An Integrated Lightning Risk Assessment of Outdoor Air-Insulated HV Substations

Siow Chun Lim *, Ong Chang Shen and Ngu Eng Eng

Faculty of Engineering, Multimedia University, Cyberjaya 63100, Malaysia
* Correspondence: clsiow@mmu.edu.my

Abstract: Although various lightning protection methods have been used in the industry, many outdoor high-voltage (HV) substations are still experiencing high failure rates due to lightning strikes. The applications of these rule-of-thumb-based methods generally lack coherence among the practitioners. IEC 62305-2 provides a systematic way for practitioners to assess the lightning risk for buildings or structures in a probabilistic way. However, this standard has not explicitly covered the application of HV substations. Moreover, IEC 62305-2 involves a tedious set of risk factors which may hinder many practitioners from applying the aforementioned standards while other preferred rule-of-thumb methods are available. As IEC 62305-2 does not specify the applicability to lightning risk assessment in HV substations, this paper proposes a novel approach to complement the standard-based risk assessment process. During this integrated risk assessment process, significant risks are identified, followed by ambiguous risks that will be adjusted in subsequent phases. The significant ambiguous risk factors such as fire load function ($rf$), environmental factor ($CE$), LPL class, and other governing factors have been analyzed and discussed. By adjusting these significant risk factors, the practitioners will understand the adjusted risk factors in relation to the practical implementation of lightning protection system (LPS). Therefore, integrating the substation characteristics, assumptions, and findings of ambiguous risk factors can result in a successful integrated lightning risk assessment process.

Keywords: lightning risk assessment; high-voltage substation; integrated process; risk factors; IEC 62305-2; striking distance

1. Introduction

Lightning is the electrostatic charges built up in the clouds, producing enormous discharge energy that potentially transfers in high current to the tall structures or ground surface [1]. The outdoor air-insulated HV substations are one of the structures that are exposed to lightning strikes. The substations serve the purpose of switching, converting, diverting, measuring, and protecting the power transmission networks to provide a stable power supply to the consumers [2]. Although the substations are equipped with a lightning protection system (LPS), it is found that lightning strikes are still causing substation failures even in modern times [3,4]. Consequently, this has caused the substation practitioners to seek an alternative approach to assess the risk of lightning strikes via the probabilistic method [5].

IEC 62305-2 has outlined the lightning risk assessment process for the general structures [6]. Recent progress in lightning risk assessment was discussed in [7,8]. Due to the rigorous nature of risk assessment, a tool has been developed to simplify the process [9]. In spite of the fact that IEC 62305-2 does not specifically refer to the risk assessment of outdoor HV substations, the lightning risk assessment process can be conducted by incorporating assumptions with similar representations to those used for building structures [10,11].

As mentioned, despite the fact that presumably all HV substations are equipped with LPS, many failure cases were still reported in the past. Table 1 shows the failure cases that caused outages and damages due to lightning incidents [12–18].
Table 1. Failure Cases due to Lightning Incidents.

| Substation/Location                                | Date of Incidents | Affected Public Residents |
|--------------------------------------------------|-------------------|---------------------------|
| Greenbrier Substation, Alabama, USA [12]          | 3 January 2022    | 3500                      |
| NSP Lakeside Substation, Nova Scotia, Canada [13] | 22 July 2019      | 45,000                    |
| FPL Substation, Fort Lauderdale, USA [14]        | 26 March 2019     | 33,000                    |
| Edison Electric Substation, Colton, USA [15]     | 31 August 2017    | 50,000                    |
| Avista Substation Troy Highway, USA [16]         | 6 May 2017        | 11,000                    |
| Mt. Auburn Substation, Missouri, USA [17]        | 21 April 2017     | 2000                      |
| PNM Substation, New Mexico, USA [18]             | 8 August 2016     | 130,000                   |

2. Literature Review

2.1. Tolerable Risk Values

IEC 62305-2 [19] provides a process for estimating the risk of loss of human life or permanent injuries (R1) and loss of service to the public (R2). The tolerable risk values (RT) for R1 and R2 are shown in Table 2. The risk of loss of cultural heritage (R3) is excluded as HV substations are not cultural heritage buildings. Moreover, due to the complexity of equipment procurement and electricity tariffs, the risk of loss of economic value (R4) is excluded as well.

Table 2. Tolerable Risk Values.

| Type of Loss                                | RT (Per Year) |
|---------------------------------------------|---------------|
| Loss of human life or permanent injuries (R1)| 0.00001       |
| Loss of service to the public (R2)          | 0.001         |

The general equation of the risk value (R) consists of the components of the number of dangerous events per annum (N), probability of damage to a structure (P), and consequent loss value (L):

\[ R = N \times P \times L \]  (1)

2.2. Lightning Strike Distance (S)

IEC 62305-2 uses striking distance (S) to determine the lightning protection level (LPL) of an LPS. The striking distance is the final jump of the stepped leader in air space to a structure or ground plane. As a result of various lightning strike distance formulas proposed by researchers over the course of history, electro-geometrical methods (EGM) such as rolling sphere methods (RSM) lack coherence of application [20–22]. The most widely used formulas are based on Love’s and Mousa’s as shown in (2) and (3) respectively [23,24]:

\[ S = 10 \times I^{0.65} \]  (2)
\[ S = 8 \times I^{0.65} \]  (3)

where I is lightning stroke current in kA.

As shown in Table 3, Equation (2) shows a closer match to the striking distances based on the LPL table presented in IEC 62305-3 [25]. Thus, the results of (2) will be compared with the LPL table in IEC 62305-3 to determine the LPL to apply in the integrated risk assessment process.
Table 3. Comparison of Striking Distance ($S$) to LPL.

| Criteria                  | LPL I | LPL II | LPL III | LPL IV |
|---------------------------|-------|--------|---------|--------|
| Minimum peak current      | 3 kA  | 5 kA   | 10 kA   | 16 kA  |
| Striking distance, $S$ (IEC 62305) | 20 m  | 30 m   | 45 m    | 60 m   |
| $S = 8 \times I^{0.65}$   | 16.3 m| 22.8 m | 35.7 m  | 48.5 m |
| $S = 10 \times I^{0.65}$  | 19.7 m| 27.4 m | 42.8 m  | 58.2 m |

2.2.1. Basic Impulse Level (BIL)

Basic impulse level (BIL) is one of the fundamental factors to determine the allowable lightning stroke current. It is the standardized withstand impulse voltage level of electrical insulation without causing the equipment to experience flashover and damage due to lightning strikes. It is the reference levels expressed in impulse crest voltage with a standard wave not longer than 1.2 by 50 μs wave and the tests applied on the equipment shall be equal to or greater than the BIL [26,27]. The common BIL ratings of the substation are based on the voltage systems of the substations.

