The Impact of Electrical Standards on MVDC Shipboard Power Cable Size

by

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Abstract

In recent years there has been rising interest in medium voltage direct current (MVDC) power systems for several reasons, including compatibility with DC loads, reduction of induced currents and magnetic signatures, and avoidance of alternating current (AC) frequency synchronization issues when combining outputs from multiple sources [1]. However, few MVDC systems are currently in operation, and little is known in terms of design and test parameters in comparison to the vast wealth of knowledge available for medium voltage alternating current (MVAC) systems. There is currently only one standard governing MVDC applications, the Institute of Electrical and Electronics Engineers (IEEE) Standard 1709, recommendations for shipboard MVDC systems [2].

The goal of this study is to provide recommendations for shipboard MVDC power cable design and test values, and to examine how existing MVAC and MVDC standards affect MVDC cable size. A review of published standards and guidelines for MVAC cable design and test values is made and includes the collection of recommended lightning-impulse Basic Insulation Level (BIL), the short-duration overvoltage Withstand Voltage Test and cable insulation thickness values. The collected MVAC cable design and test values are compared to each other as well as to the sole MVDC standard in order to provide more informed suggested MVDC cable design and test values as well as MVDC cable sizing. It was found that there is a tradeoff with the thickness of cable insulation, where a small reduction in cable system size can be achieved by a reduction in insulation thickness but at a penalty of substantially greater electric stresses within the insulation. The collected results provided a basis for a proposed MVDC cable design process and for example shipboard MVDC cable systems with layouts, rated for 75, 100, and 125 [MW] power levels, and 12 and 18 [kV] Nominal System Voltages.

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1.0 Definitions

For this study, the following terms and definitions apply. All terms are defined according to IEC Standard 60071-1 and IEEE Standard 1313 [3] [4].

Basic Lightning Impulse Insulation Level (BIL) – Dielectric strength of insulation expressed in terms of the crest value of a standard lightning impulse under standard atmospheric conditions.

Cable Nominal Voltage (U_o) – Suitable approximate value of voltage used to designate or identify a single cable within a system. For AC systems U_o is the phase-to-ground RMS voltage, for DC systems U_o is the line-to-ground voltage.
Note: The symbol U_o is used within IEC standards with the above definition and no associated term, 'Cable Nominal Voltage' is used to refer to this voltage for this study.

Highest Equipment Voltage (U_m) – Highest value of phase-to-phase RMS voltage (AC) or line-to-line operating voltage (DC) for which the equipment is designed in respect of its insulation and other characteristics which relate to this voltage in the relevant equipment standards.

Insulation Co-ordination – Selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and considering the service environment and the characteristics of the available preventing and protective devices.

Nominal System Voltage (U_n) – Suitable approximate value of voltage used to designate or identify a system. For AC systems U_n is the phase-to-phase RMS voltage, for DC systems U_n is the line-to-line voltage.

Nominal Peak Cable Voltage (U_p) – Suitable approximate value of peak voltage used for a single cable within a system. For AC systems U_p is the phase-to-neutral peak voltage, for DC systems U_p is the of line-to-neutral voltage.

Rated Insulation Level – Set of rated withstand voltages which characterize the dielectric strength of the insulation.

Root Mean Square (RMS) – For AC systems, RMS is the square root of the mean square of the voltage.

Standard Insulation Level – Set of standard rated voltages which are associated to U_n as specified in this paper.

Standard Lightning Impulse – Impulse voltage having a front time of 1.2 [µs] and a time to half-value of 50 [µs].

Standard Withstand Test – Dielectric test performed in specified conditions in the relevant standard to prove that the insulation complies with a standard rated withstand voltage. These tests include Withstand Tests, switching impulse tests, lightning impulse tests, combined switching impulse tests, and combined voltage tests.

Withstand Voltage (U_w) – Value of the test voltage, applied in a standard Withstand Test that proves the insulation complies with one or more required withstand voltages. For AC systems this value is phase-to-ground RMS, for DC systems this value is line-to-ground.

2.0 Introduction

The U.S. Navy (USN) is developing future ship classes that will have considerably larger electric power requirements than current vessels due to electric propulsion and high-load reconnaissance and weapon systems. The proposed designs call for a system with a medium voltage direct current (MVDC) bus, which is currently being researched for both naval and terrestrial applications. MVDC cables are being evaluated over the widely used MVAC cables based on studies that have found the following benefits of MVDC systems: compatibility with DC loads, better reliability and survivability of power due to dynamic reconfigurability, compatibility with electronic weaponry, and reduction of induced currents and magnetic signatures [1]. Additionally, future warships will likely use 4-cable (2 pairs of +/- conductor pairs) groups with direct current (DC) for further magnetic signature reduction [5].

Currently, a potential Nominal System Voltage for a shipboard MVDC is 12 [kV] obtained with +/- 6 [kV] cables. This voltage level is the main focal point of this study, with some additional evaluations conducted at 18 [kV] via +/- 9 [kV] [5].

One of the major barriers faced in the design of this future ship class is the novelty of the system. The knowledge and experience with MVAC systems throughout the world far outweighs that of MVDC systems, especially in the marine environment. To date there is only one active standard from a technical authority for shipboard MVDC systems, IEEE 1709 Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships [2]. This lack of knowledge and experience in shipboard MVDC systems, coupled with the global lack of experience for MVDC power systems drives many questions. The specific gap in knowledge this study will address; how can we determine appropriate cable and insulation sizing for these systems, and do test voltages such as BIL affect the insulation thickness of MVDC cables? While evaluating the full range of Medium-Voltage standards and references, this study will examine a 12 [kV] Nominal System Voltage Cable system, as this is a possible system voltage for future warships [5].

The determination of insulation thickness is additionally complicated in the medium voltage (MV) regime by standards that set insulation thickness values according to conductor diameter, voltage, and protection conditions. In contrast low-voltage cable thicknesses are set by individual application according to parameters such as heat dissipation, BIL, or mechanical wear and protection requirements. In the MV regime cable thicknesses are established more by high voltage insulation requirements, thus while variable thickness of insulation may be a possible solution for future MV power systems, the present recommended practice of fixed, discrete insulation thickness values will be used for this analysis.

There are some factors related to the differences between MVAC and MVDC cables that are not addressed in this study. Example possible differences between MVDC and MVAC cables that could result in different insulation materials and thicknesses for MVDC cables are partial discharges and space charge accumulations, both of which could shorten the cable's service life and lead to the need for thicker cable insulation [6].

