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Adoption of IEC 62305 as the Basis for One Major U.S. Electric Utility's Lightning Protection Standard

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***Abstract*— Lightning protection systems designed for electric power generation facilities in the United States, by default, are typically designed according to the specifications of NFPA 780, as this is the governing lightning protection standard in this country. These facilities use the design guidance of this standard even though this standard explicitly states that electric generating facilities are excluded from its requirements. Justification for this exclusion is given in Annex A of NFPA 780 and states, "Most electric utilities have standards covering the protection of their facilities and equipment." Therefore, electric generating facilities have no guidance on how to implement lightning protection for their facilities. Duke Energy's Fossil Hydro Operations Division performed a one to one comparison of the NFPA 780 standard and the IEC 62305 international standard to determine which of these two standards best met the lightning protection requirements of its fleet of electric power generation facilities.**

Keywords*— *Lightning Protection, Standards, Electric Power Generation Facilities

I. Introduction

The purpose of a lightning protection system (LPS) is to provide an alternate and harmless path for lightning to travel to the earth. Knowing the stated purpose of a LPS, how is lightning safely and effectively channeled to earth? What guidance is provided on how to accomplish this task? Without an explicit LPS standard, the implementation of LPSs other than those recognized by the international scientific community and approved by the United States National Fire Protection Association (NFPA) or International Electrotechnical Commission (IEC) lightning protection standards becomes a real possibility. Such systems have been refuted by recognized lightning protection authorities, as documented by M. Uman and V. Rakov in "A Critical Review of Nonconventional Approaches to Lightning Protection", (American Meteorological Society, 2002), as being no more effective in the protection of structures or living beings from the effects of lightning than traditional LPSs.

In 1882, the Royal Meteorological Society convened a lightning rod conference to formulate the existing knowledge of atmospheric electricity for the protection of property from damage by lightning, as well as, to prepare and issue a general code of rules for the erection of lightning conductors in an effort to take action for the public. The Report of the Lightning Rod Conference (Symons 1882) provided the code of rules for those who installed lightning protection systems in Britain. Following the conference proceeding, the first British code for the protection against lightning was developed.

Up until this time no guidance was available in the United States for the design and implementation of LPS. There were no texts or standards. Finally, in 1904, following the British code, W. S. Lemmon, B. H. Loomis and R. P. Barbour (Lemon et al., 1904) prepared "Specifications for Protection of Buildings Against Lightning" which was adopted for American use by the National Fire Protection Association in Quincy MA and became the first official standard, issued as NFPA 78, for the design of LPSs. After years of periodic revisions, as more has been learned about the physics of lightning and with the advancement of technology, this standard is currently issued as NFPA 780:2017, the standard for the installation of LPSs in the United States. The scope of this standard provides requirements for a traditional LPS and list installations for which these requirements shall apply. Missing from this list of installations are electric power generation facilities. The current NFPA 780 standard excludes electric power generation facilities from its requirements with the assumption that most of these facilities have existing standards that address lightning protection. Standards, such as IEEE 998: "IEEE Guide for Direct Lightning Stroke Shielding of Substations", exist that address lightning protection for electrical substations; however, no other United States standard addresses lightning protection specifically for electric power generation facilities. Therefore, the electric power generation industry has been left to adopt either NFPA 780, another existing standard, or develop its own LPS standard.

Duke Energy’s Fossil Hydro Operations Division, when developing its lightning protection criteria for its latest electric generation facilities, researched and reviewed existing lightning protection standards for adoption of the one standard that would best serve its lightning protection requirements. Being knowledgeable of both the United States NFPA 780 and the international IEC 62305 standard, Duke Energy performed a one to one comparison of these two standards when considering which should be the basis of its lightning protection engineering standard. This paper examines Duke Energy's evaluation process of these two lightning protection standards for the selection of a LPS for its coal, gas, and hydroelectric generation facilities.

