Received: May 5, 2020. Revised: June 8, 2020.

International Journal of
Intelligent Engineering & Systems

http://www.inass.org/

Touch and Step Voltage Evaluation based on Computer Simulation for a Mass Rapid Transit System in Thailand

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Abstract: This article proposed a computer-based simulation approach to estimate touch and step voltages due to a lightning strike at a mass rapid transit railway station. A purely resistive circuit model of a station lightning protection, and earthing & bonding system is formed in MATLAB/Simulink with Yaek Nonthaburi 1 passenger station of MRT purple line in Bangkok, Thailand as a case study. The simulation investigated the consequence of a lightning strike at four different locations on the roof of the station and examined whether or not the lightning protection system met the standard requirements. The results showed the touch voltages, step voltages and body currents in a steady state together with the impact on the human body standing in the station. The simulation can guarantee the effectiveness of the proposed model, and also proved that the lightning protection system of the station is able to conform to the standard and there is no harm for the passenger in the station.

Keywords: Touch voltage, Step voltage, Lightning protection system, Mass rapid transit system, Computer simulation.

1. Introduction

An impact of lightning strikes can create hazards to persons and installations not only directly by high voltages and thermal effects, but also indirectly by causing panic and damage to railway safety related systems. Buildings, bridge, outdoor installations and other structures exposed to direct lightning strikes require an external lightning protection system such as surge arresters [1]. In addition, in [2] proposed an enhanced efficiency of existing lightning protection based on lightning and surge standard mainly on the EN series 62305. Internal lightning protection of electrical equipment is also required against the danger of damage by over-voltages and partial lightning currents caused by lightning strikes. For the DC railways, there are risks of metallic corrosion due to stray current and electrical hazards leading to a danger of passengers and structural damages to the railway station. The earthing and bonding strategy developed and implemented for the elevated DC railway, for example, in Caulfield to Dandenong level Crossing Removal Project [3]. Therefore, the evaluation of an existing lightning protection is very important. In [4], a new inspection equipment and a new circuit structure has been developed to evaluate and measure both the low-frequency parameter (earth resistance) and high-frequency parameters (earth impedance and voltage difference) of the lighting protection performance of earthing system in railway substation. In addition, in [5] proposed a lightning disturbance recognition method to recognize the high-frequency components which cause the relay protection malfunction in the traction substation by using wavelet energy moment and verified by the simulation signals.

The relevant standards shall be applied for the protection of life and property against lightning. For instance, most of the mass rapid transit systems are elevated railways such as BTS skytrain and MRT purple line in Bangkok, Thailand; as a consequence, the structures of these railways are particularly vulnerable to lightning strikes during the storm season. Another example of the standardization and guidance of the lightning protection system was required to efficiently reduce the train operation disruptions due to the shutdown of power supply effected by the lightning strikes in Bogor Station of DAOP 1 Jakarta, Indonesia [6]. The awareness of the design of the lightning protection is important which eventually should ensure that fault or lightning currents would not impact the equipment and passenger in the railway station [7].

From those reasons of several damages, the estimation of touch and step voltages, which is another method to assess the lightning protection, due to lightning impulses and the impacts on the human body in a railway station is paramount. Accordingly, the simulation model is needed for the preliminary estimation in order to examine the lightning protection system's compliance with the standard prior to actual operation.

Several methods involving lightning event simulation such as touch and step voltages, safety evaluation etc. have been widely studied and discovered. In [8], an equivalent circuit of a human body was proposed to calculate the touch voltage in the scenario of a lightning strike on a telephone line. The body currents were obtained in two simulation cases: a human holding a telephone and a human standing close to a telephone. The model employed the finite-difference time-domain method (FDTD). There is a variety of research in which an electromagnetic simulation method has been performed to study the electric field intensity caused by lightning and also the touch and step voltages. Unlike the electrostatic counterpart [9], the inductive effects of lightning on the touch and step voltages can be realised [10-12]. The touch and step voltages have been studied in many aspects. Suchanek, Hinrichsen, Brocke and Muller [13] compared four step voltage limits from different sources, then IEC 60479 [14] was chosen for safety consideration. The research also used 3D FEM simulation to investigate different earth termination systems for a rectangular building. Nayel, Zhao, He, Cai and Wang [15] studied a more accurate method, i.e. by including the modelling of a tower foot as an impedance rather than a pure resistance, to calculate the touch and step voltages around a transmission tower foot. The impact of the step voltage on parts and postures of a human body was rigorously researched in [16] using voxel-based body models. Apart from the aforementioned literature, much of the research has only studied the touch and step voltages on a substation ground grid [17, 18] and a simple structure building. To expand the application of this field of research, this paper presents a method of touch and step voltages estimation using a simplified pure resistive circuit model, i.e. for ease of creating and running the large detailed model in a computer software, and uses the model to estimate the touch and step voltages, and safety consideration at one of the passenger stations of MRT purple line in Bangkok. In other words, another aim of the paper is to check if the lightning protection system of the station satisfies a standard and if the person touching a conductive part in the station is out of danger from lightning.