The first step taken for this study is to evaluate the twelve existing shipboard and terrestrial standards for the MV range for AC systems, standards for high voltage terrestrial DC systems, as well as the IEEE standard for shipboard MVDC. From these standards the prescribed levels of cable sizing and protection, in terms of lightning impulse voltage (BIL), Withstand Test Voltage (U_w), and insulation thickness are compared. This comparison showcases the difference in prescribed protection levels of the existing AC shipboard standards and illuminates possible connections between the thoroughly developed MVAC standards and sole MVDC standard. The goal of this study is to produce recommendations for cable sizing for a range of shipboard MVDC voltage classes based on the conductor size, BIL, Withstand Test Voltage, insulation thickness, and electric stress. It will be seen that because cables used in MV systems have relatively highly defined dimensions due to various standards the physical size and space requirements are relatively well defined and constrained independent of test voltages.

One outcome from the analysis of existing standards is a calculation of minimum cable bus corridor dimensions according to voltage class and total power capability. Based upon existing MVAC standards and the MVDC standard this study also provides recommended MVDC cable design and test values according to voltage class.

2.1 Standards Essential for Compatibility and Reliability

Evaluating and comparing standards is the basis of this study, as they represent the compiled knowledge and experience from a diverse group of experts in the field. Different groups of experts from various locations around the world have each produced standards, which are generally in agreement and compatible with one another. Frequently they are not identical, with relatively small deviations in values or differences in specified values. These differences will be identified in this report. These standards provide a baseline for compatibility between manufacturers, ensuring that consumers have a reference point and confidence in the product. Comparing the standards from multiple national and international governing bodies allows this study to identify a range of generally accepted design and test values for MVAC cables, and the test values from the MVDC standard to have a basis for recommendations for MVDC cable design and test values.

2.2 Lightning Events on Ships

Cable size is impacted by insulation thickness, and one of the factors in determining insulation thickness is an adequate tolerance to the expected amount of stress from a lightning event. Therefore, a discussion of lightning events on ships is warranted.

As with land-based systems, shipboard electrical systems need to be protected against the intense event of a lightning strike. A study assessing the U.S. codes for lightning protection of boats found that off the coast of Florida ~3% of moored boats were struck by lightning per year [7]. While this statistic varies due to many factors such as the geographic region in question, it illustrates that the extreme event of a lightning strike on a ship must be protected against.

Land-based lightning protection practices cannot be directly applied to shipboard systems. The consequences of a system outage due to a lightning event for a land-based system are likely less severe than a shipboard system. Ships are unable to conduct most repairs at sea and rely on all on-board systems for the safety of the crew and ability to complete its mission. Additionally, a study found that lightning appears to be more intense (having a higher peak current) over the ocean than over land due to the high electrical conductivity of sea water [8]. Other studies expand on this, emphasizing that sea water acts as a "near-perfect" conductor allowing lightning events to propagate with almost negligible attenuation of amplitude and frequency [9]. "The ratio between the peak electric fields at 5 km from the lightning channel, after fields propagate over dry soil and over sea water is 0.75. The ratio between the peak electric field derivatives under the same conditions is 0.1" [9]. The study also found similarly small ratios for magnetic fields and their time derivatives [9]. The increased intensity of lightning events over the ocean, coupled with the decreased attenuation compared to land-based systems makes shipboard systems more vulnerable to damage from lightning.

While Navy warships are generally constructed entirely of metal, this does not mean that they are inherently protected from lightning events. The study "Electric Ship Surge Environment" evaluates the threat of lightning events on warships similar to that evaluated within this study (metal warships that are powered and propelled electrically), evaluating the guidance available within the IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits, and Department of Defense

Interface Standard - Electromagnetic Environmental Effects Requirements for Systems (MIL-STD-464) [10] [11] [12]. "Electric Ship Surge Environment" discusses three different lightning events and how they could affect an electric warship:

- Direct strikes, that couple directly with the superstructure or exposed wiring. Typically, this causes the most severe surges imposing high stresses on the system and components. Direct strikes can also cause mechanical damage from the thermal stresses. Additionally, the surge can affect nearby electrical circuits "through mutual resistance, capacitance and/or inductance of the circuits", potentially interfering with equipment such as communications or control equipment [10].
- Near strikes, lightning striking the sea close to the ship that does not necessarily directly couple with the ship's power system, but can create a surge through magnetic, capacitive, or inductive coupling with the power system. The surges seen by this type of strike are typically a fraction of the direct strike [10].
- Far strikes, lightning strikes the sea at a considerable distance from the ship. Affects are further reduced from the near strike; surges are significantly smaller in magnitude. "However, repeated events may still cause disruption, deterioration or cumulative damage to sensitive electrical and electronic circuits over time" [10].

This study also addresses the difference between shipboard and land-based lightning protection, specifically for electric ships. It states that electric ships are more compact and typically have lower impedance than land-based systems, and this lower impedance coupled with the large amount of electrical power produced on the ship creates a much higher available short-circuit current [10]. Additionally, as the power generated on an electric ship is much closer to the loads of the system compared to land-based electrical power generation counterparts, the propagation of surges within system is more [10].

These studies have shown that ships have a statistically significant chance of a lightning event occurring, that could cause damage in numerous ways. Protection against such an event is considered in cable design, as the cable insulation thickness must be adequate to endure such events without a high risk of failure.

2.3 Literature Review of MVDC Cables

While there are a substantial number of recent articles concerning possible advantages of MVDC systems, until now relatively few systems have been constructed or planned [1] [5] [13]. MVDC cables are far from common in any application, with only a few systems currently utilizing them to include shipboard, railway, and distribution systems [13]. There is growing discussion for the increased use of MVDC cables due to the benefits listed in §2.0, to include offshore renewable power systems [13]. The data currently available for these existing systems is sparse, and many design and test values of existing MVDC cable relevant to this study were not able to be ascertained (e.g. cable size, or test voltage levels).

For shipboard applications, the company ForSea converted 2 diesel ferries into battery-powered vessels with 4.16 [kWh] DC power buses in 2018 [14]. It is stated that the vessels charge at 10 [kV], however, the specifications of the vessels internal power system are not available within the public domain [14]. Additionally, Kongsberg launched the 7 [MWh] autonomous battery-powered container ship the Yara Birkeland on 18 November 2021, and while it is stated to be battery-powered it is also not explicitly stated to be MVDC [15].

MVDC railways have few systems in operation, including the London Underground, the Bordeaux-Hendaye intercity line, and the Paris-Strasbourg high speed line [13]. These railways operate on the low end of the MVDC spectrum, <3 [kV] [16].