II. Design Philosophy

The 1997 edition of NFPA 780 states that "...lightning is a stochastic, if not capricious, natural process. Its behavior is not yet completely understood." Given the incomplete knowledge of the science of lightning, no LPS can be expected to be 100% effective. A system designed in compliance with any lightning protection standard does not guarantee immunity from damage as lightning is an issue of statistical probabilities and risk management. A system designed in compliance with a lightning protection standard should statistically reduce the risk to below a pre-determined threshold. Both NFPA 780 and IEC 62305 provide guidance on the design requirements of their respective LPSs, although these standards differ in their methodology for the implementation of such systems.

NFPA 780 is a single, stand-alone standard that provides lightning protection guidance defined by two classes of lightning protection which are based on the physical height of the structure being protected: Class I protection for structures 75 feet or less in height and Class II for structures greater than 75 feet in height. Based on these two classifications, each class is provided a table specifying the material requirements for the respective LPS class.

The IEC 62305 lightning protection standard was created by the European TC 81 Technical committee of the IEC and is composed of four individual parts:

IEC 62305-1 :	Protection Against Lightning- Part 1:General Principles
IEC 62305-2 :	Protection Against Lightning- Part 2: Risk Management
IEC 62305-3 :	Protection Against Lightning- Part 3: Physical Damage to Structures and Life Hazard
IEC 62305-4 :	Protection Against Lightning- Part 4: Electrical and Electronic Systems within Structures

IEC 62305-1 defines four levels of a LPS which are based on the electrical characteristics of an anticipated lightning flash. Corresponding to each lightning protection level (LPL) are four classes of a LPS (I, II, III and IV) defined as a set of construction rules and whose characteristics are defined in IEC 62305-3. Each set includes class-dependent (e.g. rolling sphere radius, mesh width etc.) and class-independent (e.g. cross-sections, materials etc.) construction rules. Each LPL is assigned a set of maximum and minimum lightning current parameters. The maximum values of the lightning current parameters for the different LPLs are given and used to derive the physical requirements of lightning protection components (e.g. cross-section of conductors, thickness of metal sheets, current capability of surge protection devices, separation distance against dangerous flash over). The minimum values define the lightning striking distance for each class of LPL.

Over time, the NFPA 780 standard has relied more and more on the IEC 62305 for guidance. Reference to the IEC 62305 standard is found throughout the NFPA 780 standard and is even referenced as an acceptable method for conducting a lightning risk assessment. References cited in the current edition of NFPA 780:2017 to the IEC 62305:2010 standard increased by 50% from the NFPA 780:2014 edition: an increase from 16 references in the 2014 edition to 24 references in the 2017 edition .

III. Risk Analysis

Whether or not a LPS is required, and if so, the extent of this system, is determined by the performance of a lightning risk analysis study of the structure being protected. The risk R that lightning damage occurs is the sum of all risk components relevant to the particular type of loss. The individual risk components R_x are derived from the following equation:

$$R_x = (N_x)(P_x)(L_x) \qquad (1)$$

where N_x is the number of dangerous events, that is, the frequency of lightning strikes causing damage in the area under consideration, P_x is the probability of damage caused by lightning, and L_x is the loss factor that is the quantitative evaluation of the damage incurred by the effects of lightning.

The frequency of lightning strikes can be ascertained from data obtained from the National Lightning Detection Network® (NLDN). From this system the ground flash density can be derived. As stated in M. Uman's The Art and Science of Lighting Protection, "The two most important and accessible factors in the analysis are the ground flash density and the equivalent collective area of the structure and its services ". Data gathered by the NLDN is invaluable in the development of the lightning risk analysis study.

A lightning risk analysis study is not a mandatory requirement of the NFPA 780 standard. Instead NFPA 780 includes its risk analysis procedure in Annex L, an informative document only and whose information is not a part of its requirements. Within this Annex, two methods are provided for the determination of lightning risk assessment: a simplified risk assessment and a more detailed risk calculation.