This paper is organised into 7 sections. A touch and step voltage calculation method and the impact of those voltages to human body according to the standard are presented in section 2 and 3, respectively. The proposed simulation modelling is described in section 4. Section 5 explains the details and structure of the study case using one of the MRT purple line passenger stations in Bangkok. The simulation results are summarised in section 6. The paper is finally concluded in section 7.

2. Calculation of touch and step voltage

A step voltage is the voltage between the feet of a person standing near an energized grounded object (lightning flash to the structure). It is equal to the difference in voltage, given by the voltage distribution curve as shown in Fig. 1, between two points at different distances from the electrode. A person could be at risk of injury during a lightning strike simply by standing near the grounding point. A touch voltage is occurred in the same process as a step voltage, but the voltage difference being considered exists between the hand and feet.

The calculation of the touch voltage can be performed by using an equivalent circuit in Fig. 2, which is either the Thevenin or Norton equivalent circuit. The circuit includes the total body impedance (Zb), the additional resistance for shoes (Ra1) and standing surface (Ra2), and the source voltage (Us) or the prospective touch voltage (Utp). Surface 1 and 2 denote the standing surface and earth, respectively. The effective touch voltage (Ute) is determined by measuring the voltage across the series resistance, Zb and Ra1. Likewise, the calculation of the step voltage can be done in the same manner as that of the touch voltage, which is further described in section 4.

The total human body impedance for a hand-to-hand current path at 50% probability is indicated in [14]. By applying the reduction factor r = 0.75 [14], the total human body impedance for a hand-to-feet current path is obtained in Table 1. In this study, the additional resistances Ra2 and Ra1 are assumed to be

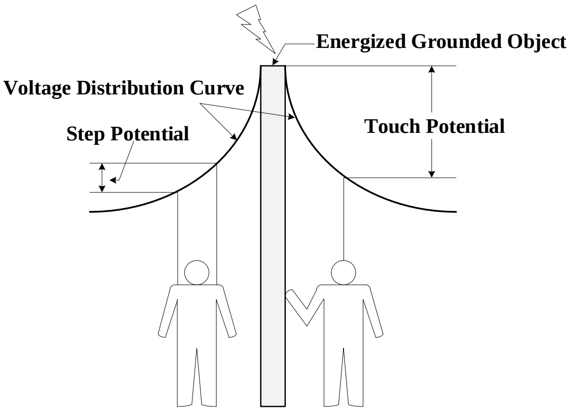


Figure. 1 Voltage distribution curve [19]

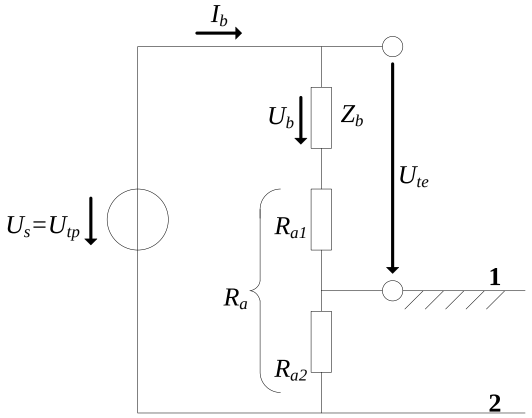


Figure. 2 Equivalent circuit for the calculation of the effective touch voltage [20]

150 Ω and 1000 Ω (for old wet shoes with a short-term condition), respectively. Generally, Ra2 can be calculated by Ra2 = ρs × 1.5 m-1, where ρs is soil resistivity at the standing surface in Ωm. According to the EN50122-1 standard, body currents, body voltages and touch voltages as a function of the time duration in DC traction systems are tabulated in Table 2.

3. Impact of touch and step voltages on human body

The risk of electrocution due to the touch voltage is greater than that of the step voltage because the passage of the flow of a current is closer to the heart region. Fig. 1 depicts the step and touch voltage gradients near the structure.

For a given current path through the human body, the danger to a person depends mainly on the magnitude and duration of the current flowing in the body. The necessary criterion is the admissible limit of the touch voltage as a function of time. The effects of alternating current (50/60 Hz) and direct current electric shock on human beings are described in IEC 60479-1 (IEC TS 60479-1:2005) covering the whole range of shock durations from 0.1 ms – 10 s. A unidirectional single impulse current of short duration, up to 10 ms, may be a source of danger. The effects of the impulse currents on human beings and livestock are illustrated in IEC 60479-2 (IEC TS 60479-2: 2007).