Terrestrial power transmission systems commonly use HVDC power lines, however, some MVDC links have been implemented to connect distribution grids [17]. The designing and planning of MVDC some distribution systems is under way for multiple cities in China, as well as model projects such as the English Angel DC Project and the German E.ON project [13] [18]. An example of MVDC distribution technology is the MVDC PLUS system produced by the company Siemens [19].

There are currently no MVDC offshore renewable energy systems, however, there has been numerous studies on the advantages of using an MVDC storage systems, such as the Siemens MVDC Plus [13] [20].

As more MVDC systems are brought online and the global experience grows, improved MVDC cable design and test values will be determined. Until such point, this study will evaluate the test values given in the sole MVDC standard and compare the range of design and test values from MVAC standards to provide prospective MVDC design and test values.

3.0 Elaboration on Terminology within Evaluated Standards

The following sub-sections elaborate on the terminology within evaluated standards used within this study. The purpose of this discussion is to provide the reader with background knowledge on the operational and test voltages, types of tests, and cable characteristics of MV system components (including cables) used throughout the electrotechnical community. These sections are not all-encompassing, but rather are especially concerned with a more thorough explanation of the terms relevant to the topic of MVDC systems.

3.1 Nominal Operating Voltage

The nominal operating voltage, often referred to as the Nominal System Voltage (U_n), is the suitable approximate average value of a system voltage that is used to identify the system. This value is approximate due to systems being non-ideal and having fluctuations in voltage level over time. For AC systems U_n is in terms of phase-to-phase RMS voltage, for DC systems U_n is in terms of line-to-line voltage. Systems designed in accordance with IEC and IEEE standards are designed by established voltage classes of nominal operating voltage to ensure all components will function properly and be held to the appropriate technical standards for quality and safety. A system being designed to a specific voltage class will not necessarily have the exact voltage of that class, but it is expected to be relatively close (e.g. a 6 [kV] class system is likely within +/- 0.5 [kV] of 6 [kV]).

3.2 BIL Tests

The Basic Insulation Level of a system is the impulse voltage level a system is designed to withstand, based on the expected transients the system would see due to a lightning event. The experienced transients a system will see are dependent on many factors including the size of conductors within the system, the presence of a path to ground and the resistance along that path, the location of the electronics and electrical equipment within a structure, the material the structure is made of, and so on. In short, estimating the expected transients and impulses within a system is an extremely complex problem. To date this lighting impulse has been modeled, according to both IEEE Standard 4 and IEC Standard 60060-1, by 1.2/50 impulses [21] [22]. These “1.2/50” values correspond to the time in microseconds an impulse takes to rise to its maximum voltage and fall to 50 % of that maximum voltage value (shown as T1 and T2 in Figure 1 below) [21]. The number of impulses applied for testing ranges from 3-15 of each polarity, depending on the standard in question. While this modeling of lighting impulses has been the standard for decades, the accuracy of the model was verified in 2016 in a doctoral dissertation. “It should be noted that the observed form of overvoltages with intense polarity variations and oscillations is far from the 1.2/50 [μs] waveform which - in the field of electromagnetic compatibility tests - simulates slow transient phenomena of high energy content. However, the appearance of the maximum peak at a time of 1-2 [μs], the double-exponential shape of the envelope and the fact that the total energy of the pulse approaches the energy transferred from a double exponential pulse, make the application of the 1.2 / 50 [μs] waveform a satisfactory approach” [23].

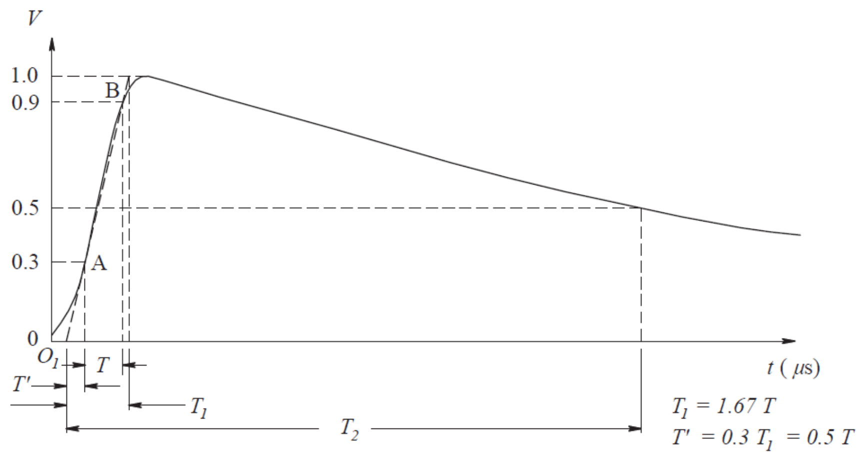


Figure 1: Lightning Impulse Model Waveform [21]

The BIL that a system is rated for refers to the peak voltage of the impulse waveform, explicitly the peak phase-to-ground voltage of the impulse. BIL is designed as overall system property, taking as many factors of the construction and design of the system into account as possible. While this rating applies to an entire electrical system, it is noteworthy that not all equipment is designed to withstand the full BIL voltage (e.g. motors). Any equipment that is not rated for the system BIL must be appropriately protected with surge arrestors or other protection methods. Within existing medium voltage cable standards, the BIL is governed by voltage class of the system (phase-to-phase RMS voltage for AC systems, line-to-line voltage for DC systems).

3.3 Withstand Tests

Withstand Tests are another means of ensuring the safety and reliability of a power system, applicable to both AC and DC systems. The premise of this test with respect to cables is to subject them to an applied overvoltage level for a defined limited-duration period so that a failure during the Withstand Test would expose any significant defects or damage to the cable and insulation. The type, magnitude, frequency, and duration of the withstand voltage (U_w) applied is dependent on the standard applied.

Historically the use of a DC withstand voltage has been prevalent for MVAC cable applications, with U_w being the line-to-ground test voltage. Some of the references evaluated in this paper recommend using a DC voltage for U_w, however, recent studies have shown that using a DC voltage to test a cable normally used for AC applications can cause damage to the cable insulation via buildup of space charges. Additionally, using a DC U_w, where there is no time variation to the applied electric field, does not readily induce the inception of partial discharges at defect sites within the cable insulation, which then cannot be detected. All this considered, DC Withstand Tests are still effective for detecting certain types of insulation defects and are still recommended by some technical authorities [24].