The simplified risk assessment takes a sampling of general information such as lightning flash density, the yearly annual threat of the occurrence of lightning, and the equivalent collection area of the structure to be protected to arrive at a tolerable risk of yearly lightning strike frequency. This calculated tolerable risk is compared to a default value of tolerable lightning frequency in the development of appropriate lightning protection measures. The detailed lightning risk calculation parallels, with some variations, the risk assessment methodology of the IEC 62305-2 standard.

Per IEC 62305-1, a risk assessment in accordance with the procedures contained in IEC 62305-2 shall be made in order to evaluate whether or not lightning protection of a structure is needed. IEC 62305-2 provides a lightning risk management procedure that incorporates a tolerable limit of risk and methods to calculate the actual risk. It then evaluates the protection methods required to reduce the actual risk to be equal or lower than the tolerable risk. The main goal of the risk assessment is to determine if lightning protection is required and, if so, to select the appropriate lightning class. The lightning class, based on the corresponding LPL, determines the minimum LPL that is used within the lightning protection design.

IV. SYSTEM DESIGN

The function of a LPS is to protect structures from both fire or mechanical damage and to protect living beings from injury or death. A complete, functional LPS consist of an external and an internal LPS. The external LPS consist of the following components:

- Air Termination System
- Down Conductor System
- Earth Termination System

The internal LPS consist of the following component:

- Surge Protection System

A. Air Termination System

The objective of the air termination system is to provide a prescribed path for lightning to safely follow to earth instead of randomly discharging into the ground. This can be provided through use of air terminals, free standing rods, catenary wires, and meshed conductors as described in both NFPA 780 and IEC 62305.

Placement of the air termination components on and around structures creates zones of protection which provide protection from direct and indirect lightning strikes. The zone of protection is defined through the use of either the rolling sphere method or the protective angle method.

The electrogeometric model recognizes that the attractive effect of the air termination system is a function of a striking distance which is determined by the amplitude of lightning current. The striking distance is the length of the final jump of the stepped leader as its potential exceeds the breakdown resistance of the last gap of air to ground and is defined by the radius of the imaginary sphere. The electrogeometric model relies directly on the assumption that a given lightning striking distance is associated with a unique first-stroke minimum peak current and is implemented by the rolling sphere method. The rolling sphere method involves rolling an imaginary sphere of a prescribed radius over the air termination network. Structures and equipment below the curved surface of the sphere are protected from a direct strike by virtue of the sphere being elevated by air terminals or other devices. Objects that touch the sphere or penetrate its surface are not protected.

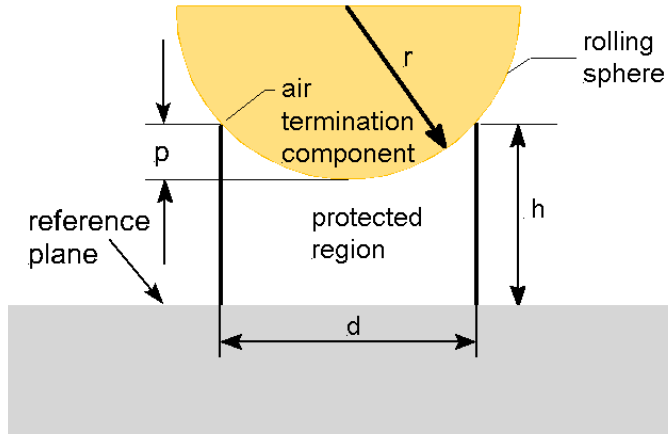

Fig. 1. Rolling Sphere Penetration Depth where:

r = radius of rolling sphere
d = separation distance of air termination components
h = height of air termination component
p = penetration depth of the rolling sphere

The rolling sphere penetration depth is calculated per the following equation:

$$p = r - \sqrt{r^2 - (d/2)^2} \quad (2)$$

where r is the rolling sphere radius (m) and d is the distance between the air termination components.

