



Evaluation of lightning protection systems proposed for small structures by electromagnetic simulation

Ashen Gomes, Chandima Gomes, Zainal Kadir and
Mehdi Izadi
Center for Electromagnetic and Lightning Protection
(CELP), Universiti Putra Malaysia, Serdang,
Selangor, 43400, Malaysia
chandima@upm.edu.my

Miachael Rock
Technische Universität Ilmenau
Department of Elect. Engineering and Infor. Technology
Group for Lightning and Overvoltage Protection
Gustav-Kirchhoff-Straße 1, D-98693 Ilmenau, Germany
michael.rock@tu-ilmenau.de

Abstract—This paper validates the performance of low-cost lightning protection systems for small structures proposed by researchers in the past. Such structures have an acute demand in the countries with very high lightning ground flash density, yet the affordability of the mass public is quite limited due to the struggling economies of the countries. The protection systems for small housing structure, and a standalone protection structure for one or few people have been investigated by implementing the structures in HFSS/ANSYS software which employs finite element method. By applying current waveforms to represent first negative return stroke, subsequent negative return stroke and positive return stroke, the electric field and potential gradient of the entire space and the current density and the thermal profile of the protective structure have been computed. The objectives were to find whether the voltage distribution in the wake of a lightning strike could initiate side flashes, generate touch potential and step potentials that exceed dangerous levels, drive current densities due to which the structure collapse under thermal effects. It has been found that the proposed protective structures could suppress side flashes and harmful effects due to step potential while the structure will be able to withstand the heat generated. However, the touch potential could still be beyond the human injury thresholds, thus a minimum separation from the lightning current passage should be advised to the occupants.

Keywords—Small structures; potential gradient; side flash; ANSYS

I. INTRODUCTION

Lightning brings impulsive current from the cloud which has double exponential wave shape at the channel base. The lightning struck object typically experience multiple stroke current pulses of which the first stroke has a peak value of 30 kA on average while subsequent strokes have 50% of that on average. The impulse current most often last for less than about 70 μ s [1]. Sometimes the impulse component is followed by a continuing current which has magnitudes in the range of few hundred Amperes and flow for several hundreds of milliseconds [2]. According to the wave profile, the impulse part of the lightning current is categorized into three types; negative first stroke, negative subsequent stroke and positive stroke [1]. Any lightning safety/protection device should be tested for all three types of these lightning currents as they have

features unique to each of them; thus hazards due to one current component may be different from the other

Since the time of Benjamin Franklin (1706-1790) it has been proposed that a person is safe only inside a sturdily built structure enclosed with a system of metallic strips which has been erroneously referred as a Faraday cage in some literature. The most up-to-date document that comprehensively specifies the design of such protection system is IEC 62305 (2010) [3]. The factors that determine the risk of lightning threats to human beings have broadly been discussed and hypothesized in [4]. The output of research presented in [5] and [6] emphasizes the gravity of lightning risk of public that earn their living by outdoor activities, in low-income societies. Personal communication with Richard Kithil, President, National Lightning Safety Institute, USA reveals that even rich industries such as mining, timber and petrochemical urgently seek suitable protective shelters for their outdoor workers operate in high lightning dense regions. In this backdrop, Gomes et al [7] provided design and implementation techniques of implementing low-cost lightning protection schemes for existing house and boat structures in low-income societies. They also suggested improvement of lightning protection in buildings with reinforced steel structure at a very competitive cost [8].

In the modern times it is not a totally viable recommendation to ask the public to be inside such sturdy protected buildings until a thunderstorm lasts, which may sometimes take 1-2 hours. Many studies conducted in Africa, Asia and Latin America in the recent past reveal that a majority of the public in these parts of the world reside permanently in very unsafe simple structures that may subject the occupants into grave risk of being injured in the event of a lightning strike [6, 9-13].