The use of AC withstand voltages is an alternative to prevent the issues with a DC U_w. The constantly changing polarity of AC voltages does not allow for the buildup of space charges at cable insulation defect sites. This characteristic allows for the detection of defects in the cable insulation, while preventing damage to cables normally used for AC voltages [24]. Most cable testing standards recommend AC U_w, in terms of phase-to-ground RMS voltage.

Within AC Withstand Testing, there are two main frequencies recommended: typical AC system frequencies (48-62 [Hz]), and very low frequency (VLF) (<0.1 [Hz]). Each frequency for U_w has its benefits and drawbacks, such as VLF requiring less power for testing, and there are current standards that contain recommendations for both types [24]. The standard AC waveshape of U_w is shown in Figure 2 below, where frequency ‘f’ has typical values of 48-62 [Hz] (AC system frequency) or 0.1 [Hz] (VLF), and duration of the test ‘T_t’ has a range of values from 1 [min] to 24 [hr] depending on the standard in question.

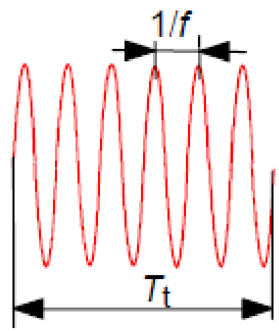


Figure 2: Withstand Voltage Model Waveform [4]

3.4 Medium Voltage

Medium voltage refers to a range of operating voltages for electrical systems, however the voltage range for systems considered to be medium voltage (MV) is far from clear. There are some papers that suggest the upper limit of MV is 52 [kV], however looking at papers dealing with MV equipment and companies advertising their products as MV, the upper limit appears to be 38 [kV] [25]. From the viewpoint of electrical standards from the IEEE and the IEC, there is concurrence that MV ranges from 1-38 [kV] [2] [26]. For this paper MV will be considered to be 1-38 [kV].

In addition to the ambiguity in the range that the title medium voltage applies to, there are different constraints and recommendations for MV voltages compared to other voltage ranges that must be considered. One of which is that cable companies and standards have adopted fixed insulation thicknesses based on the conductor diameter, the Nominal System Voltage (U_n), and the expected ground fault clearing time (often expressed as a percent increase). This third quantity by convention has 3 levels if expressed as a percentage: 100% (to be used in systems where ground faults will be cleared within 1 [min]), 133% (to be used in systems where ground fault clearing times exceed 1 [min] but are less than 60 [min]), and 173% (to be used in systems where ground fault clearing times exceed 60 [min]) [27] [28] [29]. If not expressed as a percentage, ground fault clearing time is either given as a time or not at all. Within all evaluated references insulation thickness for a given Nominal System Voltage and percent insulation level was constant for conductor diameters within the range of 8.25-25.4 mm (AWG 1/0-1000 kcmil). This is opposed to high voltage cable insulation thickness which are based on practicality and experience in engineering and manufacturing, and low voltage cable insulation thickness which considers the physical failure modes the cable insulation may experience.

3.5 Test Categories

The parameters of a test outlined by each reference depend on where the cable is in its lifecycle. The definition of each test can differ between standards. For this study, the definitions of the different test categories are as follows:

1. Type Test. A type test is a test conducted once at the production facility for a family of cables, completed before supplying the cable, to demonstrate satisfactory performance characteristics.
2. Acceptance Test. Often referred to as routine tests or factory tests, acceptance tests are made at the production facility on each completed length of cable to verify specifications are met.
3. Post-Installation Tests. Conducted after a cable is installed in its intended system to verify the integrity of the cable and accessories before placing them into service.
4. Maintenance Test. Maintenance Test. Conducted after extended time in service and used to verify expected failure-free continued service.

3.6 Test Parameters

The parameters that influence the selected BIL or Withstand Voltage test are extensive. The parameters discussed in this study include:

1. The system in which the cable is intended to be/is installed. For this study, this variable is either land-based or shipboard systems.
2. System voltage type. Either AC or DC, type of voltage of the system in which the cable is intended to be/is installed.
3. Test voltage type. Specific to Withstand Voltage Tests, the type of voltage to be applied for the test (either AC or DC).
4. Number of impulses. Specific to impulsive tests (such as BIL testing), the number of applied impulses at the specified voltage level.
5. Duration. Length of time a continuous test voltage is applied to the cable being tested.
6. Cable Length. The length of the testing specimen, being either the entire cable or a sample.
7. Test Category. The type of the test being conducted, being either type, acceptance, post-installation, or maintenance.
8. Cable temperature. Temperature at which the cable is held or pre-conditioned to for the test, typically either ambient or within a specified tolerance of the maximum rated temperature of the cable.

3.7 Cable Characteristics

All references studied in this work are applicable to shielded cables with copper conductors, and cross-linked polyethylene insulation (XLPE). These cable materials and property are considered constants for this study. Individual reference applicability to other cable properties and materials varies. As discussed later alternate XLPE cable insulation material selection or modification may be required in the case of DC voltages due to changes in possible failure mechanisms.

4.0 BIL Test Analysis

This section concerns the tests established in the evaluated references for BIL tests based on a system voltage. The BIL tests are compiled and compared to establish the range of BIL deemed acceptable for a given Nominal System Voltage by the various international committees. Additionally, this study aims to determine if MV cable sizes are influenced by the BIL and Withstand Test Voltages through required insulation thicknesses. Of note, no evaluated reference provides an insulation thickness based on the BIL, indicating that insulation thickness is not necessarily dependent on BIL. However, as will be shown, the standards imply a linkage between BIL and the insulation thickness, as the prescribed increases of insulation thickness and test voltage levels occur at the same Nominal System Voltage.

Of the parameters discussed in §3.7 for BIL tests, duration is considered constant with the duration per impulse defined in §3.2, and test voltage type is not relevant to BIL tests.

Among the references evaluated, three are applicable to DC power cables. Two of which are applicable to high voltage land-based systems (CIGRE TB 496 and IEC Std. 62895), the other to shipboard MVDC (IEEE Std. 1709). CIGRE TB 496's and IEC Std. 62895's recommended procedures contain an important distinction from other references tests on AC cables, as they call for the cable being tested to have an operational voltage applied during testing and the BIL impulse to be superimposed on top of this voltage.

This section evaluates the recommended design BIL of these DC references along with the well-established standards and recommendations for MVAC cables. This is accomplished through the following three subsections:

1. Standards and Recommended Practices. Presented data for BIL exactly as they appear in the corresponding reference.
2. Consolidation of Reference Data. Presented each reference BIL compared to a common voltage type, along with generated continuous polynomial trendlines approximating BIL as a function of system voltage.
3. Comparison of Standards and Recommended Practices. Using the common system voltage presentation of the references and the generated polynomial trendlines presented in §4.2, standards and recommended practices for BIL were compared and discussed.