As described in NFPA 780, air terminations are positioned based on an imaginary sphere having a radius equal to 150 feet. An exception provided by the standard is structures containing flammable vapors, flammable gases, or liquids that can give off flammable vapors in which case the sphere radius is equal to 100 feet. A zone of protection is formed where the sphere is resting on two or more air termination surfaces and includes the space in the vertical plane under the sphere and between the contacting air terminations. This design philosophy is applied to all structures being protected from the effects of a direct lighting strike regardless of the asset value of the structure being protected.

Per IEC 62305-1, the rolling sphere radius is calculated per the following equation:

$$r = (10)(I^{0.65}) \quad (3)$$

where r is the rolling sphere radius (m) and I is the minimum peak current (kA) shown in Table I. The minimum values of lightning current amplitude for the different LPL are used to derive the rolling sphere radius of the electrogeometric model to define the spacing requirements of the lightning protection components in order to provide protection against a direct lightning strike as shown in Table I. The height of the air termination system above the structure being protected is determined by the LPL which specifies the radius of the rolling sphere. The height of the air termination system must always be greater than the penetration depth of the rolling sphere, as shown in Fig. 1, to ensure that the rolling sphere does not come in contact with the object being protected. Contact with the rolling sphere would place the object being protected within the lightning striking distance.

TABLE I. MINIMUM VALUES OF LIGHTNING AND RELATED ROLLING SPHERE RADIUS CORRESPONDING TO LPL

Interception Criteria		**LPL**			
Criteria	Unit	I	II	III	IV
Minimum Peak Current	kA	3	5	10	16
Rolling Sphere Radius	m	20	30	45	60

The protective angle method is a derivative of the rolling sphere method. This method approximates the protected regions defined by the rolling sphere method to heights that are equal to or less than the corresponding rolling sphere radius. However, a problem exist with this method in that the rolling sphere penetrates into the presumed protected area posing a risk in that what was once considered protected is now at risk of a direct lighting strike as shown in Fig. 2 where r is the rolling sphere radius and α is the protective angle.

The protective angle method as described in NFPA 780 prescribes two protective angles; 45 and 63.4 degrees depending on the height of the structure being protected as shown in Fig. 3.The height of the air termination utilized in IEC 62305-3 is a function of the protection angle which is defined by the Class of LPS, the spacing between the air rods and the height above a particular reference plane. Placement of air terminal per IEC 62305-3 is a function of LPS class as shown in Fig. 4.

B. Down Conductor System

The down conductor system consist of electrical conductors positioned on a structure in such a way as to safely conduct the lightning current to the earth termination system while also limiting the risk of flashover to other electrical conductive elements.

NFPA 780 requires a minimum of two down conductors with spacing such that the average distance between all down conductors along the perimeter of the structure being protected does not exceed 30 meters. IEC 62305 specifies down conductors be arranged in such a way as to reduce the probability of damage due to lightning current flowing in the LPS. The number of down conductors shall be not less than two and shall be equally spaced around provided in Table II.