The specific fibrillating energy F_e for a single impulse of the peak current of I_p with the shock duration of t_i can be determined by the following equation.

$$F_e = I_{rms}^2 \times t_i \tag{1}$$

where I_{rms} is the root-mean-square (rms) value of the impulse current ($I_{rms} = I_p/\sqrt{6}$).

The threshold of ventricular fibrillation depends on the duration and magnitude of the impulse current. The thresholds for the ventricular fibrillation are shown in Fig. 3 for unidirectional impulses with shock duration of less than 10 ms.

The heart-current factor permits the calculation of the current Ih, as shown in Eq. (2), flowing through the paths other than the left-hand-to-feet path which represents the same level of danger of ventricular fibrillation as that corresponding to Iref for the left-hand-to-feet path.

$$I_h = \frac{I_{ref}}{F}, \qquad)2($$

where Iref is the body current for the left-hand-to-feet path. Ih is the body current for the paths given in Table 3. F is the heart-current factor given in Table 3.

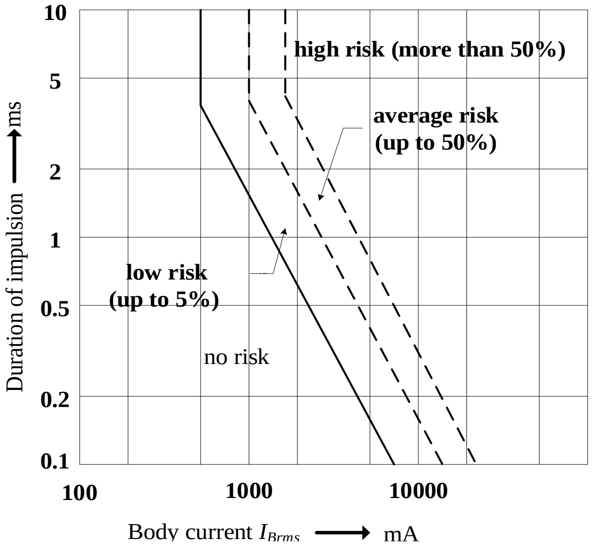


Figure. 3 Threshold of ventricular fibrillation for unidirectional impulses [21]

Table 1. Body impedance Z_b and body current I_b (Table D.1 in [20])

	a.c. system $r = 0.75$			d.c. system $r = 0.75$		
U_b V	$Z_b(100)$ Ω	$Z_b(75)$ Ω	$I_b(75)$ mA	$R_b(100)$ Ω	$R_b(75)$ Ω	$I_b(75)$ mA
25	3250	2438	10	3875	2906	9
50	2500	1875	27	2900	2175	23
75	2000	1500	50	2275	1706	44
100	1725	1294	77	1900	1425	70
125	1550	1163	108	1675	1256	100
150	1400	1050	143	1475	1106	136
175	1325	994	176	1350	1013	173
200	1275	956	209	1275	956	209
225	1225	919	145	1225	919	245
400	950	713	561	950	713	561
500	850	638	784	850	638	784
700	775	581	1204	775	581	1204
1000	775	581	1720	775	581	1720

Key

$I_b(75) = U_b/Z_b(75) \times 10^3$ or $U_b/R_b(75) \times 10^3$ body current in mA		$I_b(75)$	body current relating to Zb(75)
U_b	body voltage	$Z_b(75)$	75% of the total body impedance
$Z_b(100)$	total body impedance	$R_b(100)$	total body resistance
$R_b(75)$	75% of the total body resistance	r	reduction factor

Table 2. Body currents, body voltages and touch voltages as function of time duration in D.C. traction systems (Table D.3 in [20])

t (s)	I_{c1} (mA)	U_{c1} (V)	$U_{b,max}$ (V)	$U_{te,max}$ long-term (V)	$U_{te,max}$ short-term (V)
>300	140	153	120	120	-
300	140	153	150	150	-
1	150	160	160	160	-
0.9	160	167	165	165	-
0.8	165	170	170	170	-
0.7	175	177	175	175	-
<0.7	175	177	175	-	350
0.6	180	180	180	-	360
0.5	195	191	190	-	385
0.4	215	204	205	-	420
0.3	240	222	220	-	460
0.2	275	246	245	-	520
0.1	340	287	285	-	625
0.05	410	327	325	-	735
0.02	500	372	370	-	870

Key

$U_{te,max} = U_{c1} + R_{a1} \times I_{c1} \times 10^{-3}$ (short-term)		t	time duration of current flow
I_{c1}	body current which corresponds to curve c1 in IEC/TS 60479-1:2005	U_{c1}	body voltage, corresponds to I_{c1}
$U_{te,max}$	maximum permissible effective touch voltage	$U_{b,max}$	maximum body voltage