4.1 Standards and Recommended Practices

The standards and recommendations in this section contain system voltages and corresponding BIL test levels. It is stated within some standards, and is the expected practice, that if the desired system voltage is in-between given voltage classes, then cables are to be tested at the BIL level of the next higher voltage class. This results in a step-function nature for all figures of BIL compared to the system voltage. Relevant comparative information from each source is shown in Table 1. Each reference's applicability covers the equipment of interest for this study, power cables.

Source	Applicability	# Impulses per polarity	Test Category	Test Specimen	Test Temperature
IEC Std. 60502-2/60092-350 [30] [31]	**Equip.: Power Supply Systems** **System Type: Land/Shipboard** **Volt. Level: 6-30 [kV] U_n** **Volt. Type: AC**	**10**	**Type**	**Sample, 10-15 [m]**	**5 [°C] Above Max Rated**
IEC Std. 60071-1/2 [4] [32]	**Equip.: Power Supply Systems** **System Type: Generic** **Volt. Level: 1-1000 [kV] U_n** **Volt. Type: AC**	**3-15**	**Unspecified**	**Unspecified**	**Unspecified**
IEEE Stds. 400.1/82 [33] [34]	**Equip.: Power Cables** **System Type: Land** **Volt. Level: 5-500 [kV] U_n** **Volt. Type: AC**	**10**	**Unspecified**	**Sample, ≥9 [m]**	**0-5 [°C] Above Max Rated**
IEEE Std. 1709 [2]	**Equip.: Power Supply Systems** **System Type: Shipboard** **Volt. Level: 1-35 [kV] U_n** **Volt. Type: DC**	**3 (Alternate Test: 15)**	**Acceptance**	**Entire Cable**	**Ambient**
ICEA S-97-682 [35]	**Equip.: Power Supply Systems** **System Type: Land** **Volt. Level: 5-46 [kV] U_n** **Volt. Type: AC**	**10**	**Type**	**Sample, 2.7 [m]**	**At Max Rated**
ABS Steel Vessel Requirements Part 4 [36]	**Equip.: Vessels Systems and Machinery** **System Type: Shipboard** **Volt. Level: 1-15 [kV] U_n** **Volt. Type: AC**	**3**	**Type**	**Entire Cable**	**Ambient**
CIGRE TB 496/IEC Std. 62895 [37] [38]	**Equip.: Power Cables** **System Type: Land and Submarine** **Volt. Level: ≤ 500 [kV] U_n** **Volt. Type: DC**	**10**	**Type (Super-imposed)**	**Entire Cable**	**> Max Rated**

Table 1: Sources and Relevant Information for BIL Standards and Recommended Practices

4.1.1 IEC Standards

The IEC standards cover systems with a Nominal System Voltage (U_n) in the range of 1-30 [kV], with corresponding BIL values in the range of 60-170 [kV]. Presented are applicable to shipboard MVAC and/or land-based MVAC systems.

The first applicable standard within the IEC is Std. 60092-503, which provides guidance for shipboard AC power supply systems with 1-15 [kV] U_n, including cables. For guidance on BIL, §5.5.1 states that high voltage cables shall generally be in accordance with the relevant parts of IEC Stds. 60502, 60092-350, 60092-351, and 60092-354. High voltage within the scope of IEC Std. 60092-503 is between 1-52 [kV], which is considered to be medium voltage within this study [39]. IEC Std. 60502-2 contains BIL guidelines within the voltage range of 6-30 [kV] and thus was considered [30]. IEC Std. 60092-351 applies to systems with a nominal system voltage in the range of 1-3 [kV] and was not considered for this study as it only covers a small fraction of the lower end of the MV spectrum. IEC Std. 60092-354 covers cables with a nominal system voltage of 6-30 [kV] and directs you to IEC Std. 60092-350 for voltage testing [40]. IEC Std. 60092-350 contains BIL guidance for systems up to a 30 [kV] U_n, and thus was considered [31].

The guidance within IEC Std. 60502-2 and IEC Std. 60092-350 is identical for BIL tests. These standards specify type test BIL for land-based and shipboard MVAC power cables, respectively. §18.2.8 of IEC Std. 60502-2 contains table 14 which specifies the required BIL correlating to phase-to-ground RMS Cable Nominal Voltage/Nominal System Voltage/highest voltage for equipment [30]. A similar table with identical values is found in §7.7.8 of IEC Std. 60092-350 [31]. These BIL levels were plotted versus U_n in Figure 3, and are shown in Figure 4 as "Test voltage" (BIL) for "Rated voltages," (U_o being Cable Nominal Voltage, U being Nominal System Voltage, and U_m being highest voltage for equipment) [30]. The same sections call for 10 impulses of each polarity to be applied to a 10-15 [m] sample length of the cable heated 5 [°C] above the maximum rated operating temperature of the insulation for the impulse type test, followed by at 15 [min] Withstand Test [30].