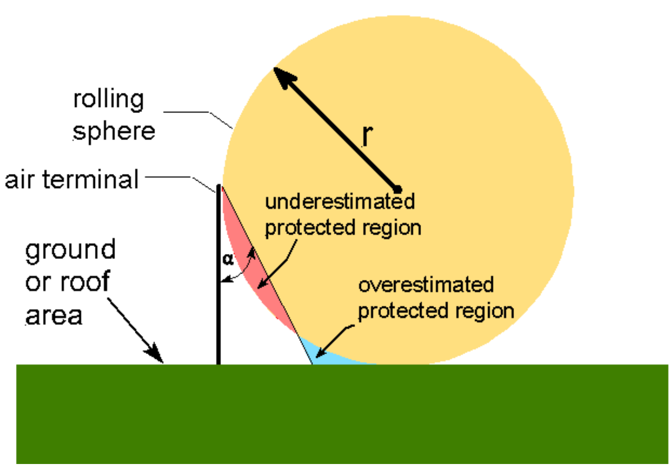

Fig. 2. Protective Angle Method Limitation

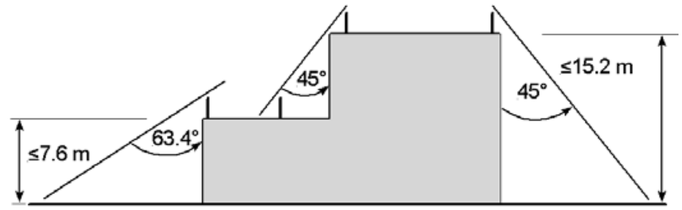

Fig. 3. Protective Angle LPS method per NFPA 780.

C. Earth Termination System

The main task of the earth termination system is to:

- Efficiently dissipate the lightning surge energy conducted via the down conductors of the LPS
- Efficiently dissipate electrical surges and faults in order to minimize the possibility of human injury from either "step potentials" or "touch potentials"
- Properly bond electrically conductive components to provide an equipotential plane under lightning strike conditions

The earth termination system is comprised of either a bonded system of earth electrodes or a ring conductor that encircles the structure being protected. Both designs are specified by the NFPA 780 and IEC 62305-3 standards. The NFPA 780 earth termination system is dimensioned and designed per applicable clauses while the earth electrode and ring conductor designs, as described in IEC 62305-3, are based on the class of LPL as shown in Fig. 5. Ring conductors, per IEC 62305-3, shall have a radius (re) of distance re $\geq l_1$ where l_1 is represented in Fig. 5 according to LPS class I, II, III and IV.

NFPA 780 specifies, based on the height of the structure being protected, that grounded metal bodies shall be bonded to the lightning protection system where located within a calculated bonding distance, D, as determined by the following equation:

$$D = h/6n + K_m \tag{4}$$

where D is the calculated bonding distance, h is the vertical bonding distance between the LPS and other conductive components, n is a pre-determined number relating to the number of down conductors, and K_m is a number related to the flashover medium insulation.

TABLE II. IEC 62305-3 RECOMMENDED DOWN CONDUCTOR SPACING

Class of LPS	**Typical Distances (m)**
I	10
II	10
III	15
IV	20

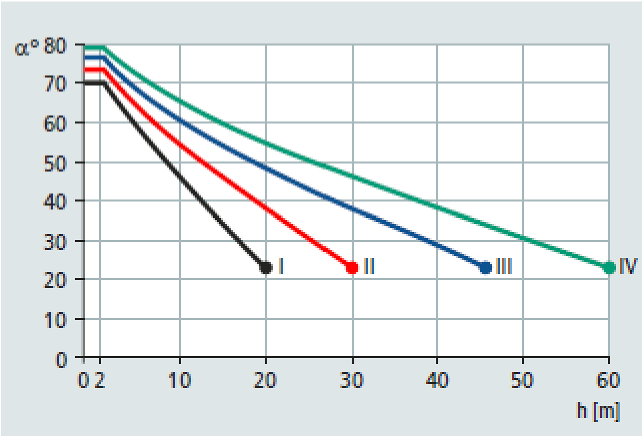

Fig. 4. Protection angle α corresponding to the class of LPS as a function of height h of air termination above the reference plane. Adapted from DEHN Lightning Protection Guide.

The IEC 62305-3 standard provides a similar equation, but an equation that relates to the class of the LPS:

$$s = (k_i)(k_c/k_m)(l) \tag{5}$$

where k_i depends on the selected class of LPS, k_m is related to the flashover medium insulation, k_c depends on the lightning current flowing on the air termination and down conductor, and l is the length (m) along the air termination and the down conductor from the point of separation being considered to the nearest equipotential bonding point or earth termination. Values of k_i, k_m, and k_c are provided in applicable tables within IEC 62305-3.