Work done in Mongolia (paper to be presented at ICLP-2016) reveals that almost 90% of the lightning accidents in the country are pertinent to the cases where victims were at wild areas. These 'wild areas' are referred to grasslands or low grown vegetation in the mountain slopes where shepherds take their livestock for grazing. These landscapes are many hundred hectares in area thus, the workers in the livestock industry that lead the animal have no place to take shelter even if they receive thunderstorm warning well in advance. Similar

observations have been made in Uganda, where people in Lake Victoria Basin are compelled to go for fishing even under overcast conditions, due to economic reasons [5]. In the event of an approaching thunderstorm, they are at the mercy of nature as it is almost impossible to abandon their operations abruptly and ride to the shore which may be a couple of hour journey. In such scenario, providing early warning to the boaters may not be as fruitful as one anticipates. Thus, the only option is to give a certain level of protection to their boats at an affordable cost.

Even in developed countries, there are many lightning accidents reported where the victims were campers, golfers, adventure-seekers, boaters etc., who could not access a safe shelter within a reasonable time due to the isolation of their location by the time they have detected the thunderstorm [14, 15].

The above background demands for more feasible and practical solutions to address this issue, rather than demanding the public to seek shelter in sturdy structures whenever there is a thunderstorm in the vicinity. As a remedy to that Wiesinger [16], Darveniza et al. [17] and Darveniza [18], developed concepts of portable lightning safety devices, few of which have been tested under laboratory conditions. However, lack of theoretical approach / testing with different human body models and the consequent retirement of the sole project leader from active research prevented the device being developed to a level of wide scientific acceptance. The other attempt on developing such personal protection system has been vaguely revealed by Prof. Liew Ah Choy of National University Singapore in 2009. During an interview with the Star Newspaper [19], he mentioned that plans are underway to develop a fabric by which lightning current could safely be dissipated into ground when a person or group of people is covered with that. However, no further information on this device is available in the public domain so far. The concept of personal lightning safety proposed by Darveniza [17] was re-taken for research in 2010/11 as an undergraduate level engineering project at Universiti Putra Malaysia [20] which was completed successfully. The project produced a lightning safety structure which has been theoretically tested for its safe handling of lightning currents. However, the device needed much extensive detailing of electrical, mechanical and thermal behavior under the injection of all possible types of lightning currents (varying their rise time, amplitude and energy content) under model simulation and then validation under HV conditions to re-confirm the acclaimed performance before being recommended for public use.

The research conducted by Mary and Gomes [5, 10] in Africa, Doljinsuren and Gomes [9] in Mongolia, Jayaratne and Gomes [21] in South Asia reveals that in under-privileged societies protection schemes for small structures are more appropriate than personal lightning protection devices due to the high cost per capita that will be incurred in developing such devices. Furthermore, the observations done in South Africa [22] and USA [23, 24] reveal that in the recreational sector, too, protective structures for small groups or protection schemes for already built small structures are more useful due

to the burden that recreationalists encounter in carrying personal protective devices and setting them up in a hurry.

In the wake of such needs and requirements demanded at global level, this study has been conducted to evaluate the electrical and thermal performance of one protection systems proposed in Gomes et al [7] for small structures; a domestic housing structure commonly found in the rural areas of Asia and Africa and another one that can act as a standalone protection system for few personnel depending on the size of the actual structure.

II. METHODOLOGY

The two selected structures and lightning protection systems (LPSs) are given in Figure-1 and 2. The separation distances between LPS and the structure given in Figure-1 has been calculated with the equation provided in [3]. The LPS material for the system given in Figure-1 was selected as aluminium and steel (separately). Aluminium has been selected due to its low cost and lightness. Steel has been selected due to the convenience of accessing reinforcement steel bars (most often used) to many under-privileged communities in Asia and Africa. Copper has been considered only for the reason of comparison. Its high cost may prevent most of the low-income societies in many countries from using copper.

The LPS of the standalone LPS has been implemented with aluminium pipes. And a metal sheet (iron was used in the computation) at ground level to minimize the step potential. The housing structure was considered as made by wood of resistivity 100 k Ω m. the thickness of the structures (of wood) has been taken as 4 cm. The relative permittivity has been fixed at 2.

The structures were simulated in HFSS/ANSYS, the systems were excited by applying lightning current waveform to a corner of the upper end of the LPS of the housing structure and a corner of the upper-most part of the standalone LPS. The parameters of the current waveforms were selected to represent 50% probability values of first negative return stroke, subsequent negative return stroke and positive return stroke [3]. The adopted parameters are given in Table-1.