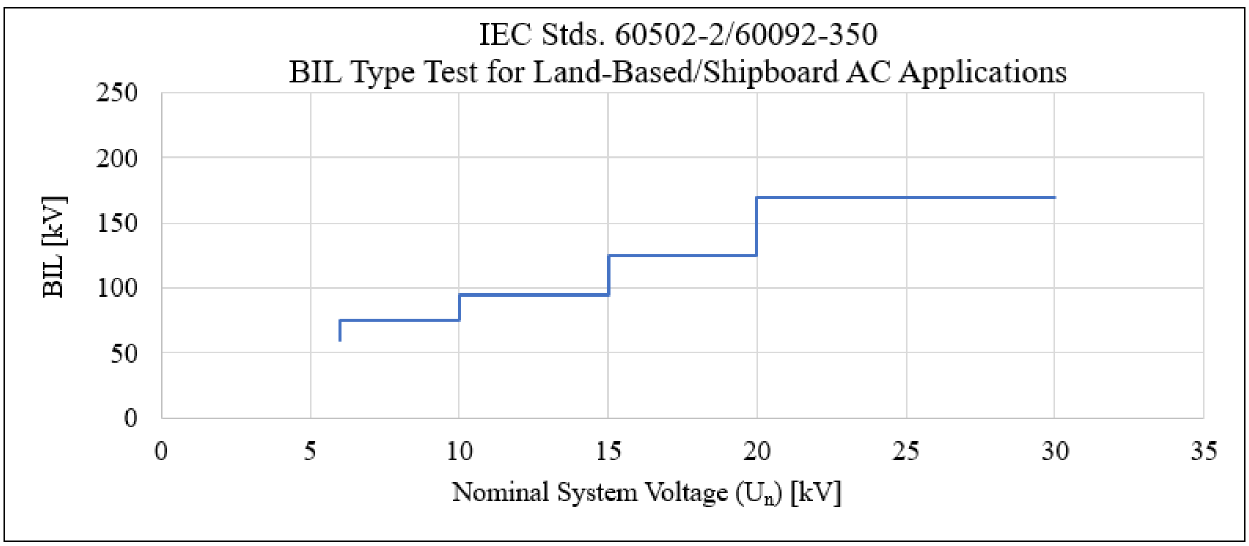


Figure 3: IEC Std. 60502-2 BIL Type Test vs. U_o, 10 Impulses of Each Polarity on a 10-15 [m] Sample of Cable while Heated

Rated voltage U_0/U (U_m)	KV	3,6/6 (7,2)	6/10 (12)	8,7/15 (17,5)	12/20 (24)	18/30 (36)
Test voltage (peak)	KV	60	75	95	125	170

Figure 4: IEC Stds. 60502-2/60092-350 BIL Applicable to Land-Based/Shipboard AC [30] [31]

IEC Std. 60092-503 also states in §4.4 that "the conditions on board ships may require certain equipment having an insulation level higher than that of the nominal voltage of the system, see IEC 60071-1 and IEC 60071-2" [39]. IEC Stds. 60071-1/2 cover insulation coordination, specifying the procedure for selecting appropriate insulation design levels for three phase AC systems [4]. Standard insulation levels are specified in §5.10 of IEC Std. 60071-1 for corresponding Highest Voltage for Equipment (U_m), plotted in Figure 5, are given in Figure 6 [4]. The range of standard insulation levels for each U_m is addressed in IEC Std. 60071-2: The lower bounds of the BIL range corresponding to each U_m are applicable to systems that are not connected to overhead lines, systems connected to overhead lines only through transformers with specific cable capacitance, or systems connected to overhead lines that have adequate overvoltage protection in the form of surge arresters [32]. This reference calls for 3-15 impulses of each polarity, depending on the acceptance criteria as described in §6.3 of IEC 60071-1 [4]. Aside from the BIL and number of applied impulses, these standards do not specify any other test parameters. These parameters are left to be "specified by the relevant apparatus committees" [4].

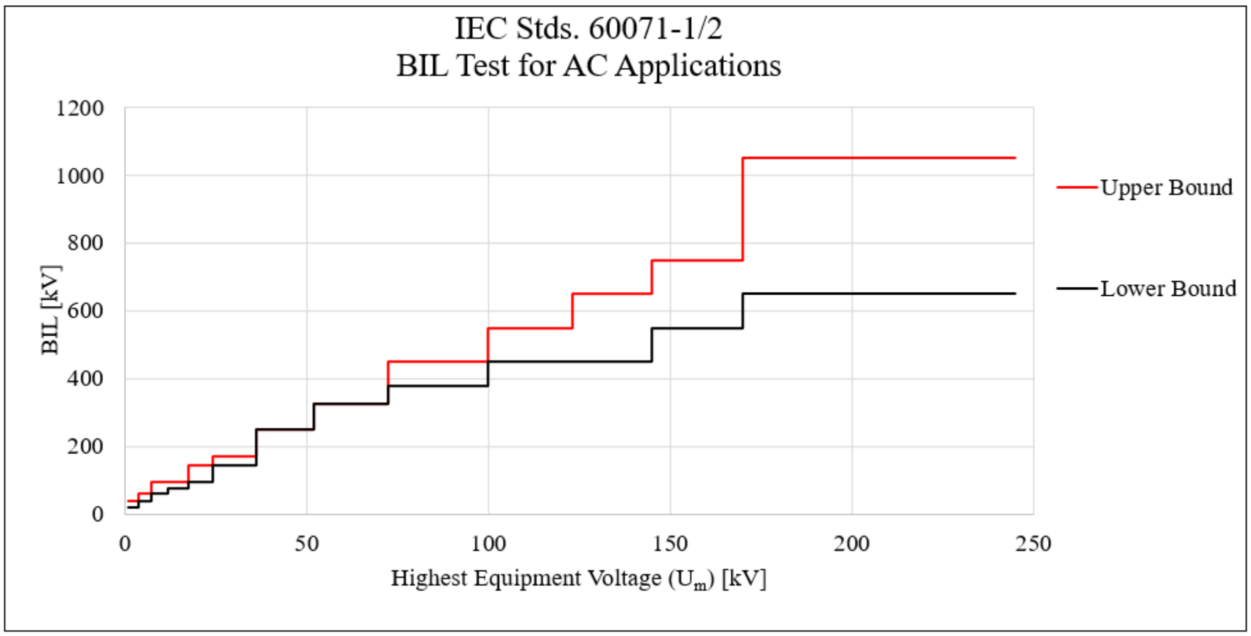


Figure 5: IEC Std. 60071-1/2 BIL vs. U_m, 3 Impulses of Each Polarity

Highest voltage for equipment, U_m kV (RMS value)	Standard rated short-duration power-frequency withstand voltage kV (RMS value)	Standard rated lightning impulse withstand voltage kV (peak value)
3,6	10	20 40
7,2	20	40 60
12	28	60 75 95
17,5 [a]	38	75 95
24	50	95 125 145
36	70	145 170
52 [a]	95	250
72,5	140	325
100 [b]	(150)	(380)
	185	450
123	(185)	(450)
	230	550
145	(185)	(450)
	230	550
	275	650
170 [a]	(230)	(550)
	275	650
	325	750
245	(275)	(650)
	(325)	(750)
	360	850
	395	950
	460	1 050

Figure 6: IEC Std. 60071-1 U_w & BIL for a Given U_m [4]

Another applicable standard within IEC is Std. 62895, covering HVDC cables up to 320 [kV]. This standard is evaluated in §4.1.5 of this study.

4.1.2 IEEE Standards

The IEEE standards cover systems with a Nominal System Voltage (U_n) in the range of 1-500 [kV], with corresponding BIL values in the range of 45-1550 [kV]. The standards presented are applicable to either generic AC systems or Shipboard DC systems.