2.2.2. Lightning Stroke Current ($I$)

The allowable lightning stroke current which will not cause the flashover or back-flashover for the equipment is based on (4) [3]. The equation is proportional to the BIL rating of the specified equipment which was connected to the system voltage lines.

$$I = \text{BIL} \times \frac{2.2}{Z_s}$$  (4)

where $Z_s$ is the surge impedance, commonly assumed as 300 Ω unless specified [22].

2.3. Lightning Flash Density

The ground flash density ($NG$) is the key factor that determines the risk assessment result. The general formula stated in IEC 62305-2 which was originally suggested by Anderson [28], estimated that 10% of thunderstorm days per year ($TD$) is the number of lightning flashes per km$^2$ per year, with an allowance for reduced numbers of flashes to lines due to shielding by trees and undulating terrain. The formula for calculating the ground flash density is shown in (5).

$$NG = 0.1 \times TD$$  (5)

When compared to the tropical and equatorial zone such as Brazil, Columbia and Mexico, $NG$ is closer to (5) and considered as practical as the annual thunderstorm days are normally recorded higher [29].

In the real case, obtaining specific local meteorological data such as $TD$ is not a straightforward task. There is an alternative method that uses optical transient density measurement, a space-based earth orbit sensor, which was suggested in IEC 62858 that the ground flash density as shown in (6) is proportional to the total cloud-to-ground and inter-cloud optical recorded flashes per km$^2$ per year ($NT$) [30,31].

$$NG = 0.25 \times NT$$  (6)

$NT$ in flashes per km$^2$ per year can be based on NASA’s space-based earth orbit sensor data as shown in [32]. By considering the case in Malaysia for example, the $TD$ range is 50 to 350 thunderstorm days per km$^2$ per year as compared to the $NT$ range of 10 to 70 optical flashes per km$^2$ per year. It is noticeable that the ground strike-point ($NSG$), as shown in (7), for new optical transient density measurement based on NASA’s data is very similar to the lightning density formula stipulated in (5) [33,34]. Thus, this method can be considered for risk assessment if the local meteorological data is unavailable.

$$NSG = 2 \times 0.25 \times NT$$  (7)
3. Methodology

Figure 1 outlines the lightning risk assessment for HV substations based on IEC 62305-2 [19]. By incorporating the assumptions to resemble the outdoor substations as the “structures” [18], the lightning risk assessment for HV substations based on IEC 62305-2 can be performed. Five HV substations with different characteristics will be selected for the case study. The actual HV substation layouts will be overlaid in CAD tools to calculate the collection areas. After that, the lightning risk assessment based on IEC 62305-2 will be performed and several significant risk factors will be identified. Among the significant risk factors, some ambiguous risk factors will be identified. Lastly, the simplified integrated risk assessment process will be proposed.

Figure 1. Process Flow of Lightning Risk Assessment.

3.1. Risk Components

The risk components are similarly evaluated based on IEC 62305-2, in which $R_1$ and $R_2$ will be calculated based on the summation of the individual risk components as shown in Table 4. These risk components are calculated based on the tabulated risk factor values suggested in the same standard. The numbers after the alphabetical character of risk components represent the type of losses. For example, $RB1$ is risk component for loss of human life due to physical damage inside the structures due to lightning. On the other hand, $RB2$ is the risk component for loss of service to the public due to the same cause. The brief explanations of the risk components are explained in Table 5.

Table 4. Risk Values of $R_1$ and $R_2$ (IEC 62305-2).

| Risk                                      | Risk Components                                                                 |
|-------------------------------------------|---------------------------------------------------------------------------------|
| Risk of loss of human life including permanent injury ($R_1$) | $R_1 = RA1 + RB1 + RC1 + RM1 + RU1 + RV1 + RW1 + RZ1$                           |
| Risk of loss of service to the public ($R_2$) | $R_2 = RB2 + RC2 + RM2 + RV2 + RW2 + RZ2$                                      |
Table 5. Definitions of Risk Components (IEC 62305-2).

| Risk Components | Descriptions and Definitions |
|-----------------|-----------------------------|
| Risk Components for a structure due to flashes to the structure | RA: Component related to injury to living beings caused by electric shock due to touch and step voltages inside the structure and outside in the zones up to 3 m around down-conductors. |
|                  | RB: Component related to physical damage caused by dangerous sparking inside the structure triggering fire or explosion which may also endanger the environment. |
|                  | RC: Component related to the failure of internal systems caused by lightning electromagnetic pulse (LEMP). |
| Risk Components for a structure due to flashes near the structure | RM: Component related to the failure of internal systems caused by LEMP. |
| Risk Components for a structure due to flashes to a line connected to the structure | RU: Component related to injury to living beings caused by electric shock due to touch and step voltages inside the structure and outside in the zones up to 3 m around down-conductors. |
|                  | RV: Component related to physical damage caused by dangerous sparking between external installation and metallic parts generally at the entrance point of the line into the structure due to lightning current transmitted through or along incoming lines. |
|                  | RW: Component related to the failure of internal systems caused by overvoltage induced on incoming lines and transmitted to the structure. |
| Risk Components for a structure due to flashes near a line connected to the structure | RZ: Component related to the failure of internal systems caused by overvoltage induced on incoming lines and transmitted to the structure. |

3.2. Collection Areas

The collection areas are determined by the horizontal span of the land surface area of the substations and the height of the structures. The outer radius of the collection area is either dependent on the height of structures or the fixed values suggested by IEC 62305-2. Based on IEC 62305-2, the collection area of the shielding structures (AD) such as gantry and lightning masts, the area covers the horizontal span of ground surface area radially which is three times the structure’s height. Besides that, the collection area near the structures (AM) covers a 500 m radius of the ground area. For the collection areas to the line (AL) and near to the line (AI) such as bare conductors and busbars within the substations, the radial span distances are 20 m and 1000 m respectively. This measurement can be performed by using CAD tools to measure the footprint of the relevant installed structures in the substations. The collection areas possess the risk and shall normally cover the interest area where the equipment and human activities are located. As a result, the maximum collection areas are only up to the substations’ fence boundary.

