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PORTABLE LIGHTNING PROTECTION STRUCTURE

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Abstract

A lightning strike is a hazardous natural phenomenon which can cause death to the human being. Hence, a lightning protection system is developed to provide protection against the lightning strike. However, the current lightning protection technique is mostly focused on building. There are situations whereby the human is unable to get into the building when a thunderstorm is approaching. This situation may occur in a large open area which has limited closed shelters. Therefore, personal lightning protection is vital during the mentioned situation. In this paper, the theory, method and design of a portable lightning protection structure are presented. The design structure must be able to protect human from a direct lightning strike. Besides that, the structure needs to be in small scale and light in terms of weight to enhance its portability. The functionality of design structure was examined by using PSCAD software. The circuit representation of design structure was modelled and simulated with a human model circuit. The simulation was done to obtain the data of potential difference and current flows into the human body when in contact with the structure that struck by lightning. The maximum current value will determine the insulation level of the structure. After that, the structure was constructed and tested by conducting high voltage testing. The structure was subjected to high impulse voltage by using Marx high impulse voltage generator at high voltage lab. No sparking was observed throughout the surface of the structure when it was subjected to high impulse voltage. This indicated that the high impulse current was effectively grounded through the structure. Hence, the designed structure is working as expected and has a potential to be used as portable lightning protection structure.

Keywords: Lightning strike, Lightning Protection, Portable, PSCAD, Human safety, Impulse voltage.

1. Introduction

Lightning is a natural phenomenon that is caused by instability charge distribution within a cloud. The negative charges will repel from the cloud and form a downward step leader. As the step leader approaches the ground, the tallest object on the ground will form an upward step leader with positive charges and attach with the downward step leader. The attachment process then created a conductive path which allows a surge of electrons rapidly falls to the ground. This phenomenal is referred as lightning [1].

National Lightning Safety Institute (NLSI) has conducted lightning density measurement around the world and concluded that Kuala Lumpur is having 48.3 lightning strikes to the ground for every square km of real estate. With this result, Kuala Lumpur was ranked fifth in the world in the year of 2009 [2]. Based on the analysis done by Malaysian Meteorological Department, the highest mean annual number of days with lightning which was recorded at KLIA, Sepang is 309 days. On the other hand, the highest mean annual number of days with thunderstorm which was recorded at Subang is 211 days [3]. This data indicates that almost 60 % of the days per year in Subang is undergoing thunderstorm and 80% of the days per year is having lightning strikes in Sepang.

A lightning strike can cause victim to experience a cardiac arrest (heart stopping) and died on the spot. Recent years, the technology of identifying and locating lightning has been developed to minimize the damage that caused by lightning strikes. A commercial network of lightning sensors with a wideband magnetic direction-finding to generate lightning location in real time is being operated at many countries. This network is used to provide lightning warning for various applications [4]. Moreover, lightning protection system is also being developed to enhance the capability of facilities, vehicles and buildings in order to withstand the effect of lightning strikes [1]. Although lightning protection technology has been developed, the research on portable lightning protection is still limited with related works available in [5-7]. The first personal lightning protection system was proposed by Jacques Barbue-Dubourg in 1773 as described in [5]. In 1997, a portable lightning protection device with a triangular frame design was developed [6]. In 2014, the design of portable lightning protection system for human property or temporary locations was patented [7]. Even though human is always protected by a properly grounded building, but there are some situations that human might not have sufficient time to get into a building especially when they are located at large open areas such as construction site and agriculture field. The current research progress is still insufficient to address this issue.

Therefore, this research is conducted to study and design a portable lightning protection structure. The structure must be able to provide lightning protection conveniently in an open area where properly grounded closed structures are not available for protection. Other than that, the structure has to be designed based on the criteria of portability.

2. Methodology

Figure 1 shows the flowchart of an overall process for this project. The project started with structure design, which includes sketching, software drawing and selection of structure materials. It is then followed by software modelling of lightning, structure and human circuit. After that, simulation is conducted to analyse the functionality of the design. After the simulation result has been validated, structure construction activities were carried out in manufacturing laboratory. Finally, high voltage testing was executed on final design structure in high voltage laboratory.

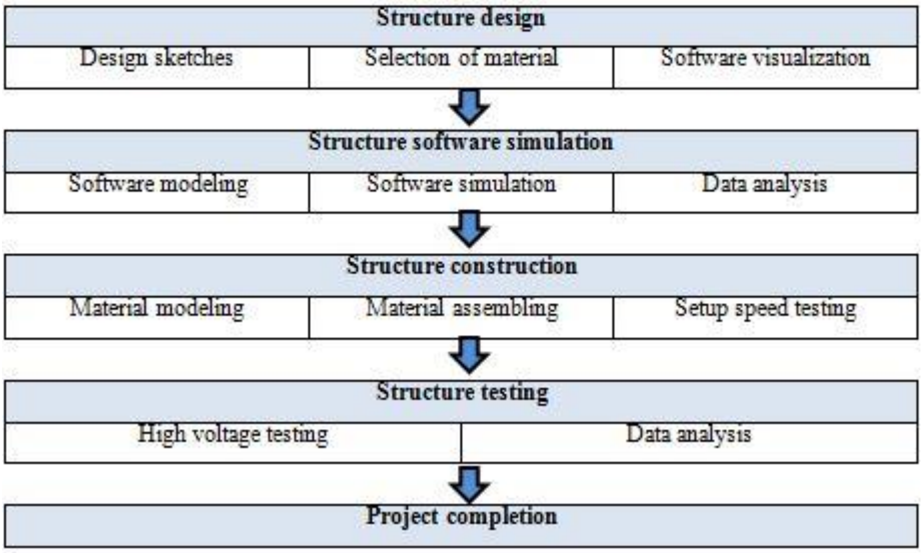

Fig. 1. Project overall flowchart.