Neither IEEE Std. 1580 nor IEEE Std. 45.8, the IEEE standards for recommended practices for marine cable, contain any guidance for BIL. For this evaluation, IEEE Std. 400 Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 [kV] and Above was examined. §4.3 of IEEE Std. 400.1 outlines BIL for a given system U_n but does not give guidance for BIL test procedures [33]. IEEE Std. 82 Standard Test Procedure for Impulse Voltage Tests on Insulated Conductors identifies BIL identical to IEEE Std. 400.1 and outlines the appropriate testing procedure [34]. This standard does not specify if the BIL test is a type or acceptance test but calls for 10 impulses of each polarity to be applied to a sample ≥ 9 [m] in length of the cable heated 0-5 [°C] above the maximum rated operating temperature of the insulation [34]. The relationship between BIL and a given cable system based on the phase-to-phase RMS voltage (U_n) for this standard were plotted versus U_n in Figure 7 and are shown in Figure 8.

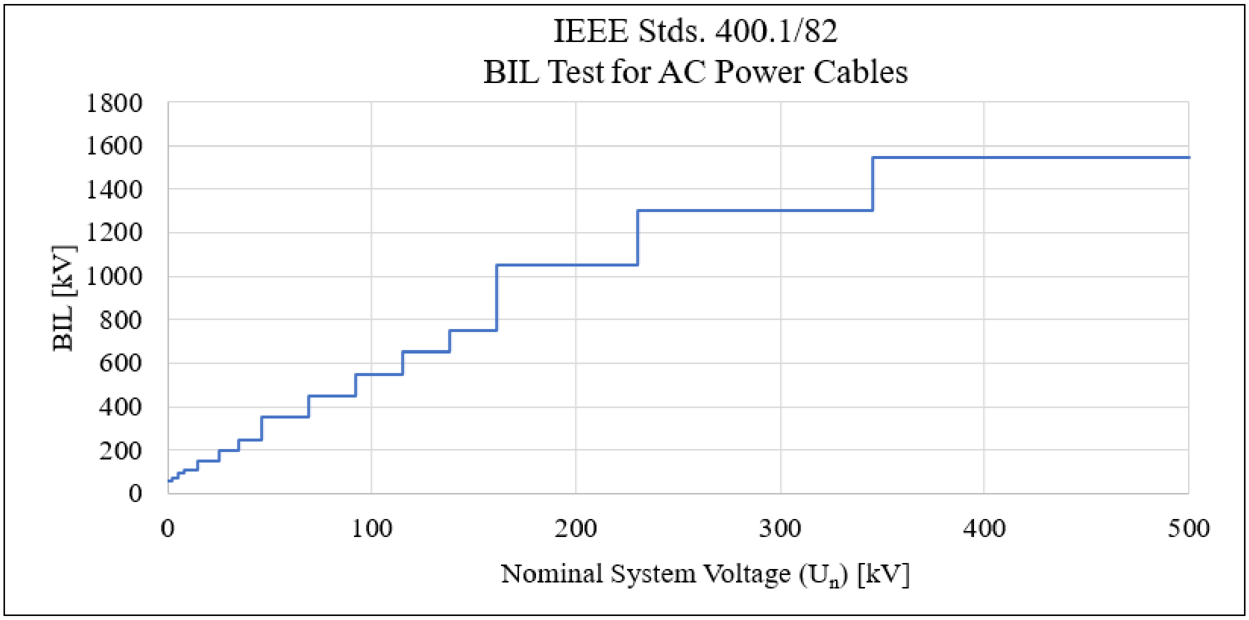


Figure 7: IEEE Stds. 400.1/82 BIL vs. U_n, 10 Impulses of Each Polarity on a ≥ 9 [m] Sample of Cable while Heated

Voltage class (kV phase-to-phase)	BIL (kV)
2.5	60
5.0	75
8.0	95
15.0	110
25.0	150
35.0	200
46.0	250
69.0	350
92.0	450
115.0	550
138.0	650
161.0	750
230.0	1050
345.0	1300
500.0	1550

Figure 8: IEEE Std. 82 BIL for a Given Nominal System Voltage (U_n), Applicable to Generic AC Systems [34]

The IEEE has also published Std. 1709, Recommended Practice for 1 [kV] to 35 [kV] Medium-Voltage DC Power Systems on Ships [2]. To the best of the author's knowledge this standard is currently the only shipboard MVDC guidance in existence. BIL for power bus components and connected loads is addressed in §5.2.3 of the IEEE standard, is plotted versus U_n in Figure 9 of this study and shown in Figure 10 as U_p [2]. The first test outlined by IEEE Std. 1709 is an acceptance test with at least 3 impulses of each polarity to be applied to the entire length of cable, with additional impulses if a disruptive discharge occurs. An alternate acceptance test is also given by IEEE Std. 1709. This alternate test calls for least 15 impulses at the short duration withstand voltage level (typically lower than BIL) of each polarity to be applied to the entire length of cable, with additional impulses if a disruptive discharge occurs. Both procedures are outlined in §8.3.1 of the standard [2]. At first glance the existence of such a standard would deem this study unnecessary, as there is publicized guidance from an international authority in the electrical safety field. However, little is known about MVDC systems in a shipboard environment and design values such as insulation thickness are not provided within IEEE std. 1709, and so this study seeks to examine the vast knowledge of existing systems and use that solid base to make recommendations into the growing field of shipboard MVDC. To that end, it is appropriate to compare any recommendations and standards to the lone MVDC standard.