The following outputs were obtained by running the simulation for each current waveform.

- a. the electric field distribution and voltage gradient in the LPS and the housing structure
- b. the current density along the conductors of the LPS and
- c. energy distribution along the conductors of the LPS.

By using the energy distribution we manually calculated the thermal profile along the conductor by segmenting it into parts of 10 cm.

The electric field and potential distribution has been used to determine whether there is any possibility of having a side flash between the LPS and the housing structure. In the case of the standalone protective structure a minimum separation was estimated for occupants to avoid side flashes from the LPS. In

the event of contact with the LPS, the possible touch potential experienced by a human being is also computed.

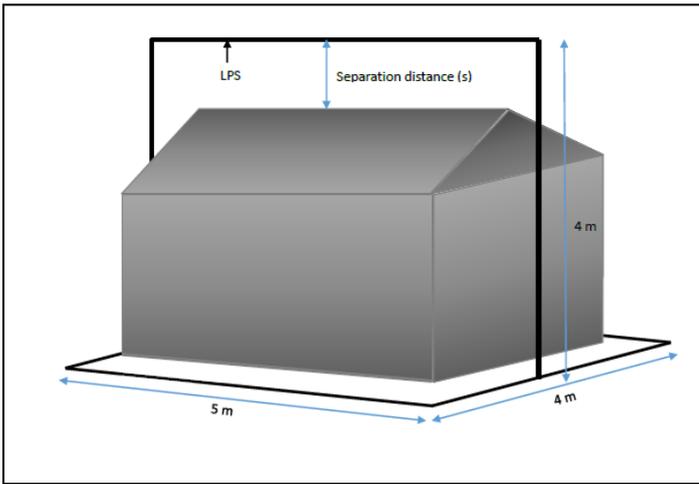


Figure-1: Simulated housing structure and LPS

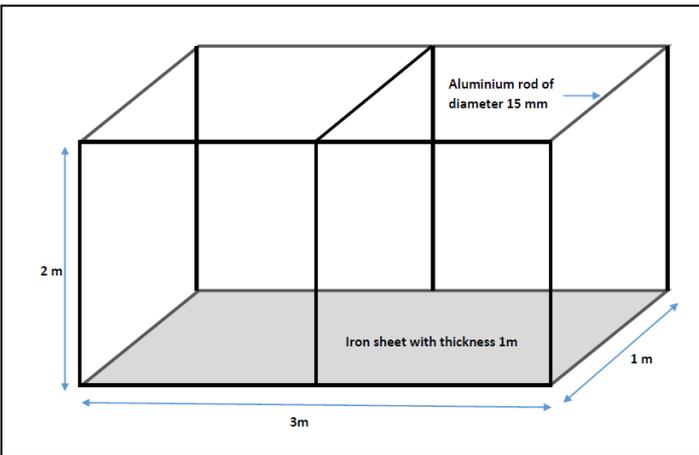


Figure-2: Simulated standalone LPS

TABLE I. PARAMETERS OF THE CURRENT WAVEFORMS USED IN THE COMPUTATIONS [3]

Parameters (50%)	Negative First Stroke	Negative sub. Stroke	Positive Stroke
Peak Value	20 kA	11.8 kA	35 kA
Front duration	5.5 μ s	1.1 μ s	22 μ s
Stroke duration	75 μ s	32 μ s	230 μ s

III. RESULTS AND DISCUSSION

The positive lightning resulted the highest action integral or specific energy (energy per unit resistance) due to the large amplitude and long duration. However, the small resistance of both aluminium and steel produced a very low energy dissipation which could not make any appreciable temperature

change in the conducting paths of both lightning protection structures. The figure-3 depicts a part of the LPS of the housing structure with its current density distribution.

The electric field and potential gradient due to the negative subsequent stroke produced highest values among the three types of waveforms. The highest potential rise was resulted when the LPS material was considered as steel. However, the potential difference between the conductor and the housing structure did not exceed the breakdown strength of air which is treated as approximately 3 MV. The maximum potential difference was resulted between the corner of the top ridge of the structure and the adjacent corner of the LPS to which the lightning current was injected. This value is in the order of 150 kV thus a separation of few centimeters could prevent arcing from LPS to the structure.