2.1. Structure design

The basic design concept is aiming for a structure that is having stable base with minimum pointy part. Therefore, a tripod structure design is selected as it fulfills the requirement. The reason of having minimum pointy part as one of the design criteria is because of the current will tend to accumulate more densely in the pointy part or sharp edges. Hence, pointy part will have more charge per unit surface area and also higher charge density. The lightning will be most likely attracted by the area that has higher charge density [8]. Sharp edges may also trigger sparking in the structure in the event of it being struck by lightning. Therefore, the design of the structure that consists of less pointy area will decrease the chances of being strike by lightning. Although sideflashing is less likely to happen in close proximity with conductive structures, having pointy edges may increase the likelihood due to the said reason [9, 10].

To provide adequate lightning protection, the structure is made up by metal which has excellent conductivity, good resistance against corrosion and feasible mechanical strength. Table 1 shows the comparison between copper, aluminum and steel [11]. By comparing each of the characteristics, aluminum is chosen as its conductivity and tensile strength is sufficient to offers lightning protection. Most importantly, aluminum has the lowest density which makes it become the lightest material among all the three metals. Apart from this, insulating material also has been studied. IEC 62305-3 states that even though the design of lightning protection system has fulfilled the criteria, the hazard due to touch or step voltage in the vicinity of the down conductor system is still present [12]. Hence, specific level of insulation will be applied on structure to protect person from the high voltage built up in lightning strike event. It is mandatory to ensure the suitable insulation level for the structure because if the voltage successfully punctures the insulating material, a partial of lightning current can flow into human body [13]. In order to determine the insulation level, software simulation was conducted to indicate the maximum potential difference between structure and human.

Table 1. Properties of copper, aluminium and steel [11].

Characteristics	Pure Copper	Pure Aluminium	Low-alloy Steel
Tensile strength (Ib/in^2)	25000	13000	75000 to 90000
Corrosion resistance	Good	Very good	Poor
Density (g/cm^3)	8.96	2.7	7.83
Electrical conductivity (by volume at 20’C)	100%	62%	12%

The proposed design of portable lightning protection structure is a tripod structure. A vertical rod was installed on the top of the structure. The vertical rod will intercept the discharge current from lightning strike and dissipate it to the ground harmlessly via down conductor. The down conductor is flexible, and a chain is installed to prevent the conductors from extending too far. Each of them is covered with a layer of insulating material for safety purpose. The structure is portable and convenient to carry. When not in used, the person can carry the structure around by folding and keeping it inside a bag. The total height of the structure is 1.73 m. Based on the studies carried out by M. A. Uman [14], the area protected by a single vertical rod is assumed to have a 45° angle cone of protection. Therefore,

$$A_c = \pi(2 \times H)^2 \qquad (1)$$

where A is the coverage area, H is the total height of lightning protection structure.

By using Eq. (1), the coverage area of portable lightning protection structure in this study can be calculated:

$$A_c = \pi(2 \times 1.73)^2 = 37.61 \text{ m}^2$$

Thus, it can be concluded that the design structure has a cone protection zone area of 37.61m^2 with a radius of 3.46 m.

2.2. Software modeling

The design of the structure was simulated by using PSCAD software. PSCAD is a simulation tool that is used to build, simulate, and model the power system. By using the software, lightning current source will be modified through the laboratory parameter defined by IEC 62305. Figure 2 shows the structure circuit subjected with an impulse current source. The applied impulse current was 10/350 μs waveform based on IEC 62305-1 [15]. The value of impulse current can be approximated by using double exponential function [16]:

$$i(t) = \frac{I_o}{\eta}.(e^{-\alpha t} - e^{-\beta t}) \qquad (2)$$

Where I_o is the peak current, η is the correction coefficient of the current peak value, α and β are the parameters of the double-exponential function.

Hence, I_m is set to be 100 kA, η is assumed to be 1 and the value of α and β is 2039 and 564382 respectively.

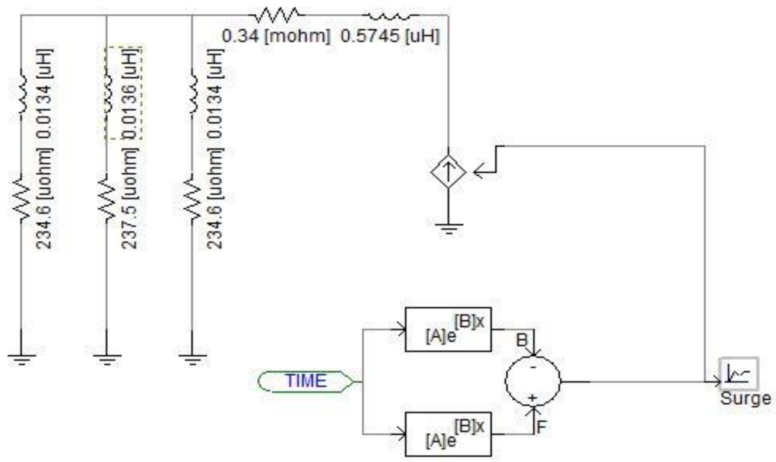

Fig. 2. Structure circuit presented in PSCAD software.

The structure circuit was modelled as resistor and inductor which are dominant characteristics of an electrical conductor. It is noted that capacitances have been neglected in this study. This is because the simulation is conducted under high frequency. Under this frequency, the capacitive effect is insignificant compared to inductive effect [17]. The value of resistance and inductance is calculated by using the Eqs. (3) and (4). Equation (4) was derived by using electromagnetic approach. The structure was assumed to be perfectly grounded although it is not the case in reality. In fact, some of the grounding practices as advocated in IEC 62305 are actually ambiguous [18].

$$R = \frac{\rho l}{A} \tag{3}$$

where ρ is the resistivity, l is the length, and A is the surface area.

$$L = \frac{\mu l}{2\pi}\left[\frac{4a^4 \ln\left|\frac{b}{a}\right| + a^4 - b^4}{4(a^4 - b^4)}\right] \tag{4}$$

Where μ is the permeability, a is the inner radius, and b is the outer radius.