D. Surge Protection

When lightning attaches to a power or signal line or induces voltage on these lines by a nearby lightning strike, a lightning electromagnetic impulse (LEMP) is generated on the lines creating an overvoltage and/or overcurrent referred to as a surge. Even though lightning accounts for a small fraction of transient voltages, its effects are far greater than those caused by other sources of transient voltage. To protect a structure from lightning induced transient voltages, lines entering a structure must be equipped to protect structures and persons from the devastating effects of lightning. Lightning electromagnetic impulse protection measures (SPM) must be implemented to limit transient voltages by diverting or by limiting surge current. SPM must also be capable of repeating these functions as specified. Protection against LEMP can be considered one of the most important components of a LPS. IEC 62305-2 notes that if it is determined from the lightning risk analysis study that an air termination system is not require, that as a minimum , protection against LEMP must be provided through the application of SPM systems.

NFPA 780 requires that protection against LEMP be provided for all power service entrances as well as entrances of conductive communications and antenna systems by means of surge protective devices (SPD). NFPA 780 provides

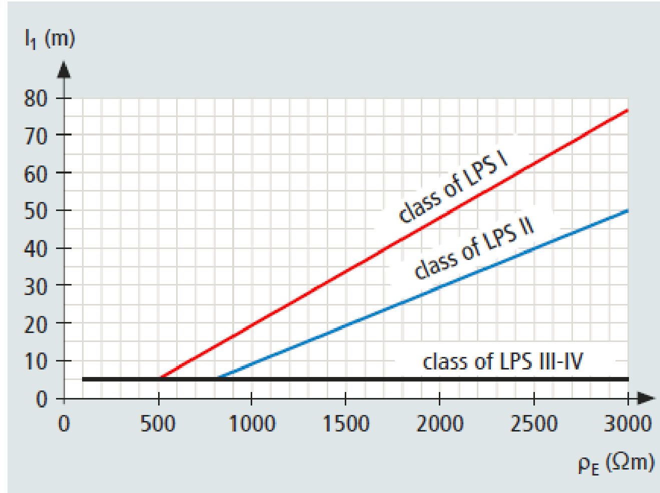

Fig. 5. Minimum length of each electrode according to the class of LPS. Adapted from DEHN Lightning Protection Guide.

an exception to this requirement by stating that SPDs shall not be required where, under engineering supervision, it is determined that the surge threat is negligible or that the lines are equivalently protected or where installation of SPDs compromises safety. The standard recognizes that there can be acceptable exceptions and consequently allows for such exceptions to the requirements for surge suppression on electrical utility, data, and other signal lines, provided a competent engineering authority has determined that the threat is negligible or that the system is protected in a manner equivalent to surge suppression. Determinations made by an engineering authority for exempting installation of SPDs should focus on the likelihood of lightning activity in the region, the level of damage that might be incurred, and the potential loss of human life or essential services due to inadequate overvoltage protection. If SPDs are determined as a requirement, SPDs shall protect against surges produced by a 1.2/50µs and 8/20µs combination waveform. SPDs protecting service entrance electrical lines shall have a nominal rating of at least 20kA, 8/20µs per phase. Signal, data, and communications SPDs shall have a maximum discharge current rating of at least 10kA, 8/20µs when installed at the entrance.