The potential distribution within the ring conductor remains at levels below any harmful step potential for a human being. The maximum value is around 0.2 kV between a 50 cm gap. However, it is advisable to have a layer of insulation material on the ground, both inside and outside the structure. Although we did not computed due to program limitations, it is of importance to investigate the potential distribution outside the ring. As the value may be much higher than that inside, it is strongly advisable to inform the occupants not to be outside the ring during thunderstorm periods.

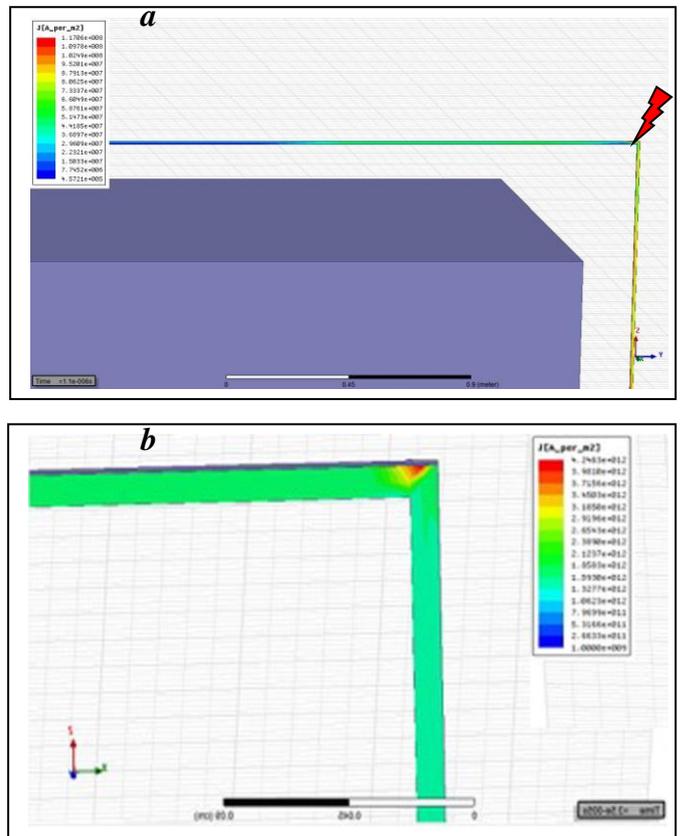


Figure-3: Current density distribution of the aluminium conductor as a positive stroke strikes the corner *a*. A part of the arrangement *b*. The corner of the LPS enlarged

With the values of current density distribution along the conductors the temperature increment in the material has been calculated from the following equation considering a one meter length of material.

$$m C \Delta T = \int_0^{\tau} R(t) i^2(t) dt$$

Where

m : mass of one meter length of the material

C : Specific heat capacity of the material

R : Resistance of the material

$$i = \int_0^s J. ds$$

The calculation has been done for the vertical rod that extends from the lightning current injected corner to the earth ring which carries the maximum current. The following assumptions were made in the calculations.

A1: Current distributes evenly in a given cross section

A2: Resistance of the material remains constant with temperature.

A3: The heat energy dissipation takes place instantaneously following the current.

In order to assess the maximum risk due to temperature rise we repeated the calculation by adopting the fixed value specified for the action integral for Level Protection Level (LPL) I in IEC 62305 (2010); 10,000 kJ/Ω. Table-2 depicts the results.

It clearly shows that the temperature increment is not significant at all for even steel (applied the parameters for iron steel used for building reinforcement). Even at the specified values at LPL I, the increment in temperature in steel is comparable with diurnal variation of the ambient temperature. Thus, whether there is copper aluminium or reinforcement steel both the LPS materials and any other materials close by is free from melting or fire risk. Note that the point of injection of current to the LPS may reach to a much higher temperature (refer Figure 2b) compared to the rest of the structure. Hence, the occupants of the house may strongly advised that the LPS should not be used for any purpose other than its original intension; i.e. lightning protection. This advice may be of high importance in many less privileged communities where such structures are regularly used for drying cloth and other material and tying ropes and strings for various purposes.