In addition, the human body was electrically modelled as shown in Fig. 3. The circuit is formed by few lumped circuit that consists of resistor and capacitor which were arranged according to the impedance of each part of human body. The values of every component are obtained from [19].

2.3. Software simulation

In the process of software simulation, the modeling for structure and human body model was first to be done. After that, a total of five different types of scenarios with different position of human under the structure will be simulated to examine the validity of lightning protection under various circumstances. The configuration of the structure remains constant throughout all the scenarios. All types of scenario are presented in Fig. 4 and the circle on the figure is indicating the human contact point with the structure. The scenarios are described as:

- Human is touching the structure with head.
- Human is touching the structure with one hand.
- Human is touching the structure with head and one hand.
- Human is touching the structure with both of the hands.
- Human is touching the structure with head and both of the hands.

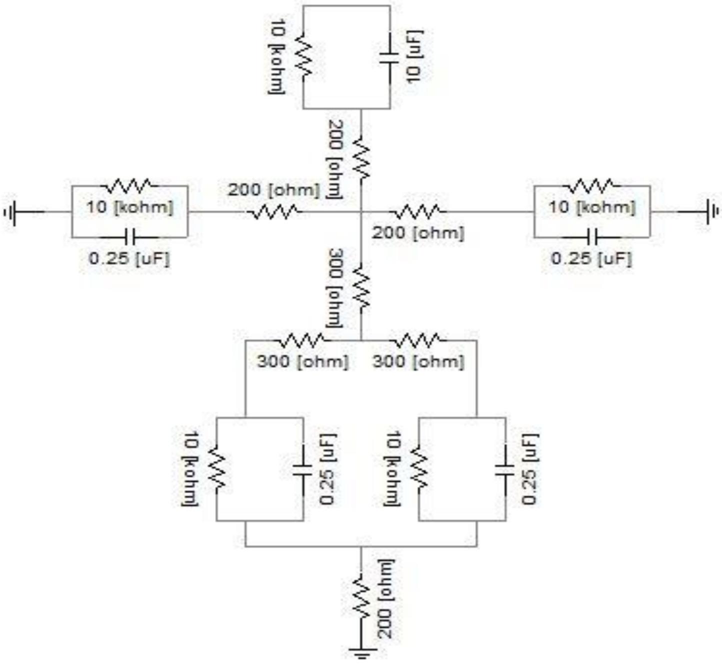

Fig. 3. Human body model [19].

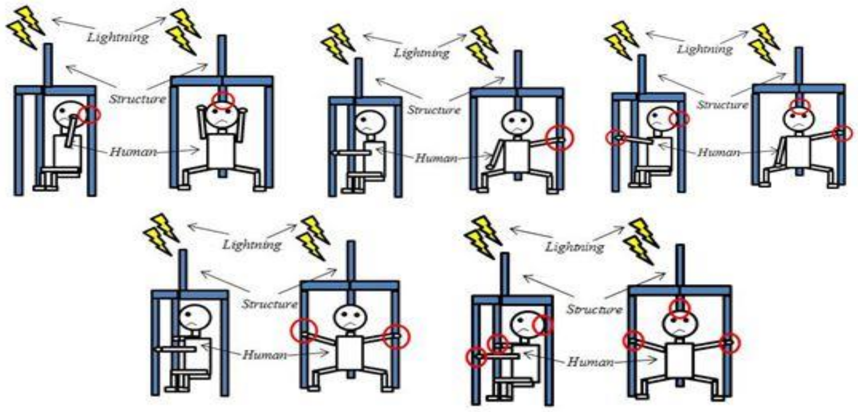

Fig. 4. Five different human positions under the structure.

2.4. Structure construction

The construction process was carried out in manufacturing lab located in Taylor's University Lakeside Campus. Cutting machine, milling machine, grinding machine, lathe machine and other tools such as jigsaw and hand grinder were used to manufacture and fabricate the structure parts shown in Fig. 5. The complete assembled structure with insulation is presented as isometric view and back view in Fig. 6. The total height of the complete structure is 1.73 m with the maximum extension length of 1.9 m.

Fig. 5. Structure parts.

Fig. 6. Assembled lightning protection structure.

2.5. High voltage testing

The high voltage testing was carried out by using Marx high impulse voltage generator as shown in Fig. 7. The Marx generator has the capability of generating standard high impulse voltage (1.2/50μs) following the IEC standard [20] up to magnitude of 400 kV. In this study, a total of 8 stages of high impulse have been applied to the structure. The range of impulse voltage applied was 100 kV to 275 kV with 25 kV increment per stage. A control system was used to manipulate the value of impulse voltage produced by Marx generator. There are two different methods applied in the testing. In the first method, the impulse current was directly injected to the structure through the tip of the vertical rod of the structure. In the second method, a 5 cm length of impulse voltage spark was created and transfer from the conducting rod of the Marx generator to the vertical rod located at the top of the structure. Both of the setups are shown in Fig. 8. The surface activities were observed by using high-speed camera. The testing was conducted in a low light intensity environment. Hence, if there is any flashover or sparks occur on the structure surface, the camera will be able to capture those events. Figure 9 shows the setup of high-speed camera and control system.