Table 3. Heart-current factor *F* for different current paths

Current path	Heart-current factor *F*
Left hand to left foot, right foot or both feet	1.0
Both hands to both feet	1.0
Left hand to right hand	0.4
Right hand to left foot, right foot or to both feet	0.8
Back to right hand	0.3
Back to left hand	0.7
Chest to right hand	1.3
Chest to left hand	1.5
Seat to left hand, right hand or to both hands	0.7
Left foot to right foot	0.04

4. Simulation modeling

To simulate the touch and step voltages caused by a lightning strike, a software that allows using various forms of electrical sources, e.g., AC, DC or impulse is necessary. The earthing and bonding model, which is a combination of the air termination system, the down conductor system and the earth termination system, is constructed by using a concept of resistive circuits. This model is energized by various sources to enable the study of the touch and step voltages simulation. To exhibit the use of computer modeling and simulation in this scope of work, MATLAB/Simulink is a tool to perform this simulation.

The model is comprised of the source of lightning, the resistive network of the structure and a human represented by a resistor (R_b), see Fig. 4, i.e. the figure shows a simplified resistive network of the model. The resistive circuit of the building structure is obtained by creating an equivalent circuit from the structure drawings, particularly a given earthing and bonding drawing. The lightning current is represented by a current source in which the current is the peak value of the lightning impulse. The Thevenin or Norton equivalent source can be established from the resistive circuit and the lightning current source; this equivalent source replaces the voltage source (U_s) in Fig. 2, then the final equivalent circuit to determine the touch voltage is given as shown in Fig. 5 (a). The Thevenin equivalent voltage (V_{TH}) and resistance (R_{TH}) are determined by using the measuring blocks in MATLAB/ Simulink. In addition to the touch voltage calculation, the equivalent circuit for determining the step voltage is slightly adapted from that of the touch voltage. The additional structural component is the resistive model of the floor material; this equivalent resistance of the floor is incorporated into the Thevenin equivalent resistance. The body current path is left-foot-to-right-foot or right-foot-to-left-foot, as a consequence, the resistance of the path includes the body resistance and shoes resistance as shown in Fig. 5 (b), where U_{step} denotes the voltage across two feet.

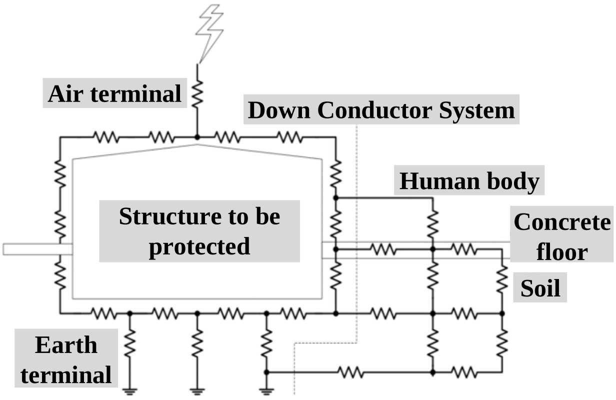
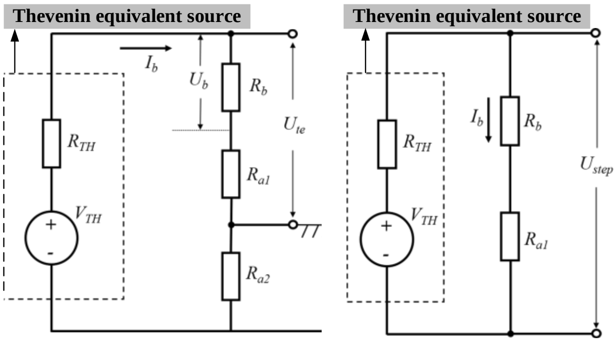


Figure. 4 Resistive network of the step and touch voltage calculation model



(a) (b)

Figure. 5 Equivalent circuit of the touch voltage calculation: (a) touch voltage and (b) step voltage

5. Case study

A Yaek Nonthaburi 1 passenger station (S09) of MRT purple line in Bangkok, Thailand is a case study for validation of the simulation model as shown in Fig. 6. The resistive model of the station contains the pier (type C1) and the steel structure of the station roof; the model is formed according to the structure drawings together with the earthing and bonding drawings. The diagram showing the composition of the model and the resistive network model of the station are exhibited in Figs. 7-10. The complete simulation block model built in MATLAB/Simulink is exhibited in Fig. 11.

Figure. 6 Yaek Nonthaburi 1 station (S09)

The simulation is broken down into four cases, each of which has different lightning strike locations at the roof top (air terminals). Fig. 8 also indicates the locations of the lightning strike. Two types of the lightning impulses, i.e. positive and negative impulse, are employed in each simulation case; the impulse curves are shown in Fig. 8 with the dotted line representing the negative impulse and the solid line representing the positive impulse. Even though the lightning current is in the impulse form, in this simulation only adopts the peak values as a constant current source: 100 kA for the negative impulse and 200 kA for the positive impulse.

