; (b) with the HPEM excitation voltage of IEC standard

Given the HPEM pulse seen in Fig. 5(b) or Fig. 5(c), the voltage is injected to the power/ground planes whose size is the factory building of interest, and its field is calculated with the use of the aforementioned modal analysis method. Two sets of numerical and comparative experiments are conducted: One is to see the difference of the electric field behaviors in between the power/ground structures with the 1V injection(intrinsic mode) and with the HPEM lightning standard excitation, and the other is to check the levels of the electric fields of the cavity model before and after lumped element loading to come up with an idea to lower the chance and amount of damage. For all the tests, the effect of steel pillars in the power/ground planes has been included by assuming that their density equals 1/100 of the area of the plane and $\mu_{r,ave}$=50 is put in the calculation together with the dielectric($\varepsilon_{r,ave}$=3) similar to the ray tracing technique for indoor propagation. And the voltage excitation is done at (X_f =0,Y_f =0), and (X_f, Y_f) is (0,0) and (50cm,50cm) for the self-term and mutual-term electric fields, respectively. Also, the loaded case means a metal pillar of radius 25cm positioned at (50m, 25m) in the xy-plane, and the metal pillar is modeled as a PEC via whose equivalent circuit expression is found in [7].

In the first place, it should be addressed that Fig. 6(a) is the electric field behavior of the rectangular box with the 1V excitation, but Fig. 6(b) is that with the HPEM pulse of Fig. 5(b). Inside Fig. 6(a), there are three curves of electric field, ‘unloaded and self-term’, ‘loaded and self-term’, and ‘loaded mutual-term’ all with the excitation of 1V. Before applying the HPEM pulse, we can see the intrinsic electric field behavior of the building, and the metal pillar loading can reduce the electric field intensity effectively and mitigate the damage in a lower frequency regime. The arrow named ‘Change 1’ implies that the metal pillar loading shifts the dip frequency of the electric field from 0.054MHz to 0.015MHz, which causes the field intensity to decrease from +100V/m ~ +50V/m to +0V/m ~ -50V/m as the arrow named ‘Change 2’. Likewise, the level of the electric field in the extremely low frequency regime drops by 50V/m when we follow the arrow named ‘Change 3’. It is good to see the appropriate lumped element loading can reduce the electric field that is caught and possibly generating hot spots in the cavity, and especially this reduction scheme working properly in the lower frequency can diminish the damage to electric appliances and electronic devices. This perspective is also found from Fig. 6(b) where the HPEM pulse is applied to the cavity model. At first sight, the curves of the 1V excitation case and the HPEM case show the same tendency. The difference between Fig. 6(a) and Fig. 6(b) is the level of the field inside the structure. This results from the scaling factor from 1V to Fig. 5(b). The loaded cavity has the lower dip frequency and the decreased self-term electric field intensity in the very low frequency region as with Change 1 and Change 2. At the lowest frequency, the magnitude of the electric field has also fallen shown with Change 3. This represents that in order to mitigate the upset or damage due to the electric field, the dip frequency should be as low as possible by proper loads.

4. Conclusion

In this paper, the influence of the HPEM pulse on a wide rectangular box has been examined and a method to reduce its negative effect to the internal space of the structure has been suggested. The power/ground plane model has been adopted and the cavity modal analysis method has been used to calculate the electric field of the wide rectangular box about the HPEM lightning pulse excitation. The accuracy of the numerical calculation method has been proven by the comparison with the measurement for a simple model. This numerical method has been applied to an enlarged structure imitating a factory building under the standard HPEM pulse. The electric field inside the structure has been obtained for the cavity without and with a metal pillar for the lightning excitation voltage. The finding is that the appropriate load can effectively lower the electric field inside the structure and reduce the risk of the possible damage to the electronic equipment placed in the building. Though a simplified modeling for the HPEM energy penetration is proposed and used presently, an efficient prediction method will have to be developed to tackle more complicated and large structures.

Acknowledgements

This work was supported by the U.I. Research Promotion Program

References

[1] Sub-committee 77C: "Immunity to high altitude nuclear electromagnetic pulse (HA-NEMP)," Doc. 77C (Secretariat)l, Mar. 1992.

[2] IEC 61000-1-3 TR: "The effects of high-altitude EMP on civil equipment and systems", May, 2008.

[3] M. Ianoz, B. I. C. Nicoara, and W. A. RadaskyI, "Modeling of an EMP Conducted Environment," *IEEE Trnasactions on Electromagnetic Compatibility*, vol. 38, no. 3, August 1996.

[4] M. Ianoz, C. A. Nucci, and F. M. Tesche, "Transmission line theory for field-to-transmission line coupling calculations," *Electromag.*, vol. 8, no. 2 4 , pp. 171-211, 1988.

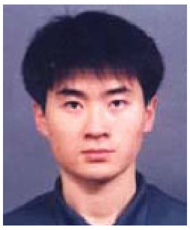
[5] T. Okoshi, Planar Circuits for Microwaves and Lightwaves, Berlin, Germany: Springer-Verlag, 1985

[6] S. Kahng, "GA-Optimized Decoupling Capacitors Damping the Rectangular Power-Bus' Cavity-Mode Resonances," *IEEE Microwave And Wireless Components Letters*, vol. 16, no. 6, pp.375-377, June 2006.

[7] G. Jang, and S. Kahng, "Design of a Dual-Band Metamaterial Bandpass Filter using Zeroth Order Resonance," *Progress in Electromagnetics Research C*, vol. 12, pp.149-162, 2010

[8] S. Kahng, "The Rectangular Power-Bus With Slits GA-Optimized to Damp Resonances," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 6, pp.1892-1895, 2007

[9] C. Wang, M. Leone, J. L. Drewniak, and A. Orlandi, "Coupling between the differential signals and the DC power-bus in multilayer PCB," *IEEE Transactions on Advanced Packaging*, vol. 28, no. 2, pp.337-345, 2005



Sungtek Kahng He received the Ph.D. degree in electronics and communication engineering from Hanyang University, Korea in 2000, with the specialty in radio science and engineering. From year 2000 to early 2004, he worked for the Electronics and Telecommunication Research Institute, developing the RF passive components for satellites. Since March 2004, he has joined the department of Information and Telecommunication Engineering at the university of Incheon, researching microwave components and antennas including metamaterial technologies, MIMO communication and wireless power transfer.

Hyeong-Seok Kim He received the B.S., M.S. and Ph.D. degrees in electrical engineering from the Seoul National University, Seoul, Korea, in 1985, 1987 and 1990 respectively. From 1990 to 2002, he was with the Division of Information Technology Engineering, Soonchunhyang University, Asan, Korea. In 2002, he transferred to the School of Electrical and Electronics Engineering, Chung-Ang University, Seoul, Korea as a professor. His current research interests are numerical analysis of EM analysis, RF passive and active components.