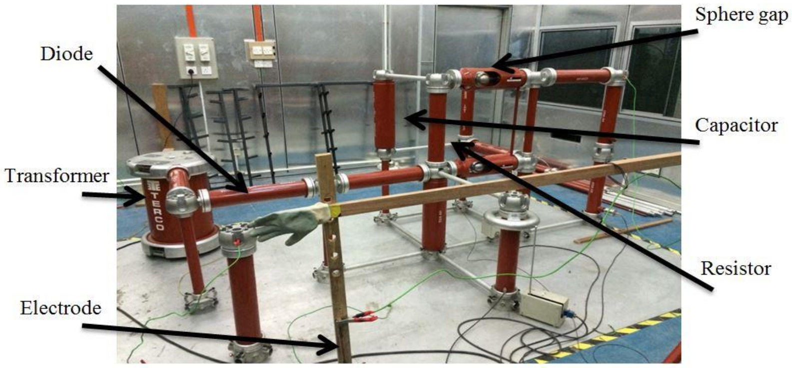

Fig. 7. Marx high impulse voltage generator.

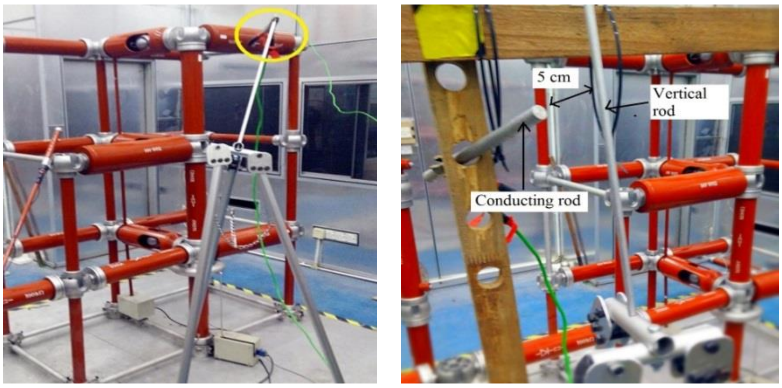

Fig. 8. The setup of high voltage testing.

Fig. 9. High speed camera setup and control system of generator.

3. Result and Discussions

3.1. Software simulation

The lightning impulse current subjected to the circuit is constant regardless of the scenario. Lightning is classified as a high transient current discharge [1]. Hence, it increases rapidly and reaches the peak within a short period of time. The waveform of impulse current generated by PSCAD software is shown in Fig. 10. In this study, 10/350 μs lightning waveform with 100 kA peak current was employed as the impulse current source. This type of waveform is taken from the standard IEC 62305-1, which is used to determine the maximum values of lightning current quantities of the first return stroke for lightning protection [15]. The types of waveform are determined by the front time and tail time of the waveform [16]. A 10/350 μs lightning waveform indicates that the current will reach the peak within 10 μs and drops to half of the peak current by the time of 350 μs.

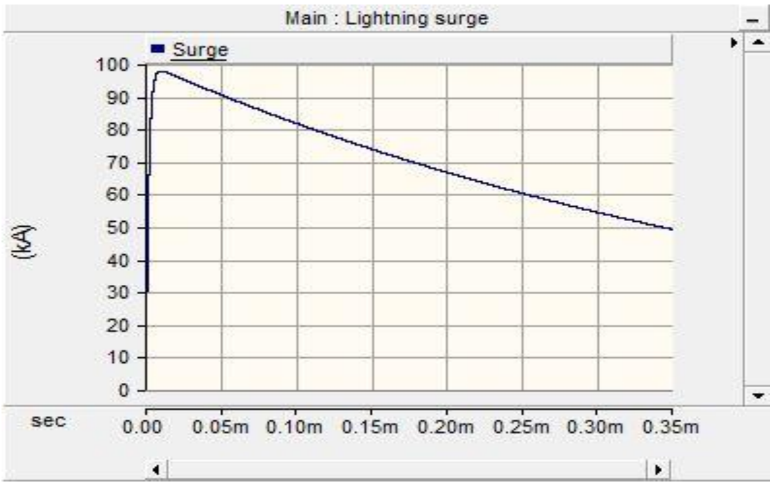

Fig. 10. Waveform of impulse current generated.

Figure 11 shows the circuit connection presented in PSCAD software between human body model and lightning protection structure with impulse current source under one of the scenarios. When lightning strikes an object, the current will flow in and generate a potential difference between two parts of the object [21]. In this study, when a lightning impulse current source with amplitude of 100 kA is applied to the structure, a potential difference is generated between the structure and human body. This is because human is touching the structure which is being struck by the lightning. The higher the value of the potential difference, the larger the damage resulted from lightning.

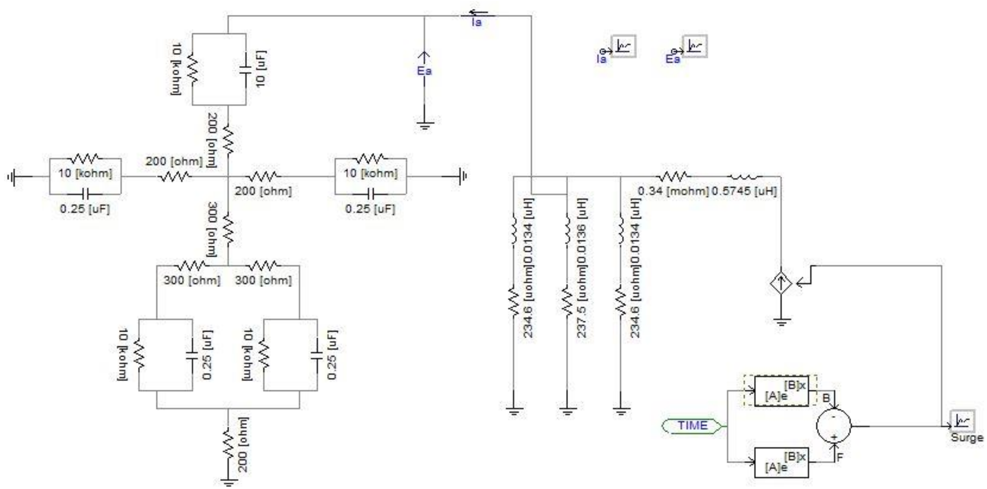

Fig. 11. Circuit connection under Scenario 1 simulation.