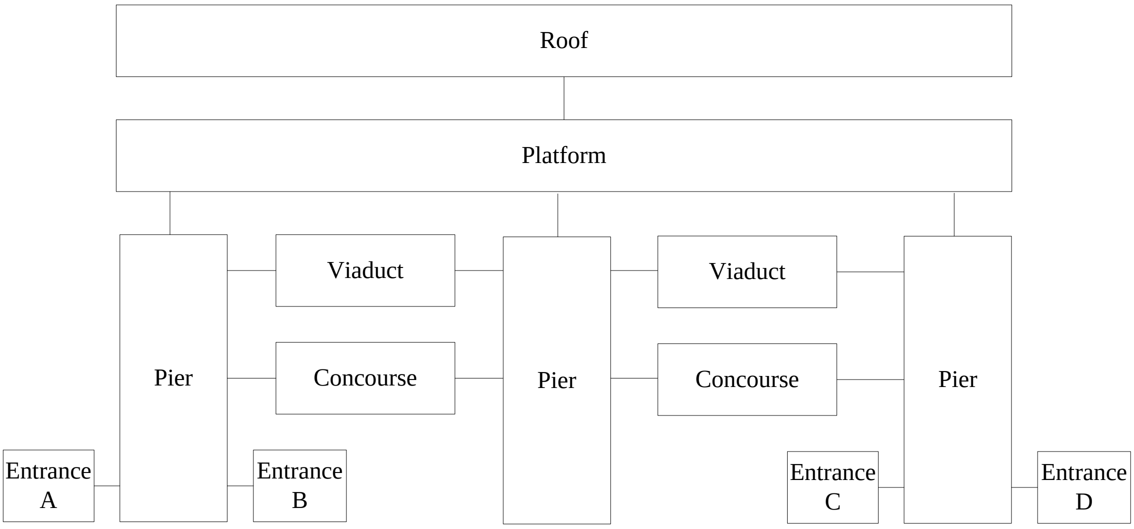


Figure. 7 Internal connection diagram of the simulation model

Table 4. Input data and system parameter setting

Parameters	Values
Human resistance for touch voltage calculation	1000 Ω
Resistivity/resistance of DB25 (A = 490.9 mm^2)	$0.2385\mu\Omega.m$ ($0.486m\Omega/m$)
Resistivity/resistance of bare copper (A=70 mm^2 and 120mm^2)	$0.0168\mu\Omega.m$ $0.341m\Omega/m$for 70 mm^2 $0.14m\Omega/m$for 120 mm^2
Resistivity of galvanized steel pipe (Ø25mm, 4mm thickness) (A = 263.9 mm^2)	$0.1\mu\Omega.m$
Resistivity of concrete resistance (320 ksc.)	$100\mu\Omega.m$
Resistivity/resistance of ground rod (Ø16 mm x 3000 mm) (A = 201.1 mm^2)	$0.0168\mu\Omega.m$ ($83.5m\Omega/m$)
Resistivity of roof (metal sheet), 4mm thickness	$0.1\mu\Omega.m$
Resistivity of steel plate (40x5mm)	$0.1\mu\Omega.m$
Resistivity of roof column (Ø406.4mm, 9mm thickness) (A = 11,236 mm^2)	$0.1\mu\Omega.m$
Resistivity/resistance of lightning air terminal (Ø16 x1000 mm) (A = 201.1 mm^2)	$0.0168\mu\Omega.m$ ($83.5m\Omega/m$)
Resistivity/resistance of copper tape (25x3 mm, A = 75 mm^2)	$0.0168\mu\Omega.m$ ($0.224m\Omega/m$)
Earthing resistance	0.2 Ω
Peak of lightning surge current (class I: IEC62305-1)	positive impulse = 200 kA negative impulse = 100 kA