3.3. Case Studies

Five cases of substations from three different countries have been chosen for the lightning risk assessment. The characteristics of the HV substation cases have been recorded as shown in Table 6. The substation characteristics primarily cover the location, voltage system (Ur), layout design, types of shielding, and sources of lightning flash density. LPL classes are determined based on Table 3.
Table 6. Characteristics of the HV Substation Cases.

| Location | Unit | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|----------|------|--------|--------|--------|--------|--------|
| State, Country | | Kuala Lumpur, Malaysia | New South Wales, Australia | Selangor, Malaysia | Leyte, Philippines | Terengganu, Malaysia |
| Ur (kV) | | 132 | 132 | 500 | 230 | 132 |
| Standard | | IEC 61936-1 [35] | AS 2067 [36] | IEC 61936-1 | IEEE C62.82.1 | IEC 61936-1 |
| BIL (kVp) | | 650 | 650 | 1550 | 1050 | 650 |
| Area (Fence) (m²) | | 20,690 | 8400 | 208,030 | 1360 | 5230 |
| NG/NGS (km²/year) | | 28 | 3 | 16 | 28 | 20 |
| S (m) | | 28 | 28 | 49 | 38 | 28 |
| LPL Class [19] | | - | I | III | II | I |

4. Results and Discussions

The results of R1 and R2 for five substation cases are shown in Tables 7 and 8. The bolded results indicate the cumulative risk values or the individual risk components which exceeds the tolerable risk RT as shown in Table 2. It is found that RB1, RC1, RV1, and RW1 are the significant risk components which exceeds RT for R1 in some cases. On the other hand, RB2, RC2, RV2, and RW2 are the significant risk factors that contribute to high values in results for the R2 case. RZ1 and RZ2 are zero values due to the risk factor selection that the earth bonding for the aerial power line shields to the internal equipment bonding bar (CLI) are commonly joint. Besides that, RM1 and RM2 have shown less significant risk values due to the selection of the continuously covered shields for internal equipment (KS2) and bonded metal cable trays to lay the internal cabling (KS3).

Table 7. Result of Risk Value of Loss of Human Life (R1).

| Risk Component | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|----------------|--------|--------|--------|--------|--------|
| R1 | $1.17 \times 10^{-4}$ | $4.47 \times 10^{-6}$ | $2.75 \times 10^{-3}$ | $2.82 \times 10^{-5}$ | $1.81 \times 10^{-3}$ |
| RA1 | $1.56 \times 10^{-11}$ | $4.10 \times 10^{-13}$ | $2.64 \times 10^{-10}$ | $3.17 \times 10^{-12}$ | $1.74 \times 10^{-12}$ |
| RB1 | $2.06 \times 10^{-5}$ | $1.35 \times 10^{-6}$ | $8.72 \times 10^{-4}$ | $1.05 \times 10^{-5}$ | $5.76 \times 10^{-6}$ |
| RC1 | $7.81 \times 10^{-5}$ | $2.05 \times 10^{-6}$ | $1.32 \times 10^{-3}$ | $1.27 \times 10^{-5}$ | $8.72 \times 10^{-6}$ |
| RM1 | $4.60 \times 10^{-21}$ | $2.05 \times 10^{-22}$ | $1.38 \times 10^{-19}$ | $7.16 \times 10^{-21}$ | $9.84 \times 10^{-21}$ |
| RU1 | $1.60 \times 10^{-12}$ | $8.04 \times 10^{-14}$ | $4.17 \times 10^{-11}$ | $3.81 \times 10^{-13}$ | $3.49 \times 10^{-13}$ |
| RV1 | $2.12 \times 10^{-6}$ | $2.65 \times 10^{-7}$ | $1.37 \times 10^{-4}$ | $1.26 \times 10^{-6}$ | $1.15 \times 10^{-7}$ |
| RW1 | $1.60 \times 10^{-5}$ | $8.04 \times 10^{-7}$ | $4.17 \times 10^{-4}$ | $3.81 \times 10^{-6}$ | $3.49 \times 10^{-7}$ |
| RZ1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table 8. Result of Risk Value of Loss of Service to the Public (R2).

| Risk Component | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|----------------|--------|--------|--------|--------|--------|
| R2 | $1.54 \times 10^{-4}$ | $6.36 \times 10^{-6}$ | $3.92 \times 10^{-3}$ | $4.11 \times 10^{-5}$ | $2.53 \times 10^{-5}$ |
| RB2 | $3.75 \times 10^{-5}$ | $2.46 \times 10^{-6}$ | $1.58 \times 10^{-3}$ | $1.90 \times 10^{-5}$ | $1.05 \times 10^{-5}$ |
| RC2 | $9.37 \times 10^{-5}$ | $2.46 \times 10^{-6}$ | $1.58 \times 10^{-3}$ | $1.52 \times 10^{-5}$ | $1.05 \times 10^{-5}$ |
| RM2 | $5.53 \times 10^{-21}$ | $2.46 \times 10^{-22}$ | $1.66 \times 10^{-19}$ | $8.60 \times 10^{-21}$ | $1.18 \times 10^{-20}$ |
| RV2 | $3.85 \times 10^{-6}$ | $4.82 \times 10^{-7}$ | $2.50 \times 10^{-4}$ | $2.28 \times 10^{-6}$ | $2.09 \times 10^{-7}$ |
| RW2 | $1.93 \times 10^{-5}$ | $9.64 \times 10^{-7}$ | $5.00 \times 10^{-4}$ | $4.57 \times 10^{-6}$ | $4.19 \times 10^{-6}$ |
| RZ2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
4.1. Risk Factor Characteristics

Based on IEC 62305-2, the characteristics of the risk factors can be summarized in Table 9. The characteristics are basically divided into three main categories: fixed value factors, measurable risk factors, and ambiguous risk factors.

| Risk Factors | Fixed Value Factors | Measurable Risk Factors | Ambiguous Risk Factors |
|--------------|---------------------|-------------------------|------------------------|
| Number of dangerous events (N) | CI, CT | AD/ADJ, AM, AL, AI | CD, CE |
| Probability of the Losses (P) | KS2 | KS1 | PTA, PTU, PB, PSPD, PEB, PLD, PIJ, CLD, CLI, KS3, Uw (KS4) |
| Loss Values (L) | LT, LF, rt, hz | nz, nt | rf, rp |

The fixed value factors are uniform in selection due to the clear descriptions of the risk factors shown in the standard. For measurable risk factors, practitioners are required to perform the calculation such as identifying the collection areas by using CAD tools. Lastly, there is a group of risk factors that may be found ambiguous for practitioners to select when performing the risk assessment.

4.1.1. Common Values of Risk Factors

The risk factors that are having common fixed values for outdoor HV substation cases are shown in Table 10.

| Risk Factors | Selection | Value |
|--------------|-----------|-------|
| CI           | Aerial    | 1     |
| CT           | HV Power  | 0.2   |
| LF           | Substation | 0.33 |
| LT           | Injury due to electrical shock | 0.01 |
| rt           | Gravel, moquette, carpets | 0.0001 |
| hz           | Low-level panic (less than 100 people) | 2 |

4.1.2. Significant Range of Risk Factors

The range of risk factors can be estimated by registering the highest to lowest values of the risk factors, and by estimating the ratio of the factor values to obtain the approximate range of risk values for each component. Some of the significant range of risk factors based on IEC 62305-2 are shown in Table 11. The value of these risk factors varies depending on the substations’ characteristics. For example, the environmental factor (CE) and function of fire and explosion risk of structure (rf) have shown the potential of change of risk values in the maximum range of 100 and 1000.