Figure 12 shows the waveform of the potential difference generated between lightning protection structure and contact point of human body model. The result is presented in two different timeframes, which are millisecond and microsecond. The voltage waveform is oscillating with decreases of amplitude within a short period of time. Based on Table 2, the potential difference between lightning protection structure and human body model is approximately 492 V. The waveform achieves its peak voltage instantly, but it requires longer time to reaches zero during the decay process. It reaches peak voltage in 0.001 µs. There is an oscillation with decreasing voltage and it ended when the time approaches 0.007 µs. The waveform undergoes a slow decay and reaches 0 kV in 9.982 µs. The potential difference has a similar value under different scenario as the value of current flow within the structure and impedance of human body model remains constant.

It is observed that the waveform is oscillating in a short period of time due to high transient lightning which is capable of exciting the natural frequency of conductor and produces oscillatory transients during the striking process [22]. On the other hand, the value of potential difference fades to zero when the time reaches 9.982 µs. This is because the voltages are induced in the magnetic field of a closed conductor loop that carrying lightning current. The lightning current subjected has 10 µs front times and 350 µs tail time. Hence, the duration of potential difference is 9.982 µs, which approximately equal to 10 µs.

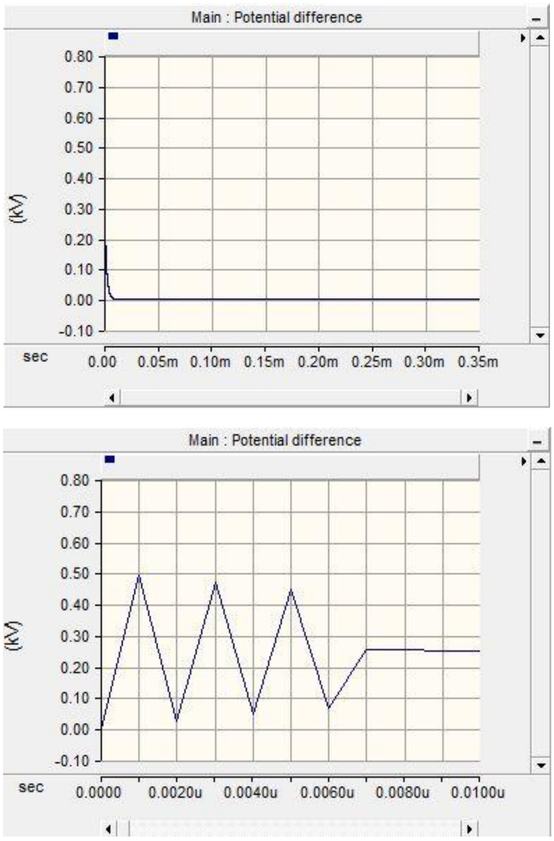

Fig. 12. Potential difference waveform.

Table 2. Potential data collected from the waveform.

Potential difference between structure and human	Voltage value (kV)	Time (μsec)
Peak	0.492	0.001
End of oscillation	0.251	0.007
Zero	0.000	9.982

By comparing the results obtained in Table 3, scenario 1 has the highest value among all. Figure 13 shows the simulated current waveform under scenario 1. In the first scenario, the structure circuit is directly connected to human head as shown in Fig. 11. This is the most lethal condition as there is no any other pathway to separate the current that flowing into human body. Furthermore, the current is directly flow into head and every part of the human body which are connected to ground. This results in a most deadly condition as the current could damage brain and heart. Meanwhile for scenarios as captured in Figs. 14 to 21, as there are several current paths provided, the current is able to divide into smaller value.

Apart from that, current pathway is one of the major factors that need to be taken into account because it will determine the type of injury which is caused by lightning. There are different types of pathway such as hand-to-hand, hand-to-foot and head-to-foot. The worst-case scenario is when the current is lead directly to the heart through the vessels and probably conducted through the veins [23]. Hence, it is not advisable to touch the lightning protection structure, because even hand-to-hand pathway has the possibility to lead the current into heart.

Table 3. Current data obtained from simulation under five scenarios.

Current flows		**Current value (mA)**	**Time (μsec)**
Scenario 1	Peak	1707	0.001
	Oscillation	876.7	0.007
	End	0	7.665
Scenario 2	Peak	1394	0.001
	Oscillation	712.1	0.007
	End	0	6.123
Scenario 3 (through head and hand)	Peak	963.4	0.001
	Oscillation	496.7	0.007
	End	0	6.399
Scenario 4 (through right and left hand)	Peak	332.5	0.001
	Oscillation	167.6	0.007
	End	0	7.389
Scenario 5 (through head and both hands)	Peak	231.8	0.001
	Oscillation	116.9	0.007
	End	0	6.838