The standalone lightning protection structure showed a much less dangerous potential distribution than the LPS of the housing structure; both due to the higher number of parallel paths and the lower height. The maximum potential difference between the ground level and the current injected point (a

corner of the structure) was about 9 kV, value too small to have an arc at a reasonable distance. However, due to the touch potential hazard and the possibility of getting higher currents, it is advisable to keep a distance of about 20 cm between the LPS (specially the upper parts) and the human body. This can easily be achieved if the occupant adopt crouching position inside the structure.

The above discussed standalone structure is applicable at many locations where people conduct continuous outdoor activities. Such locations are mining sites, outdoor construction sites, recreational and entertainment parks, camping sites, isolated low grown or bare landscapes etc. The structure can be augmented with a non-inflammable roof or aluminium cover inside the LPS frame for protecting the occupants from rain and wind.

TABLE II. Maximum temperature increment as the impulse current of a positive return stroke flows through the LPS

Material	$\Delta\theta$ (°C) for 50% lightning current	$\Delta\theta$ (°C) for fixed value of action integral for LPL I
Cu	0.06	0.92
Al	0.14	2.15
Steel	0.49	7.54

IV. CONCLUSIONS

This paper computes the safety parameters of two selected lightning protection schemes; an LPS for a small housing structure and a standalone LPS, with the view of validating the suitability of the proposed low-cost LPSs in the literature for their intended applications. Our simulation and manual computation results show that LPS designed with both steel and aluminium for the housing structure and the standalone structure could provide reasonable protection to the occupants. The components of the safety structures withstand the thermal effects of the lightning current without any dangerous temperature rise in the materials or surrounding except for the point of injection of lightning current. The results emphasize that both aluminium and reinforcement steel are comparable in performance with copper, thus it can be concluded that the two metals could adequately be used as alternative materials for copper which is expensive and theft-prone. Thus, there is a high chance that people in less privileged communities will opt for this solution, whereas they were totally denied by their financial status to afford for a copper based total solution.

In the case of the standalone structure it is emphasized to keep a safety distance of about 20 cm between any human body and the LPS components to avoid rare possibility of arcing or dangerous touch potentials. In the case of the housing structure one has to take several precautions when they use steel for the LPS components as the large value of relative permeability of iron may induce larger voltages in the conductor than that in other metals, so that the chances of side flashing and touch potential hazards may increase.

The LPS for the small housing structure could be applied in many similar buildings that could be found in all parts of Africa and many parts of South and South East Asia. The

standalone structure could be used at various locations such as mining sites, outdoor construction sites, recreational and entertainment parks, camping sites, isolated low grown or bare landscapes etc. It can be made with an internal non-inflammable roof or aluminium cloth for protecting the occupants from rain and wind.

This paper fulfills the second step of the introduction of low-cost safety shelters to under privileged communities that has been proposed by Gomes et al [7]; verification of the safety level of the proposed structures by computer simulation and theoretical calculations. The third step is the experimental investigation of the shelter under laboratory HV conditions and possibly be under triggered lightning currents as well. Following the successful completion of the third stage, the structures could be introduced to the market.

ACKNOWLEDGMENT

The authors would like to acknowledge the facilities and support rendered by the Centre for Electromagnetic and Lightning Protection, University Putra Malaysia in making this project a success.