After tabulating the major risk factors as shown in Table 11, the ratio of the factor values can be registered as shown in Table 12 to estimate the approximate range of the risk values for each component in the power of ten. For example, it is shown that RV is having the highest variation of risk values mainly due to CE and rf. Besides that, KS3 is the risk factor with the highest range in variation of value which mainly affects RM.
Table 11. Major Significant Range of Risk Factors.

| Risk Factors | Highest Factor Value | Lowest Factor Value | Factors Ratio & Affected Risk Components |
|--------------|----------------------|---------------------|------------------------------------------|
| CE (Rural)   | 1                    | 0.01 (Urban with high building) | 100 RU, RV, RW, RZ                       |
| PTA (No protection) | 1                  | 0.01 (Effective soil equipotentialization) | 100 RA                                    |
| PTU (No protection)  | 1                  | 0.01 (Electrical Insulation) | 100 RU                                    |
| KS3 (Unshielded cable) | 1                | 0.0001 (Shielded cables in metal conduits) | 10,000 RM                                 |
| rf (Solid explosive) | 1                 | 0.001 (Low fire) | 1000 RB, RV                              |

Table 12. Accumulated Variation of Risk Values for Risk Components.

| Risk Factors | RA | RB | RC | RM | RU | RV | RW | RZ |
|--------------|----|----|----|----|----|----|----|----|
| CD           | 8  | 8  | 8  | 8  | 8  | 8  | 8  |    |
| CE           | 100|     |    |    | 100|    |    |    |
| PTA (No protection) | 100|     |    |    |    |    |    |    |
| PTU (No protection)  | 10 | 10 |    |    |    |    |    |    |
| PSPD         | 5  | 5  | 10,000 | 6  |      |    |    |    |
| KS3 (Unshielded cable) | 100|     |    |    |    |    |    |    |
| KS4         |    |    |    |    |    |    |    |    |
| PEB          | 2  | 2  |    |    |    |    |    |    |
| PLD          | 50 | 50 |    |    |    |    |    |    |
| PLI          |    |    |    |    |    |    | 10 |    |
| CLD          |    |    |    |    |    |    |    | 10 |
| CLI          |    |    |    |    |    |    |    |    |
| hz           | 10 | 2  |    |    |    |    |    |    |
| rt           |    |    |    |    |    |    | 2  |    |
| rf           | 1000|     |    |    |    |    |    |    |
| rp           | 2.5 |     |    |    |    |    |    |    |
| Total        | $8 \times 10^4$ | $4 \times 10^5$ | $4 \times 10^1$ | $3 \times 10^5$ | $8 \times 10^7$ | $4 \times 10^8$ | $2 \times 10^5$ | $5 \times 10^4$ |
| $x$, for 10^4 | 4  | 5  | 1  | 5  | 7  | 8  | 5  | 4  |

4.1.3. Ambiguity of Risk Criteria

The ambiguity in the risk criteria arises due to the lack of risk factor criteria selection options to represent substation case. For example, the probability of persons being injured because of the failure of internal systems (Lo) has a limited set of selection options, which limits them to select the only “risks of explosion”. In addition, in fact, that the operators find it much easier and more frequent to access urban substations in the aspect of CE than rural substations, which carry a greater risk of injury. The ambiguous risk criteria which are commonly found in a typical HV substation are shown in Table 13. Note that typical HV substation means a conventional HV substation that is outdoors.
Table 13. Ambiguous Risk Criteria.

| Risk Factors | Discussions and Remarks |
|--------------|-------------------------|
| **CE**       | Rural substations are not necessarily more likely to cause injury to humans when compared to urban substations, and the relative topological location and pollution level of the substation have not been considered. Besides that, the future development around the substations will be re-evaluated over time. Moreover, most rural substations are in autonomous mode and without an on-site operator. |
| **PTA**      | For effective soil equipotentialization in the substation especially for touch voltages, the steel gridded carpet is bonded to the earth grids for operators to stand on. The effectiveness of earthing grid is also depending on the actual soil condition. Earthing resistance test shall be conducted and verified after the installations. Practitioners shall reserve the possibility of high acidic soils and theft events causing the discontinuity of connection and affecting the effectiveness of the earthing over time. |
| **PTU**      | The actual performance of the insulation is based on the test results of the equipment. The degraded insulation of the aging equipment shall be considered over the years. |
| **PB**       | Some down-conductors or bonded structures are having the same size or even bigger than the LPL classes of substations. Besides that, the factor to have segregation of space between the dangerous sparks and the combustible fuel to cause the fire is absence. |
| **PSPD/PEB** | The level of LPL for SPDs is independently specified and not necessary to match the LPL of LPS. |
| **Uw (KS4/PLD/PLI)** | The selection of the rated impulse withstand voltage of the internal system is dependent on the product design and type test history. Most of the LV equipment is tested up to 1000 DC volts for insulation. The sensitive electronics are normally protected via external SPDs and are not susceptible to impulse voltage due to lightning. |
| **KS3**      | The internal wiring includes the intrinsic circuitry of the internal systems which is unable to be quantified practically. Sometimes, several sections of the connected wires of internal systems are directly buried in the ground or exposed to air. |
| **rt**       | The resistivity of the soil is depending on the infiltration such as events after rain and flood. Besides that, substations will have multiple layers of soil unlike the uniformed soil specified in the standard. |
| **nz, nt**   | The hours of operators working in the structure and the zone per day are unpredictable depending on the daily activities on site. The continuous ongoing construction activities at the site may expose higher risk. |
| **hz**       | The level of panic based on the special hazards is undefined for the outdoor substation cases due to non-uniformed designs. The effective egress path in the substation may affect the safety of operators. |
| **Lo**       | Only having “Risk of explosion” can be selected for the substation case. |

4.1.4. Ambiguity of Risk Values

The risk values published by IEC 62305-2 are very comprehensive and critically useful to perform the risk assessment. In spite of the convenience of applying straightforward risk values to the risk assessment process, practitioners may find it difficult to comprehend the basis of the risk values provided by the standard. Moreover, the current standard also lacks specific guidance for practitioners to apply in the HV substation context. The ambiguous risk values based on IEC 62305-2 for a typical HV substation are shown in Table 14.

Table 14. Ambiguous Risk Values.

| Risk Factors | Discussions and Remarks |
|--------------|-------------------------|
| **CD**       | The sensitivity of change of risk values in relation to the substation structures’ height compared to surrounding structures is not defined. |
| **CE**       | The risk value is dependent on the relative height of the surrounding object. The standard does not present the sensitivity of risk values to the features of the surrounding structures. |
| **PTA**      | The risk value has not reflected the level of the equipotentialisation as the earthing grid system with low resistance is normally applied to HV substations to prevent the built-up induced overvoltage. Besides that, the level of insulation of the protected equipment is absent as well in relation to the risk value. |
Table 14. Cont.