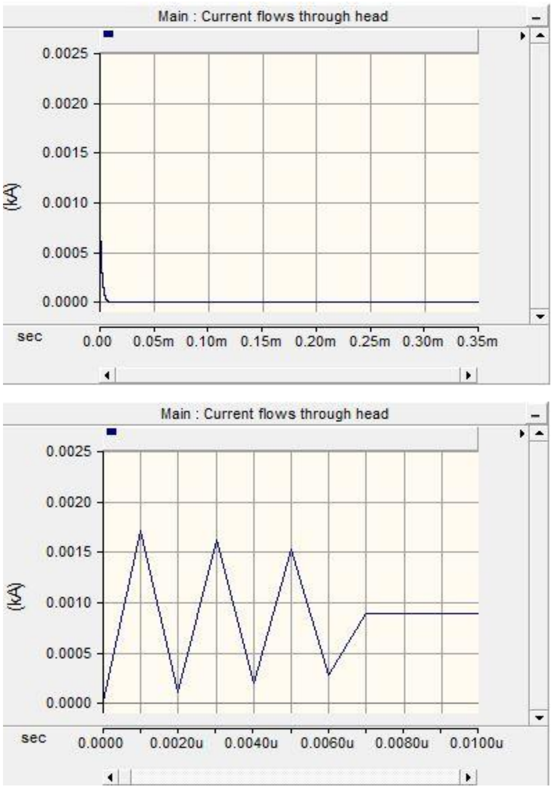

Fig. 13. Simulated current waveform in scenario 1.

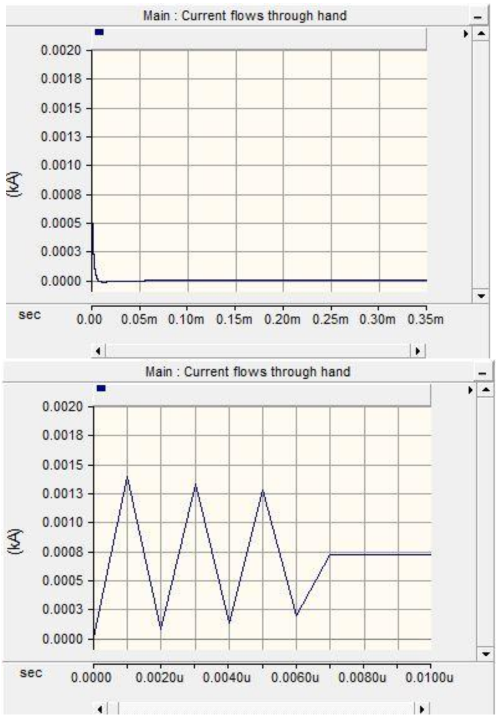

Fig. 14. Simulated current waveform in Scenario 2.

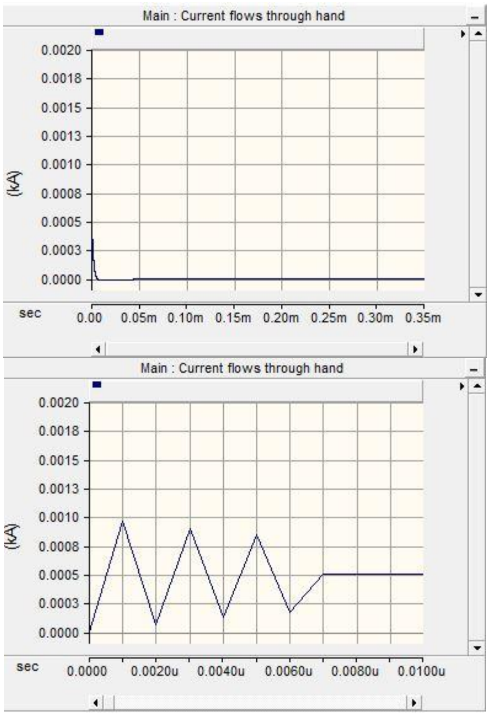

Fig. 15. Simulated current waveform through hand in Scenario 3.

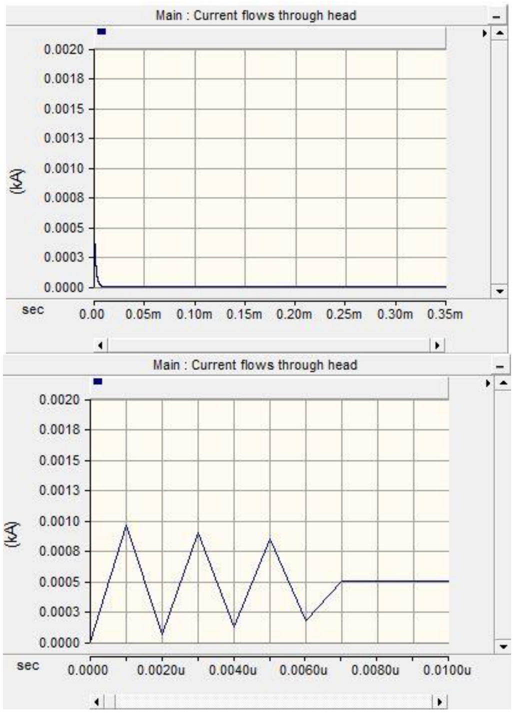

Fig. 16. Simulated current waveform through human head in Scenario 3.

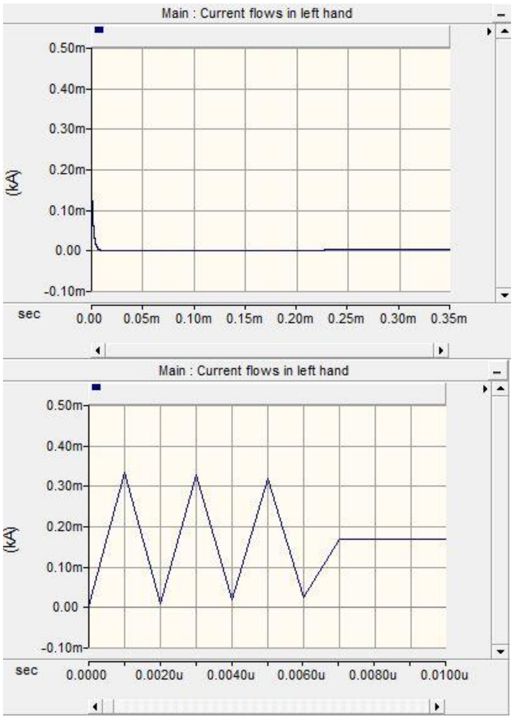

Fig. 17. Simulated current waveform through left hand in Scenario 4.