REFERENCES

- [1] V. Cooray, The lightning flash, IET, 2003
- [2] V. Rakov and M. Uman, Long continuing currents in negative lightning ground flashes, *J. geophys. Res.*, 95, 5455-5470, 1999
- [3] IEC 62305 (1-4): Protection against lightning, Ed-2, 2010
- [4] C. Gomes and M. Z. A. Ab. Kadir, A Theoretical Approach to Estimate the Annual Lightning Hazards on Human Beings, *Atmospheric Research*, 101, 719-725, 2011
- [5] A. K. Mary and C. Gomes, Lightning safety of under-privileged communities around Lake Victoria, *Geomatics, Natural Hazards and Risk*, 6 (8), pp. 669-685, 2015
- [6] F. C. Lubasi, C. Gomes, M. Z. A. Ab Kadir and M. A. Cooper, Lightning Related Injuries and Property Damage in Zambia, 31st ICLP, Vienna, Austria, 2012
- [7] C. Gomes, M. Z. A. Ab Kadir and M. A. Cooper, Lightning safety scheme for sheltering structures in low-income societies and problematic environments, 31st ICLP, Vienna, Austria, 2012
- [8] M. Doljinsuren and C. Gomes, Lightning incidents in Mongolia, *Geomatics, Natural Hazards and Risk*, 6 (8), 686-701, 2015
- [9] Gomes C. and Z. A. Ab Kadir, Efficient lightning protection: Optimization of economic, environmental and safety aspects, *Environmental Engineering and Management Journal*, Issue 8, Volume 14, 1975-1985, September, 2015
- [10] A. K. Mary and C. Gomes, Lightning Accidents in Uganda, 31st ICLP-2012, Vienna, Austria, 2012
- [11] A. Gomes and C. Gomes, Hierarchy of Hazard Control to Minimize Lightning Risk, 32nd International Conference on Lightning Protection-2014, pp 1218-1228, Shanghai, China, October 2014
- [12] K. L. Rasmussen, M. D. Zuluaga, R. A. Houze, Severe convection and lightning in subtropical South America, *Geophys. Res. Lett.*, 41, 7359-7366, 2014
- [13] M. B. Shrigiriwar, R. K. Gadhari, V. T. Jadhao, C. V. Tingne, N. B. Kumar, Study of Fatalities due to Lightning in Nagpur Region of Maharashtra, *Journal of Indian Academy of Forensic Medicine*, Vol. 36, No. 3, July-September 2014
- [14] B. Mills, D. Unrau, C. Parkinson, B. Jones, J. Yessis and K. Spring, Striking Back: An Assessment of Lightning-related Fatality and Injury Risk in Canada, Publication of Adaptation & Impacts Research Division, Environment Canada, Waterloo, Canada, 2009
- [15] M. Cherington, Lightning injuries in Sports: Situations to avoid, *Sports Medicine*, 31, 4, 301-308, 2001
- [16] [16] V. J. Wiesinger, Blitzsichere Zelte, *Bull. SEV* 59, 21, 1012-1016, 1968
- [17] [17] M. Darveniza, D. Mackerras, R. Watson and S. Wright, Portable personal lightning protection, *Proceedings of 24th International Conference on Lightning Protection*, 820-825, Birmingham, UK, 1998
- [18] M. Darveniza, A new concept for personal lightning protection, *International Symposium on Lightning Protection Proceedings*, Sao Paulo, Brazil, 256-263, 1999
- [19] S. Andrew, Shielding public spaces: Interview with Prof. Liew Ah Choy, *The Star*, May 17, 2009
- [20] S. C. Lim, Construction of a portable lightning protection device, FYP Report, Faculty of Engineering, Universiti Putra Malaysia, 2011
- [21] C. Jayaratne and C. Gomes, Public Perceptions and Lightning Safety Education in Sri Lanka, 31st International Conference on Lightning Protection-2012, Vienna, Austria, September, 2012
- [22] R. Blumenthal, The forensic investigation of fatal lightning strike victims: Reconsidered and revised. Preprints, *International Conference on Lightning Protection*, September 2-7, Vienna, Austria, 2012
- [23] M. A. Cooper and R. L. Holle: Lightning Safety Campaigns – USA Experience, 32nd International Conference on Lightning Protection, Vienna, September, 2012
- [24] M. A. Cooper, R. L. Holle, and C. Andrews, Distribution of lightning injury mechanisms, 2nd International Lightning Meteorology Conference, Tucson, Arizona, USA, May, 2008
- [25] M. A. Cooper, A fifth mechanism of lightning injury. *Acad. Emerg. Med.*, 9, 172-4, 2002
- [26] M. A. Cooper, C. J. Andrews, and R. L. Holle, Lightning injuries. Ch. 3, *Wilderness Medicine*, 5th Edition, C.V. Mosby, ed. P. Auerbach, 67-108, 2007
- [27] C. Gomes, "Lightning safety of animals", *International Journal of Biometeorology*, 56:1011-1023, 2012