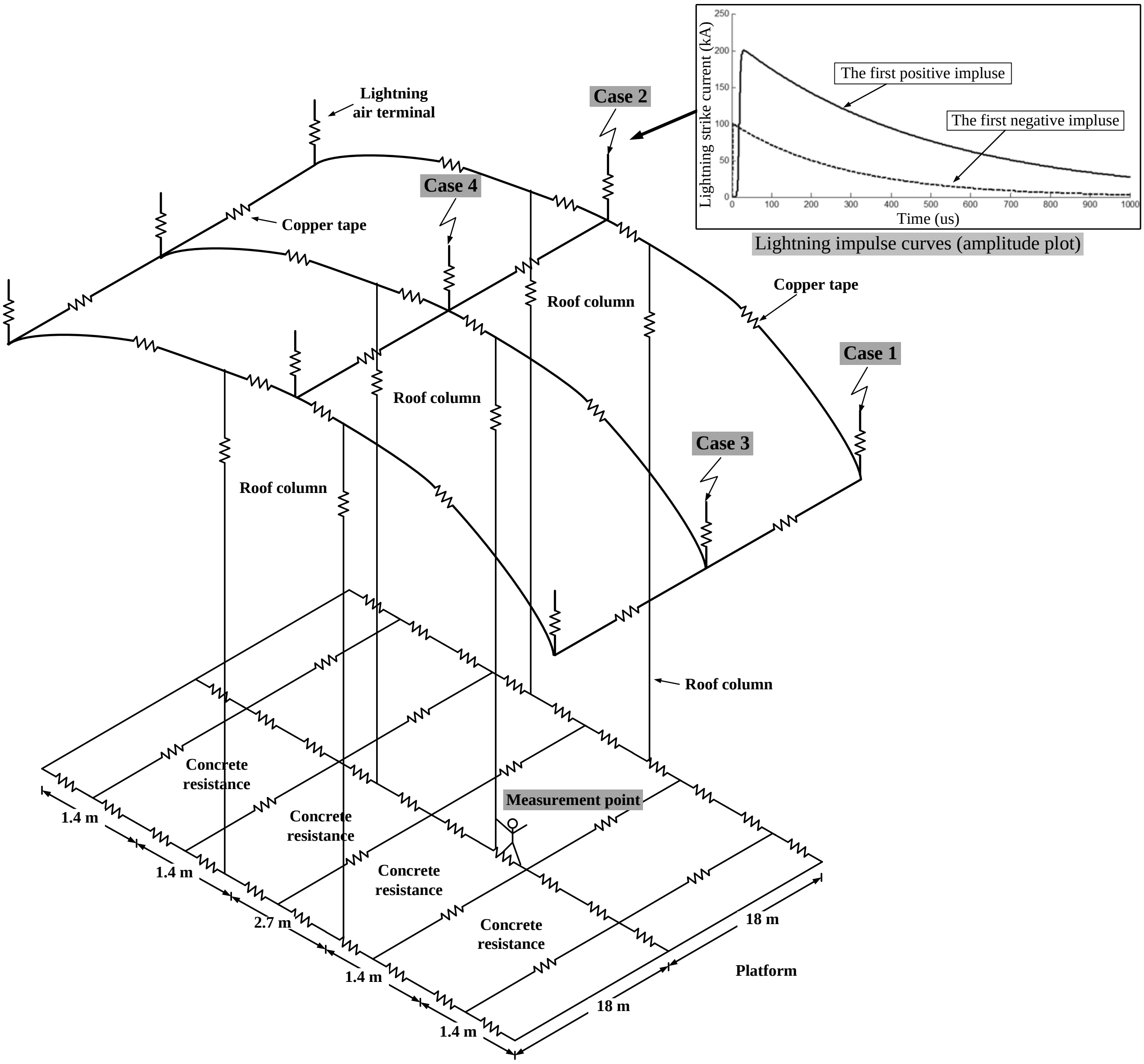


Figure. 8 Roof model, platform model and lightning strike locations for simulation

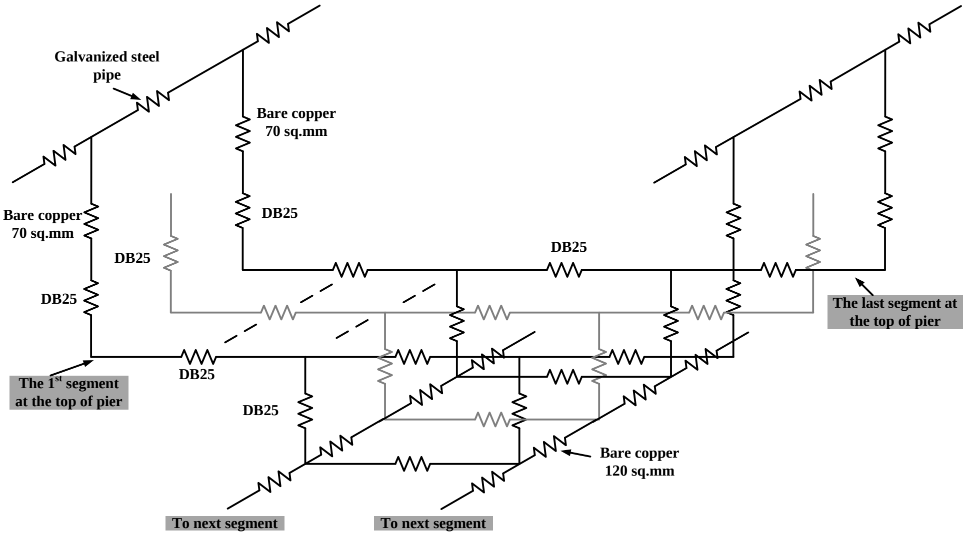


Figure. 9 Viaduct model for simulation (some connections are not shown)