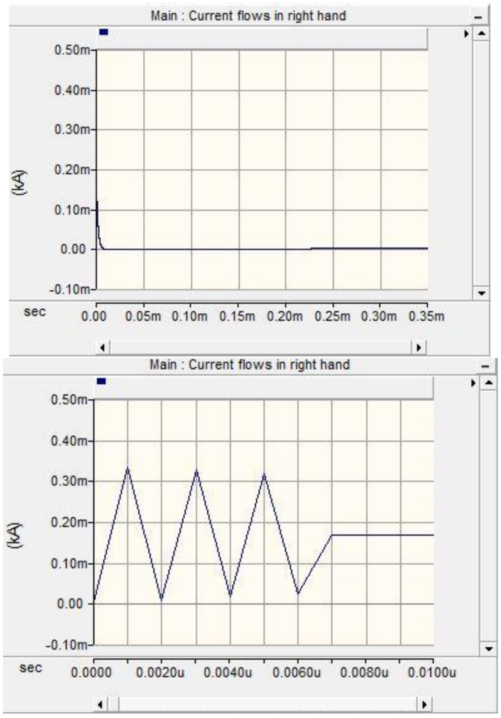

Fig. 18. Simulated current waveform through right hand in Scenario 4.

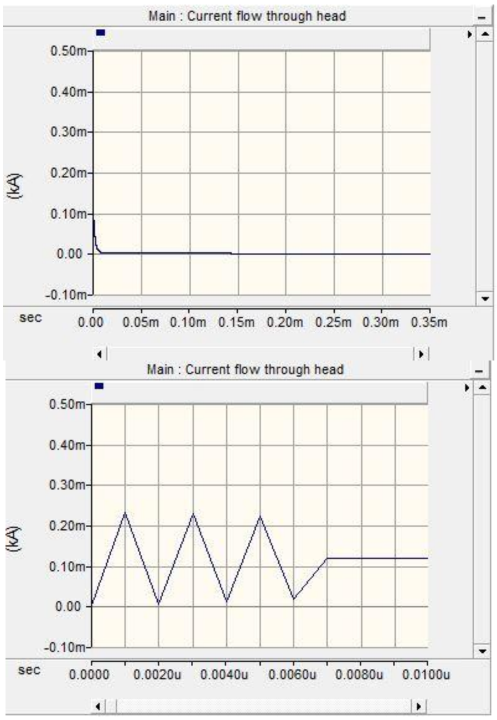

Fig. 19. Simulated current waveform through human head in Scenario 5.

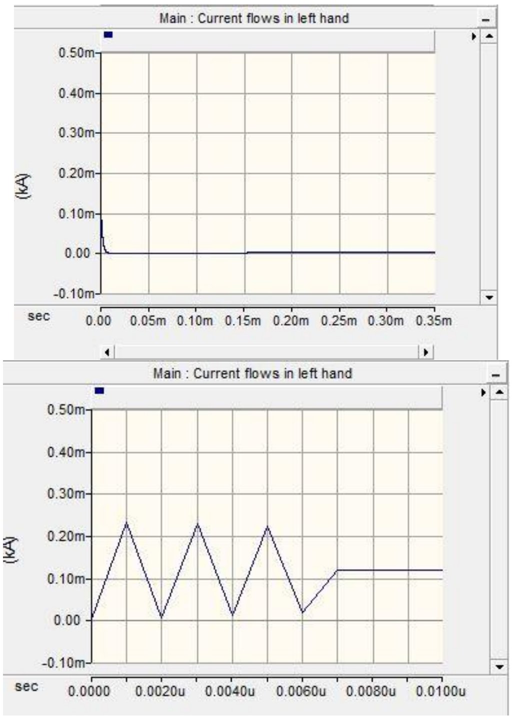

Fig. 20. Simulated current waveform through left hand in Scenario 5.

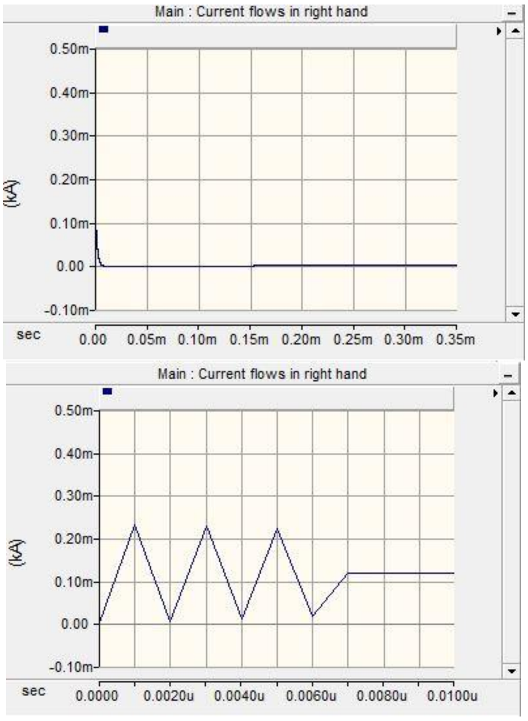

Fig. 21. Simulated current waveform through right hand in Scenario 5.