Protection from lightning generated transient voltages per IEC 62305-4 is based on the lightning protection zone (LPZ) concept in which the zone containing systems to be protected shall be divided into LPZs (Fig. 6). These zones are assigned part of space where the LEMP severity is compatible with the withstand level of the internal systems enclosed. Successive zones are characterized by significant changes in the LEMP severity. One method recommended for protection against LEMP is the establishment of a coordinated SPD system. An SPM system using a coordinated SPD system alone is only suitable to protect equipment which is insensitive to radiated magnetic fields. If protection of equipment sensitive to radiated magnetic fields is required, then an SPM system employing spatial shields and a coordinated SPD system will

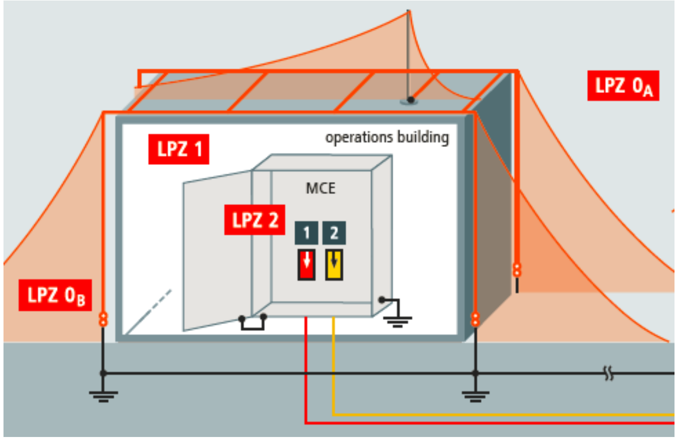

Fig. 6. Lightning Protection Zone concept. Adapted from DEHN Lightning Protection Guide.

protect against radiated magnetic fields and against conducted surges. SPDs specified by IEC 62305-4 shall protect against surges characterized by a 10/350µs and 8/20µs waveform. The purpose of the 10/350µs waveshape is not intended to represent the lightning discharge, but instead, is intended to evaluate the ability of a device (SPD, conductor, component within a LPS, etc.) to handle large energy depositions, comprising the elements of: charge, peak current and time. The 10/350µs waveshape is used within IEC standards when a conductor, (or SPD), is expected to carry direct or partial lightning currents when the SPD serves as an equipotential bonding device. This waveform is applied to those SPDs that are installed at the line entrance into the structure. All other SPDs in a coordinated SPD system are rated for an 8/20µs waveform.

The IEC 62305-4 standard takes the worst case approach to the sizing of the SPDs such that when no specific calculation of current sharing amongst conductors is carried out, a general assumption is made that 50% of the lightning current is injected into the local ground and 50% returns via the equipotential bonding SPD(s). For SPD selection, the injected current is determined from the maximum current relating to the class of LPS. SPDs installed at the line entrance into the structure and subject to the effects of direct lightning strikes shall be rated at 50% of maximum current rating of the class of LPS as shown in Table III.

TABLE III. LPS CLASS MAXIMUM CURRENT RATING

Class of LPS	**Total SPD Surge Current (waveform = 10/350µs)**
I	100 kA
II	75 kA
III	50 kV
IV	20 kV

V. CONCLUSION

Having completed the detailed analytical comparison of the NFPA 780 and IEC 62305 lightning protection standards, it was apparent to Duke Energy that the IEC 62305 standard provided a superior lightning protection system for Duke Energy's electric power generation facilities. The NFPA 780 standard is defined as a constructive approach to lightning protection design by specifying a lightning protection system as a function of the geometry of the structure being protected whereas the IEC 62305 suite of standards relies on the current understanding of the electrical characteristics of lightning and the latest technological advances, such as the NLDN. The IEC 62305 standard, as is the NFPA 780 standard, is recognized by UL as an inspection standard that qualifies for the UL Master Label Certification Program so long the LPS is installed by a UL certified installer and passes a UL inspection by a UL lightning protection inspector.

Ultimately it is desired that this paper will lead to a dialog on the need for a specific lightning protection standard, based on the IEC 62305 standard, for electric power generation facilities, much like the IEEE 998 lightning protection standard for electric substations. By adoption of the IEC 62305 as the basis for its lightning protection standard, Duke Energy has taken the initiative within the U.S. electric power industry of providing a lightning protection system which will provide the needed protection from the destructive effects of lightning and which shall enhance its ability to continue delivering safe, reliable, economic electric power to its customers.

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