| Risk Factors | Discussions and Remarks |
|--------------|-------------------------|
| **PTU**      | The selection has shown the absence of the probability when the human is electrocuted when touching the bonded structures during lightning strikes in relation to the magnitude of stroke currents, earthing design, and insulation level. |
| **PB**       | The down-conductor connections for other LPL classes are not mentioned and defined. Besides that, the minimum stroke current and striking radius are based on the assumed fixed value of surge impedance. |
| **CLD/CLI**  | The risk values depend on the effectiveness of shielding, grounding, and isolation conditions. |
| **Uw (KS/PLD/PLI)** | The sensitivity of impulse voltage selection to cause the change of risk values is not defined. |
| **rf**       | The explosion or fire incidents in outdoor substations are dependent on the volume of combustible oil and fuel containment at the site. Besides that, the degradation of equipment insulations may contribute high risk of unnoticed internal failures. Moreover, the fire load ($q_c$) is dependent on the total calorific value of the insulating oil over the specific floor area where oil spillage on the uncertain surrounding surface may affect the spread. It is assumed that the substation is designed with an adequate fire radius from the fire source by not breaching the safe fire distance to the nearby oil-filled transformers. The risk value based on the selected fire risk factors may have a lack of consideration of the mentioned combined factors. |
| **rp**       | In the event of an explosion or major fire incident, the location of the substation may determine the time for firemen to reach the site. The fire-fighting measures are depending on the initial planning and the efficiency during execution. These efficiency factors vary among utilities. |
| **CT**       | The risk values are supposedly dependent on the effectiveness of the lightning shielding on the lines. The standard has not covered the level of effective shieldings. |
| **LT**       | The only assumption is that 1% of people will experience an electric shock. |
| **LF**       | The only assumption is that 1/3 of the people on site will experience the injury due to fire. |
| **Lo**       | The risk values of power interruption due to damage to the internal system and the major equipment are similar. However, it also depends on the contingency level of switching to another network supply and the time duration for the repair and replacement of the faulty equipment. |

4.1.5. Ambiguity Level of Risk Factors

In order to identify the ambiguous risk factors that potentially influence the significance level of risk values, Tables 13 and 14 are analyzed. The risk factors which are mentioned in both Tables 13 and 14 are summarized in Table 15. As a result, $RU$, $RV$, and $RZ$ have shown a high level of ambiguity. It is known that the results shown in Tables 7 and 8 indicate that $RB$, $RC$, $RV$, and $RW$ have higher risk values, which are towards exceeding the tolerable risk. Due to this, when comparing the actual results with Table 15, $RB$ and $RV$ with ambiguous risk factors in the range of 10 and 10,000, respectively, could potentially bring the results to exceed the tolerable risk values. Practitioners will be made aware of these ambiguous risk factors through subsequent risk assessments.

Table 15. Risk Factors Shown in Both Tables 13 and 14.

| Risk Factors | RA  | RB  | RC  | RM  | RU  | RV  | RW  | RZ  |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $CE$         | 100 |     |     |     | 100 |     |     | 100 |
| $PTA$        | 100 |     |     |     |     | 100 |     |     |
| $PTU$        |     |     |     |     |     |     |     | 100 |
| $PB$         | 5   | 5   |     |     |     |     |     |     |
| $PLD$        | 50  | 50  | 50  |     | 50  | 50  |     |     |
| $PLI$        |     |     |     |     |     |     |     | 10  |
| $hz$         | 2   |     |     |     |     |     |     | 2   |
| Total        | $5 \times 10^2$ | $1 \times 10^1$ | 0   | 0   | $5 \times 10^5$ | $1 \times 10^4$ | $5 \times 10^2$ | $1 \times 10^3$ |
| $x$, for $10^x$ | 2   | 1   | 0   | 0   | 5   | 4   | 2   | 3   |
On the other hand, Table 16 has shown the risk factors which are only mentioned in either Table 13 or Table 14. RB, RM, and RV have shown a high level of ambiguity when the risk assessment is performed. Similarly, when comparing the actual results, the ambiguous risk factors found in RB and RV are considered significant and will be highlighted in subsequent risk assessments.

### Table 16. Risk Factors Only Shown in Either Table 13 or Table 14.

| Risk Factors | RA | RB | RC | RM | RU | RV | RW | RZ |
|--------------|----|----|----|----|----|----|----|----|
| CD           | 8  | 8  | 8  | 8  | 8  | 8  | 8  | 8  |
| PSPD         | 2  | 2  | 2  | 2  | 2  | 2  | 2  | 2  |
| KS3          | 10,000 | 6  |
| CLI          | 2.5 | 2.5 |
| rp           | 1000 | 1000 |
| rf           | 10  | 10  |
| rt           | 10  | 10  |
| Total        | $8 \times 10^1$ | $2 \times 10^4$ | $1.6 \times 10^1$ | $1.2 \times 10^5$ | $1.6 \times 10^2$ | $4 \times 10^4$ | $1.6 \times 10^1$ | $2 \times 10^3$ |
| x, for $10^7$ | 1  | 4  | 1  | 5  | 2  | 4  | 1  | 1  |

In conclusion, the ambiguous risk factors will impact the results of the risk values. Tables 13 and 14 summarise the risk factors which practitioners would find ambiguous if they are to conduct the risk assessment as per IEC 62305-2. These ambiguities and the lengthiness of the process of IEC 62305-2 may potentially cause the inaccurate representation of lightning risk on substations. However, the onerous summarized findings of the significant ambiguous risk factors can be emphasized for future assessments and research.

4.1.6. Comparison of Ambiguous Factors to Actual Cases

Based on the actual results shown in Tables 7 and 8, RB, RC, RV, and RW are the prominent risk components for all cases. RB, RV, and RW have a high level of ambiguity. Furthermore, the significant risk factors such as CE, PLD, PLI, KS3, rt, and rf have to be emphasized and selected carefully while performing the lightning risk assessment.

4.2. Integrated Process of Lightning Risk Assessment

The integrated process is based on the required inputs to perform the lightning risk assessment. This process can be summarized in the flowchart shown in Figure 2. Furthermore, the process can be simplified by creating the risk assessment sheets by identifying the groups of risk factors as discussed earlier. Besides that, integration such as adopting IEEE 998 to determine the rolling sphere radius is crucial to determining the LPL risk values. By having CAD tools, the collection areas can be determined as well. In addition, the ambiguous risk factors can be adjusted to run the iterations of risk assessments.

**Iterations of Lightning Risk Assessment**

After obtaining the required inputs, practitioners can proceed to perform the lightning risk assessment by using the process flow and risk tables based on IEC 62305-2. The selection of risk factors should be taken into consideration when considering ambiguous risk factors as described in earlier sections. It is imperative to test the sensitivity of the result values in successive iterations with the range of probable changes in risk factors.
the groups of risk factors as discussed earlier. Besides that, integration such as adopting IEEE 998 to determine the rolling sphere radius is crucial to determining the LPL risk values. By having CAD tools, the collection areas can be determined as well. In addition, the ambiguous risk factors can be adjusted to run the iterations of risk assessments.

Figure 2. Integrated Process of Lightning Risk Assessment.