Based on the standard, the human body impedance under the wet condition is approximately 500 ohm [24]. The minimum current which can cause ventricular fibrillation is 370 mA. Ventricular fibrillation is defined as rapid and repeated uncoordinated contractions of the heart ventricles. This symptom can alter the heart pumping action, which probably cause fatality in human [25]. Using Eqs. (5) and (6) below [26], the minimum step voltage and touch voltage can be calculated.

$$U_s = (R_b + 2 \times 3\rho)I_0$$
$$= (500 + 2 \times 140.63)(370\ \text{mA}) = 289.07\ \text{V} \tag{5}$$

$$U_t = (R_b + 0.5 \times 3\rho)I_0$$
$$= (500 + 0.5 \times 140.63)(370\ \text{mA}) = 211.02\ \text{V} \tag{6}$$

where U_s is step voltage, U_t is touch voltage, R_b is human body impedance, ρ is soil resistivity (assumed as 45 Ωm [27]), and I_0 is minimum current which can cause ventricular fibrillation.

The calculated minimum lethal step voltage and touch voltage is 289 V and 211 V respectively. Besides, the minimum current that can cause ventricular fibrillation is 370 mA. Based on the software simulation result, both the potential difference and current flow has exceeded the value calculated above. The potential difference value is 492 V while the highest current flow is 1707 mA. However, the exposed conductor parts will be insulated by using electrical insulation tape with a voltage breakdown of 24 kV. Since the generated potential difference (492 V) does not exceed the voltage breakdown of insulating material, the voltage would not able to puncture the insulation and allow the partial lightning current from entering the human body. Thus, it can be concluded that the person will be protected from electrocuting even if he/she accidentally touches the structure that is struck by lightning.

3.2. Hardware function testing

The total assemble parts of design structure consists of a vertical rod and down conductor as shown in Fig. 22. The setup procedure is simple, user only needs to set up the down conductor tripod and put the vertical rod into a hole located at the upper part of the structure. The chain was pre-installed to prevent the structure from extending too far. It also serves a purpose in improving the stability of the structure. The insulation was properly done on exposed part which might be in contact with the user.

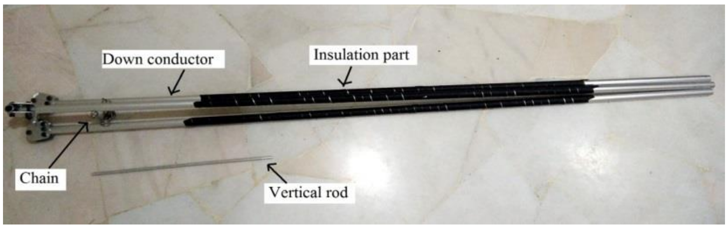

Fig. 22. Parts of portable lightning protection structure.

Figure 23 shows the demonstration of user operating the structure. According to lightning safety handbook [28], the safety position should be practice during the thunderstorm. The person should crouch down, duck the head as low as possible, put the feet close together and cover the ears by hand. Therefore, when operating the structure, the user is advised to practice the first position in Fig. 23. However, if the user is forced to be in contact with the structure, he/she must hold the insulated part as shown as the second position in Fig. 23. Besides that, it is expected for the user to stay under the structure all the time during the thunderstorm for the intended protection. This is because the lightning will have the chance to strike the user instead of the structure if the user is standing outside of the protection coverage area.

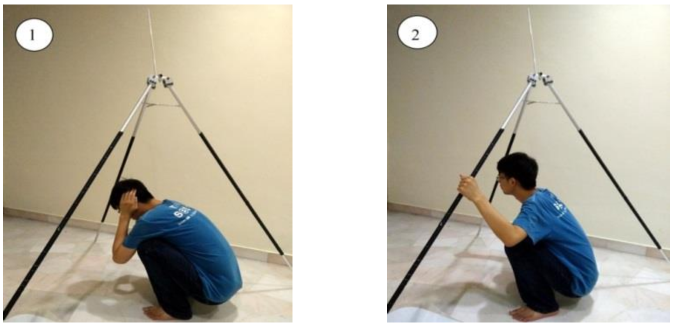

Fig. 23. Structure usage demonstration.

In the process of high voltage testing, the structure was subjected to a high impulse voltage up to 275 kV. During the injection of impulse voltage, the activity of structure surface was observed by using a high-speed camera. The moment when impulse voltage hits the structure was captured as shown in Fig. 24. The flashover event should not happen on the structure surface. This is because flashover occurs when the electric field strength exceeds the dielectric field strength in the air [29]. The high electric field strength indicates high potential differences in the structure. Yet, from the result shown in Fig. 24, it can be noticed that the structure surface did not trigger any spark or flashover event. Thus, it can be concluded that the structure is able to transfer the high impulse voltage to ground safely without triggering any spark.

Fig. 24. Sparks emitted from conducting rod to vertical rod.

4. Conclusions

Malaysia is geographically situated in close proximity with the equator. As the result, it is a zone with high lightning density. Therefore, it is necessary to emphasize the importance of personal lightning protection. The study based on lightning protection technologies has been conducted. A tripod design was proposed, sketched and visualized by Solidworks. By using PSCAD, the design is presented in circuit model and simulated with an impulse current source to determine the potential difference and current flows of the structure. After confirmed the validity of the structure and insulation level, the structure has been constructed. To further examine the functionality of the structure, high voltage testing is conducted to observe the possibility of spark occurrence on structure surface. The outcome was satisfying as there is no flashover occurs on the structure during the testing.

In a nutshell, a portable lightning protection structure had been constructed and tested. The design structure is aiming to provide personal lightning protection. Hence, it is presented in small scale design which only able to cover one person. The future improvement should be focused on more detailed simulation and enhancement of the portability of the structure. Other than 10 /350 μs waveform, different types of waveform based on another standard also will be applied in the simulation. The additional scenario of different human positioning within the structure can be considered in the simulation also. Moreover, to further enhance the structure portability, the leg of the structure will be designed to be retractable for more convenient transportation.

Acknowledgement

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