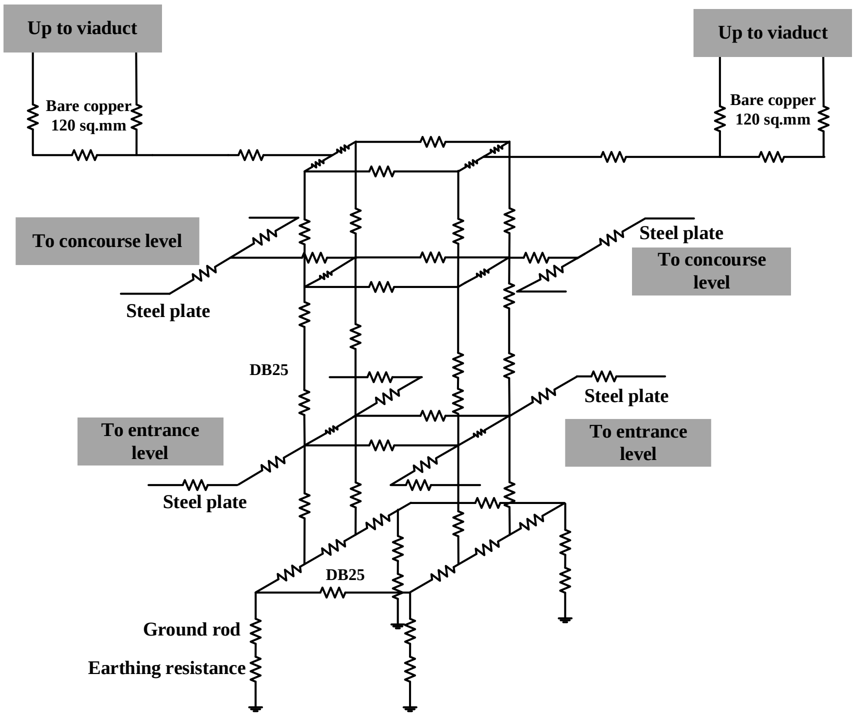


Figure. 10 Pier model for simulation

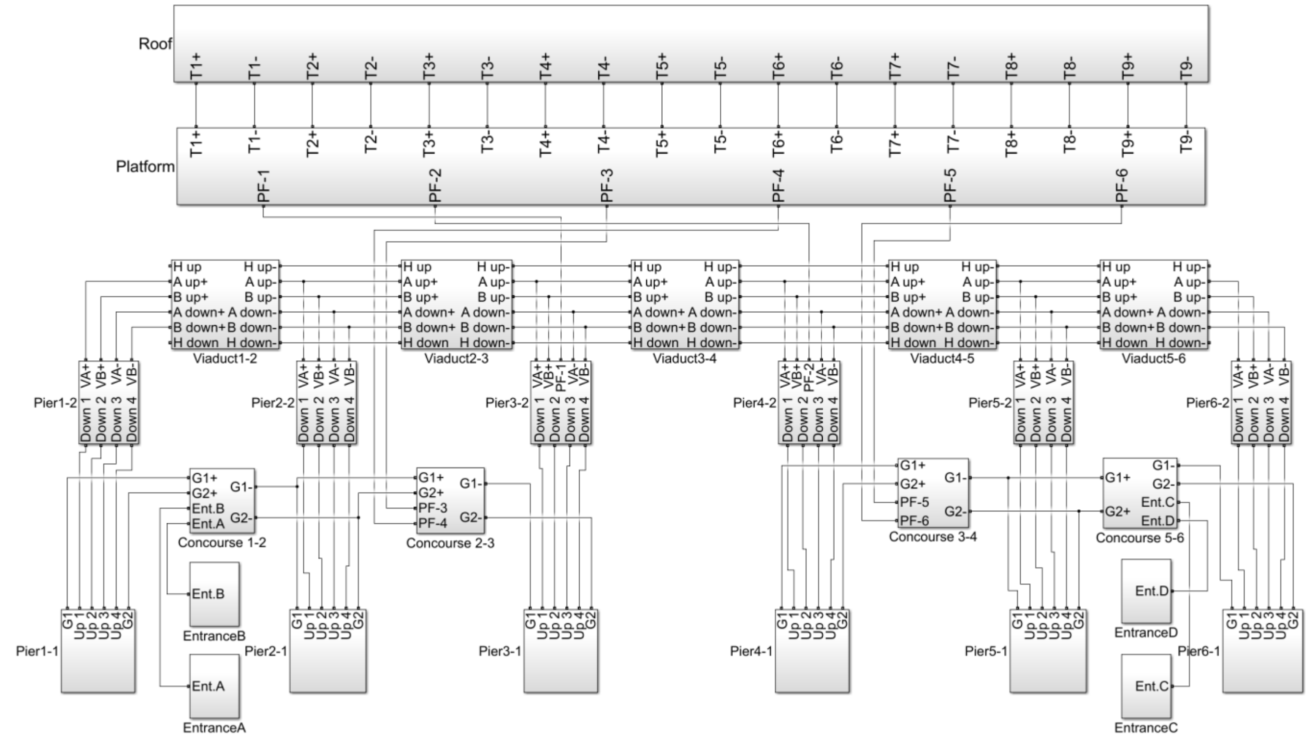


Figure. 11 Connection diagram of the block model in MATLAB/Simulink

In view of using the constant current source, the outcome of the maximum current is obtained in a steady state; the steady state results will suffice to estimate the touch and step voltages and the safety for humans, hence no transient effects are investigated. The parameters used in the simulation are given in Table 4 [14, 22-24].

6. Simulation results

The simulation results of the touch and step voltages for the case study are summarised in Table 5 and Table 6. The results are composed of the rms values of the touch and step voltages, body currents

Table 5. Simulation results of the touch voltages

Lightning impulse	Case	V_{touch} (V)	Body current I_{Brms} (mA)	Results
Positive impulse	1	12.06	0.846	no fibrillation
	2	12.22	0.857	no fibrillation
	3	30.23	2.897	no fibrillation
	4	30.52	2.924	no fibrillation
Negative impulse	1	6.03	0.423	no fibrillation
	2	6.11	0.429	no fibrillation
	3	15.12	1.060	no fibrillation
	4	15.26	1.070	no fibrillation

Table 6. Simulation results of the step voltages

Lightning impulse	Case	V_{step} (V)	Body current I_{Brms} (mA)	Results
Positive impulse	1	28.87	0.111	no fibrillation
	2	29.26	0.112	no fibrillation
	3	79.22	0.483	no fibrillation
	4	79.94	0.487	no fibrillation
Negative impulse	1	14.43	0.040	no fibrillation
	2	14.63	0.041	no fibrillation
	3	39.61	0.152	no fibrillation
	4	39.97	0.153	no fibrillation

and the impact on the human body. Considering Fig. 3 and c_1 curve, the body currents in every case are all in the no-risk zone. As a result, no ventricular fibrillation is observed – in other words the personals or passengers in the S09 station are surely safe during the lightning strike at the roof top. Regarding the touch voltage, and body current as function of time duration in d.c. traction systems shown in Table 2, the results show that the maximum touch voltage and body current of the lightning strike of both positive and negative of 30.52 V and 2.924 mA are lower than the minimum touch voltage and body current of 120 V and 140 mA, respectively. This means that the duration of time of the touch voltage and body current are able to flow through the body with no danger of ventricular fibrillation is more than 300 s. Moreover, the peak current of the positive impulse is twice as many as that of the negative one, then touch and step