It is known that the previously generated results have shown some risk components exceeding the tolerable risk values. Thus, it is important for designers and practitioners to identify the risk factors that can be adjusted to improve the design. In principle, it is unlikely to change the fixed geographical aspects to improve the risk values. However, some other risk factors such as substation design such as LPS class and installations can be improved. Although the improvement measures will reduce the lightning risk values, it is noted that the additional materials and installations will incur higher costs. Based on these adjustments, the utilities and designers can at least make a fair decision to consider the exposed risk values and the incurred cost. The adjusted factors to improve the risk results are shown in Table 17. The improved-case results are shown in Tables 18 and 19. The bolded results indicate the cumulative risk values or the individual risk components which exceeds the tolerable risk $RT$.

Table 17. Proposed Adjustment of Risk Factors-Improved-case.

| Risk Factors | Proposed Adjustment |
|--------------|---------------------|
| $PB$, $PSPD$, $PEB$ | To next better LPS class, more provisions allocated |
| $PLD$, $U_w$ | Install higher rated impulse withstand voltage equipment on site and lower resistance earth conductors |
| $rp$ | Install automatic operated extinguisher and alarm that fireman to arrive within 10 min |
Table 18. Result of Risk Value of Loss of Human Life (R1) - Improved-case.

| Risk Component | Case 1     | Case 2     | Case 3     | Case 4     | Case 5     |
|----------------|------------|------------|------------|------------|------------|
| R1             | $8.88 \times 10^{-6}$ | $5.40 \times 10^{-7}$ | $6.15 \times 10^{-5}$ | $1.48 \times 10^{-6}$ | $2.03 \times 10^{-6}$ |
| RA1            | $7.81 \times 10^{-12}$ | $2.05 \times 10^{-13}$ | $6.41 \times 10^{-12}$ | $3.86 \times 10^{-12}$ | $8.72 \times 10^{-13}$ |
| RB1            | $1.03 \times 10^{-6}$ | $2.70 \times 10^{-7}$ | $3.49 \times 10^{-5}$ | $8.38 \times 10^{-7}$ | $1.15 \times 10^{-6}$ |
| RC1            | $7.81 \times 10^{-6}$ | $2.05 \times 10^{-7}$ | $2.64 \times 10^{-5}$ | $6.35 \times 10^{-7}$ | $8.72 \times 10^{-7}$ |
| RM1            | $1.28 \times 10^{-12}$ | $5.69 \times 10^{-25}$ | $7.68 \times 10^{-23}$ | $9.95 \times 10^{-24}$ | $2.73 \times 10^{-23}$ |
| RUI            | $3.21 \times 10^{-15}$ | $1.61 \times 10^{-16}$ | $1.67 \times 10^{-14}$ | $3.81 \times 10^{-16}$ | $6.98 \times 10^{-16}$ |
| RV1            | $4.24 \times 10^{-9}$ | $2.12 \times 10^{-10}$ | $2.20 \times 10^{-8}$ | $5.03 \times 10^{-10}$ | $9.21 \times 10^{-11}$ |
| RW1            | $3.21 \times 10^{-8}$ | $6.43 \times 10^{-8}$ | $1.67 \times 10^{-7}$ | $3.81 \times 10^{-9}$ | $6.98 \times 10^{-9}$ |
| RZ1            | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       |

Table 19. Result of Risk Value of Loss of Service to the Public (R2) - Improved-case.

| Risk Component | Case 1     | Case 2     | Case 3     | Case 4     | Case 5     |
|----------------|------------|------------|------------|------------|------------|
| R2             | $2.96 \times 10^{-5}$ | $8.15 \times 10^{-7}$ | $9.53 \times 10^{-5}$ | $2.29 \times 10^{-6}$ | $3.15 \times 10^{-6}$ |
| RB2            | $1.87 \times 10^{-5}$ | $4.92 \times 10^{-7}$ | $6.34 \times 10^{-5}$ | $1.52 \times 10^{-6}$ | $2.09 \times 10^{-6}$ |
| RC2            | $9.37 \times 10^{-6}$ | $2.46 \times 10^{-7}$ | $3.17 \times 10^{-5}$ | $7.61 \times 10^{-7}$ | $1.05 \times 10^{-6}$ |
| RM2            | $1.53 \times 10^{-23}$ | $6.83 \times 10^{-25}$ | $9.21 \times 10^{-23}$ | $1.19 \times 10^{-23}$ | $3.28 \times 10^{-23}$ |
| RV2            | $3.08 \times 10^{-7}$ | $3.86 \times 10^{-10}$ | $4.00 \times 10^{-8}$ | $9.14 \times 10^{-10}$ | $1.67 \times 10^{-10}$ |
| RW2            | $1.16 \times 10^{-6}$ | $7.71 \times 10^{-8}$ | $2.00 \times 10^{-7}$ | $4.57 \times 10^{-9}$ | $8.37 \times 10^{-9}$ |
| RZ2            | 0.00       | 0.00       | 0.00       | 0.00       | 0.00       |

For example, R1 for Case 3 is still exceeding $RT$, mainly due to the large collection areas and the risk of fire or explosions. Although the on-site autotransformers are generally having higher oil volume due to their higher MVA ratings, the comparison of fire spread area around the hazardous oil-filled autotransformers is relatively small compared to the overall switchyard. This has also shown that selecting the fire risk factors due to lightning strikes as discussed earlier remains ambiguous. The improved results have narrowed the list of concerned risk components, and this will help the practitioners to pay close attention to those risk factors.

Conversely, practitioners can expect worse-case risk results by assuming some less stringent designs. By adjusting the ambiguous risk factors to higher values, the practitioners can notice the changes in results. As discussed, some of the ambiguous factors such as $CE$ has been interpreted wrongly in the text. The practitioners shall revisit the actual risk values to suit the actual case. Moreover, by applying higher risk values of LPS due to the leniency of selecting the next higher striking distance, practitioners can predict the potential increase of risk values due to human mistakes and aging installations. Besides that, there is a potential that conditions of actual bonding and shielding are not fully established in the substations. It could be due to broken connections after many years. The adjustment of risk factors is shown in Table 20. The worst-case results are shown in Tables 21 and 22. The bolded results indicate the cumulative risk values or the individual risk components which exceeds the tolerable risk $RT$.

After both improved and worse-case iterations have been performed, the practitioners will be able to identify the adjusted ambiguous risk factors which significantly affect the result. As the process reaches completion, it is considered satisfactory when no further adjustments of risk factors are required to improve the situation for the HV substations.
Table 20. Proposed Adjustment Risk Factors-Worse-case.

| Risk Factors | Proposed Adjustment |
|--------------|---------------------|
| CE           | If the surrounding structure or tree around the urban substation is not higher than the substation’s structures, the environmental factor shall be considered “rural”. |
| PB, PSPD     | To next worse LPS class |
| PB, PSPD, PEB| To next better LPS class, more provisions allocated |
| CLD/CLI      | Separate bonded earth points |
| KS3          | The internal wiring is not shielded and has no routing precaution when directly buried in a large area below the ground. |

Table 21. Result of Risk Value of Loss of Human Life (R1) -Worse-case.

| Risk Component | Case 1   | Case 2   | Case 3   | Case 4   | Case 5   |
|----------------|----------|----------|----------|----------|----------|
| R1             | $2.55 \times 10^{-4}$ | $9.70 \times 10^{-6}$ | $3.65 \times 10^{-3}$ | $6.56 \times 10^{-5}$ | $3.94 \times 10^{-5}$ |
| RA1            | $3.90 \times 10^{-11}$ | $1.02 \times 10^{-12}$ | $5.28 \times 10^{-10}$ | $6.35 \times 10^{-12}$ | $4.36 \times 10^{-12}$ |
| RB1            | $5.15 \times 10^{-5}$ | $3.38 \times 10^{-6}$ | $1.74 \times 10^{-3}$ | $2.09 \times 10^{-5}$ | $1.44 \times 10^{-5}$ |
| RC1            | $1.56 \times 10^{-4}$ | $4.10 \times 10^{-6}$ | $1.32 \times 10^{-3}$ | $3.17 \times 10^{-5}$ | $1.74 \times 10^{-5}$ |
| RM1            | $9.21 \times 10^{-13}$ | $4.10 \times 10^{-14}$ | $1.38 \times 10^{-11}$ | $1.79 \times 10^{-12}$ | $1.97 \times 10^{-12}$ |
| RJ1            | $3.98 \times 10^{-12}$ | $1.61 \times 10^{-13}$ | $4.17 \times 10^{-11}$ | $9.52 \times 10^{-13}$ | $6.98 \times 10^{-13}$ |
| RV1            | $5.26 \times 10^{-6}$ | $5.30 \times 10^{-7}$ | $1.37 \times 10^{-4}$ | $3.14 \times 10^{-6}$ | $2.30 \times 10^{-7}$ |
| RW1            | $3.98 \times 10^{-5}$ | $1.61 \times 10^{-6}$ | $4.17 \times 10^{-4}$ | $9.52 \times 10^{-6}$ | $6.98 \times 10^{-6}$ |
| RZ1            | $1.84 \times 10^{-6}$ | $8.20 \times 10^{-8}$ | $2.76 \times 10^{-5}$ | $3.17 \times 10^{-7}$ | $3.49 \times 10^{-7}$ |

Table 22. Result of Risk Value of Loss of Service to the Public (R2) -Worse-case.

| Risk Component | Case 1   | Case 2   | Case 3   | Case 4   | Case 5   |
|----------------|----------|----------|----------|----------|----------|
| R2             | $3.41 \times 10^{-4}$ | $1.41 \times 10^{-5}$ | $5.54 \times 10^{-3}$ | $9.37 \times 10^{-5}$ | $5.63 \times 10^{-5}$ |
| RB2            | $9.37 \times 10^{-5}$ | $6.15 \times 10^{-6}$ | $3.17 \times 10^{-3}$ | $3.81 \times 10^{-5}$ | $2.62 \times 10^{-5}$ |
| RC2            | $1.87 \times 10^{-4}$ | $4.92 \times 10^{-6}$ | $1.38 \times 10^{-3}$ | $3.81 \times 10^{-5}$ | $2.09 \times 10^{-5}$ |
| RM2            | $1.11 \times 10^{-12}$ | $4.92 \times 10^{-14}$ | $1.66 \times 10^{-11}$ | $2.15 \times 10^{-12}$ | $2.36 \times 10^{-12}$ |
| RV2            | $9.56 \times 10^{-6}$ | $9.64 \times 10^{-7}$ | $2.50 \times 10^{-4}$ | $5.71 \times 10^{-6}$ | $4.19 \times 10^{-7}$ |
| RW2            | $4.78 \times 10^{-5}$ | $1.93 \times 10^{-6}$ | $5.00 \times 10^{-4}$ | $1.14 \times 10^{-5}$ | $8.37 \times 10^{-6}$ |
| RZ2            | $2.21 \times 10^{-6}$ | $9.84 \times 10^{-8}$ | $3.32 \times 10^{-5}$ | $3.81 \times 10^{-7}$ | $4.19 \times 10^{-7}$ |

5. Conclusions

Historically, many HV substations have experienced lightning shielding failures in the past, despite various lightning protection methods that have been implemented in the design, such as RSM, direct angles, and empirical curves. This has made designers and practitioners face difficulties to analyze the adequacy of the designs which are fundamentally conducted incoherently. IEC 62305-2 has provided an alternative method for practitioners to estimate the risk values via the risk assessment process. As discussed in earlier sections, although IEC 62305-2 has not specifically stated the applicability of the lightning risk assessment on the HV substations, a similar representation of the substations to the structures [11] can be made. Besides that, the characteristics of the outdoor HV substations such as BIL will be used as the inputs to determine the LPL of the LPS. Apart from that, this integrated risk assessment process requires some inputs which are generated from the CAD tools and based on some external resources such as meteorological data and other international standards. Moreover, the integrated process will also involve identifying the significant risk factors which are governing the results. IEC 62305-2 specifies a limited selection of risk factors for HV substations. It is crucial that practitioners adjust any
ambiguous risk factors in subsequent assessments to estimate the significance of the results. The adjustment of the significant risk factors is crucial for the practitioners to identify the risk factors that can be brought forward to improve the LPS designs.