voltages of the positive impulse cases are approximately double those of the negative impulse cases. It is also noteworthy that the touch and step voltages of Case 3 and 4 for both the positive and negative impulse are considerably greater than the other cases; this outcome is attributed to the closer vicinity of the lightning strike locations. The positive and negative impulse does not provide any significant difference to each other but the magnitudes of the touch voltages, step voltages and body currents.

The simulation results are a preliminary estimation of the touch and step voltage and their impacts on the humans in the S09 station and also validate the proposed model; they guarantee the human protection against lightning and indicate that the lightning protection system of the S09 station is well-designed and compliant with the standard.

7. Conclusion

This paper presents a model for the evaluation of the touch and step voltages due to a lightning strike using MATLAB /Simulink. The model is created as a resistive network of the building structure according to the given earthing and bonding drawings. Yaek Nonthaburi 1 passenger station (S09) of MRT purple line in Bangkok is taken as a simulation case study. The simulation has 4 different cases with different lightning strike locations. The results show the touch voltages, step voltages and body currents of each case including the impact on the human body. Among all cases, the maximum touch voltage is 30.52 V with the body current of 2.924 mA and the maximum step voltage is 79.94 V with the body current of 0.487 mA. Both voltage and current are lower than the minimum voltage and body current of 120 V and 140 mA, respectively, which poses no harm to the human body. The simulation validates the proposed model and also proves that the lightning protection system of the station conforms with the standard; the touch voltages, step voltages and body currents do not exceed the safety criteria. It is concluded that no additional air terminals are required.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

conceptualization, Chaiyut; methodology, Chaiyut; software, Chaiyut and Kritsada; validation, Tosaphol and Thanatchai; formal analysis, Chaiyut; investigation, Tosaphol; resources, Chaiyut and Kritsada; data curation, Chaiyut; writing—original draft preparation, Chaiyut; writing—review and editing, Kritsada; visualization, Tosaphol; supervision, Thanatchai.

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