Author Contributions: Conceptualization, S.C.L. and O.C.S.; methodology, O.C.S.; software, S.C.L. and O.C.S.; validation, S.C.L., O.C.S. and N.E.E.; formal analysis, O.C.S.; investigation, O.C.S.; data curation, O.C.S.; writing—original draft preparation, O.C.S.; writing—review and editing, S.C.L., O.C.S. and N.E.E.; visualization, O.C.S.; supervision, S.C.L. and N.E.E.; project administration, S.C.L.; funding acquisition, S.C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and the APC was funded by Multimedia University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the Faculty of Engineering, Multimedia University for the support provided for this research.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Wagner, C.F.; McCann, G.D.; Lear, C.M. Shielding of substations. IEEE Electr. Eng. 1942, 61, 96–99. [CrossRef]
2. Lusby, J.R. Fundamental Concepts in Substation Design. In Rural Electric Power Conference; IEEE: New York, NY, USA, 1993.
3. IEEE 998; Guide for Direct Lightning Stroke Shielding of Substations. IEEE: New York, NY, USA, 2012.
4. Gamble, R.D.; Laughner, T. Lightning Studies to Improve Power Quality. In Proceedings of the 24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference, San Diego, CA, USA, 18–21 April 2016.
5. Meliopoulos, A.S.; Kokkinides, G.J. Substation Lightning Shielding and Risk Assessment. ETEP 2003, 13, 407–412. [CrossRef]
6. Cruz, F.A.; Sarramegna, S.; Taine, W.S. Lightning Risk Evaluation-Field Experience. In Proceedings of the ICLP 33rd Conference, Estoril, Portugal, 25–30 September 2016.
7. Abulaban, H.; Siow, C.L. Recent Progress on Lightning Risk Assessment and its Applications in Malaysia. Int Rev. Electr. Eng. 2021, 16, 41–49. [CrossRef]
8. Abulaban, H.; Siow, C.L.; Saleh, M.H. Lightning Risk Assessment of Selected Buildings in Cyberjaya: A Case Study. In Proceedings of the 2021 35th International Conference on Lightning Protection (ICLP) and XVI International Symposium on Lightning Protection (SIPDA), Colombo, Sri Lanka, 20–26 September 2021. [CrossRef]
9. Fathi, M.A.; Siow, C.L.; Pay, I.L. Development of a Template for the Risk Assessment for Lightning Protection System Design based on. In Proceedings of the 2018 34th International Conference on Lightning Protection (ICLP), Rzeszow, Poland, 2–7 September 2018. [CrossRef]
10. Hernandez-Guiteras, J.; Arevalo, L.; Hammarsten, H. Applicability of the Risk Assessment in International Standards to HVDC Converter Stations. In Proceedings of the 34th International Conference on Lightning Protection, Rzeszow Poland, 2–7 September 2018.
11. Ong, C.S.; Siow, C.L.; Ng, E.E. Lightning Risk Assessment on Outdoor HV Substations based on IEC 62305-2: A case study. In Proceedings of the 2021 IEEE 19th Student Conference on Research and Development (SCoReD), Online, Malaysia, 23–25 November 2021.
12. Norman, N. Most Athens Utilities Customers have Power; Warming Centers Open for Seniors without Power. 2022. Available online: https://www.rocketcitynow.com/article/news/local/athens-utilities-greenbrier-substation-damage/525-9e02036d-3589-4ba7-9e67-7137e712c496 (accessed on 5 March 2022).
13. Faulkner, J. Power Knocked Out to Thousands Following Severe Thunderstorms on Sunday. 2019. Available online: https://www.iheartradio.ca/bounce/nova-scotia/news/power-knocked-out-to-thousands-following-severe-thunderstorms-on-sunday-1.9495710 (accessed on 5 March 2022).
14. Parker, J.; Bugante, K. Power Restored After Lightning Strike Starts Fire at Broward FPL Substation. 2019. Available online: https://www.nbcmiami.com/news/local/fort-lauderdale-power-outage-broward-county/79852/ (accessed on 5 March 2022).
15. Valenzuela, B.E. Lightning Strike Causes 50,000 to Lose Power in Colton; Storms, Heat Cause Thousands of Others to Lower Power, Too. 2017. Available online: https://www.sbsun.com/2017/08/31/more-than-a-thousand-without-power-in-the-ie/ (accessed on 5 March 2022).
16. Nadauld, T. Major Power Outage Hits Moscow. 2017. Available online: https://dnews.com/local/major-power-outage-hits-moscow/article_17b82e7f-6309-5295-bb09-c486a53f7a1.html (accessed on 5 March 2022).
17. Murray, J. All Power Restored in Cape Girardeau Co., MO after Lightning Strikes Substation. 2017. Available online: https://www.kfvs12.com/story/35207276/all-power-restored-in-cape-girardeau-co-mo-after-lightning-strikes-substation/ (accessed on 5 March 2022).

18. Matlock, S. PNM: Worst Power Outage in 15 Years. 2016. Available online: https://www.santafenewmexican.com/news/local-news/pnm-worst-power-outage-in-15-years/article_9b66f8a8-bf44-51a4-86e9-bc0039c67d34.html (accessed on 5 March 2022).

19. IEC 62305–2: Protection against Lightning—Part 2: Risk Management. 2nd ed. IEC: Geneva, Switzerland, 2010.

20. Hileman, A.R. The Lightning Flash. In Insulation Coordination of Power System; Willis, H.L., Ed.; CRC Press Taylor & Francis: Boca Raton, Florida, USA, 1999; pp. 195–240.

21. Mousa, A.M. A Survey of Industry Practices regarding Shielding of Substations against Direct Lightning Strokes. IEEE Trans. Power Deliv. 1993, 8, 38–47. [CrossRef]

22. Orrell, J.T. Direct Stroke Lightning Protection. In Proceedings of the EEI Electrical System and Equipment Committee Meeting, Washington, DC, USA, 25 October 1988.

23. Love, E.R. Improvements in Lightning Stroke Modelling and applications to the Design of EHV and UHV Transmission Lines. Master’s Thesis, University of Colorado, Denver, CO, USA, 1973.

24. Mousa, A.M.; Srivastava, K.D. The Implications of the Electrogeometric Model regarding Effect of Height of Structure on the Median Amplitude of Collected Lightning Strokes. IEEE Trans. Power Deliv. 1989, 4, 1450–1460. [CrossRef]

25. IEC 62305–3: Protection against Lightning—Part 3: Physical Damage to Structures and Life Hazard. 2nd ed. IEC: Geneva, Switzerland, 2010.

26. IEC 60071–1; Insulation Co-Ordination—Part 1: Definitions, Principles and Rules. 9th ed. IEC: Geneva, Switzerland, 2019.

27. IEEE C62.82.1; Insulation Coordination-Definitions, Principles, and Rules. IEEE: New York, NY, USA, 2010.

28. Anderson, J.G. Lightning Performance of Transmission Lines. In Transmission Line Reference Book- 345 kV and Above; Electric Power Research Institute: Palo Alto, CA, USA, 1982.

29. IEEE 1410; Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines. IEEE: New York, NY, USA, 2010.

30. Chrisholm, W.A. Estimates of Lightning Ground Flash Density using Optical Transient Density. In Proceedings of the Transmission and Distribution Conference and Exposition, Dallas, TX, USA, 7–12 September 2003.

31. IEC 62858; Lightning Density based on Lightning Location System (LLS)—General Principles. IEC: Geneva, Switzerland, 2019.

32. Global Hydrometeorology Resource Center. High Resolution Full Climatology Map. Available online: https://ghrc.nsstc.nasa.gov/pub/lis/climatology/LIS-OTD/HRFC/browse/HRFC_COM_FR_V2.3.2015.png (accessed on 19 July 2016).

33. Hartono, Z.A. Thunderstorm day and ground flash density in Malaysia. In Proceedings of the National Power and Energy Conference, Bangi, Malaysia, 15–16 December 2003; pp. 217–219.

34. Abdul Kadir, M.Z.A. Lightning severity in Malaysia and some parameters of interest for engineering applications. Therm. Sci. 2016, 20 (Suppl. 2), 437–450. [CrossRef]

35. IEC 61936–1; Power Installations Exceeding 1kV a.c.—Part 1: Common Rules. 2nd ed. IEC: Geneva, Switzerland, 2010.

36. AS 2067; Substations and High Voltage Installations Exceeding 1kV a.c. 2nd ed. Standards Australia: Sydney, Australia, 2016.