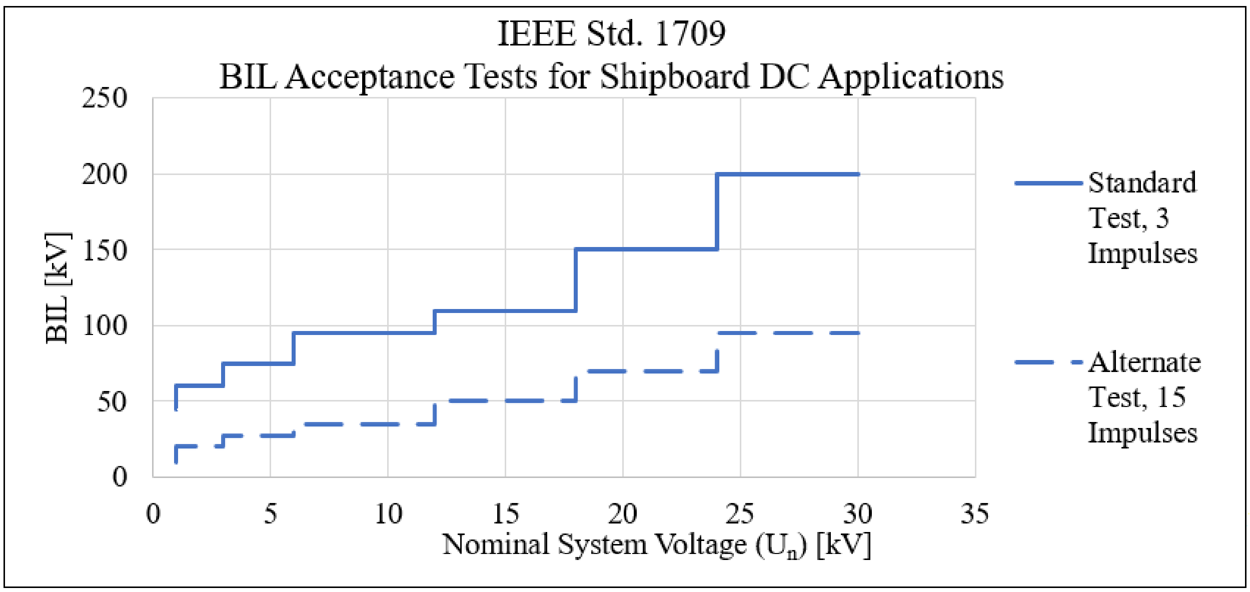


Figure 9: IEEE Std. 1709 BIL Acceptance Test vs. U_n, 3-15 Impulses of Each Polarity on the Entire Cable

MVDC class	Rated short-duration withstand voltage to ground U_d kV for 1 min	Rated lightning impulse withstand voltage to ground U_p kV (peak value)
1	10	45
3	20	60
6	27	75
12	35	95
18	50	110
24	70	150
30	95	200

Figure 10: IEEE Std. 1709 Withstand Voltage (U_w) and BIL for a Given Nominal System Voltage (U_n), Applicable to Shipboard DC [2]

4.1.3 American Bureau of Shipping Requirements

The ABS Steel Vessel Requirements covers power systems with a Nominal System Voltage (U_n) in the range of 1-15 [kV], with corresponding BIL values in the range of 40-95 [kV]. The standard is applicable to Shipboard AC systems, including power cables.

The American Bureau of Shipping (ABS) Steel Vessel Requirements Part 4 specifies MVAC system BIL in §4.8.5.3.7.1 for all equipment within a system [36]. This requirement covers from 1-15 [kV] U_n, with BIL corresponding to U_n plotted in Figure 11 and shown in Figure 12. This impulse type test is to be carried out in accordance with §5.2.3.1 of IEC 61800-5-1, which calls for 3 impulses per polarity to be applied to the entirety of the cable [41].

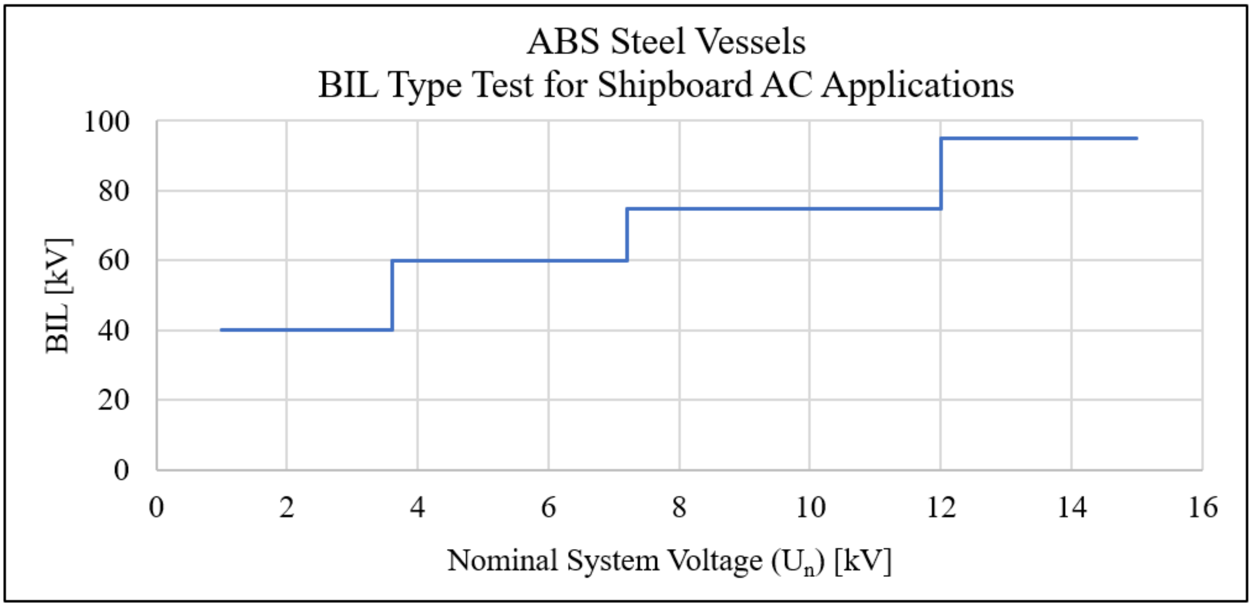


Figure 11: ABS BIL Type Test vs. U_n, 3 Impulses of Each Polarity on the Entire Cable

Rated Voltage kV	*Rated Impulse Withstand Voltage kV (peak value)*
3.6	40
7.2	60
12	75
15	95

Figure 12: ABS BIL for a Given Nominal System Voltage (U_n), Applicable to Shipboard AC [36]

4.1.4 ICEA Standard

The Insulated Cable Engineers Association (ICEA) develops cable standards for electric power, control, and telecommunications industries, many of which are approved by the American National Standards Institute (ANSI) [42]. Cable manufacturers around the world use ICEA guidance for the cable design process. The evaluated standard covers systems with a Nominal System Voltages (U_n) 5-46 [kV], with corresponding BIL values in the range of 60-250 [kV]. The standard evaluated is applicable to AC utility power cables.

ICEA S-97-682 Standard for Utility Shielded Power Cables Rated 5 Through 46 [kV] outlines a BIL type test in §10.1.4. Of note for this procedure, the ICEA specifies that lightning impulse be applied on a cable that is at the "rated emergency overload temperature of the cable" [35]. This impulse type test calls for 10 impulses per polarity to be applied to a 2.7 [m] sample length of the cable [35]. The magnitude of BIL for a given U_n is plotted in Figure 13 and shown in Figure 14.

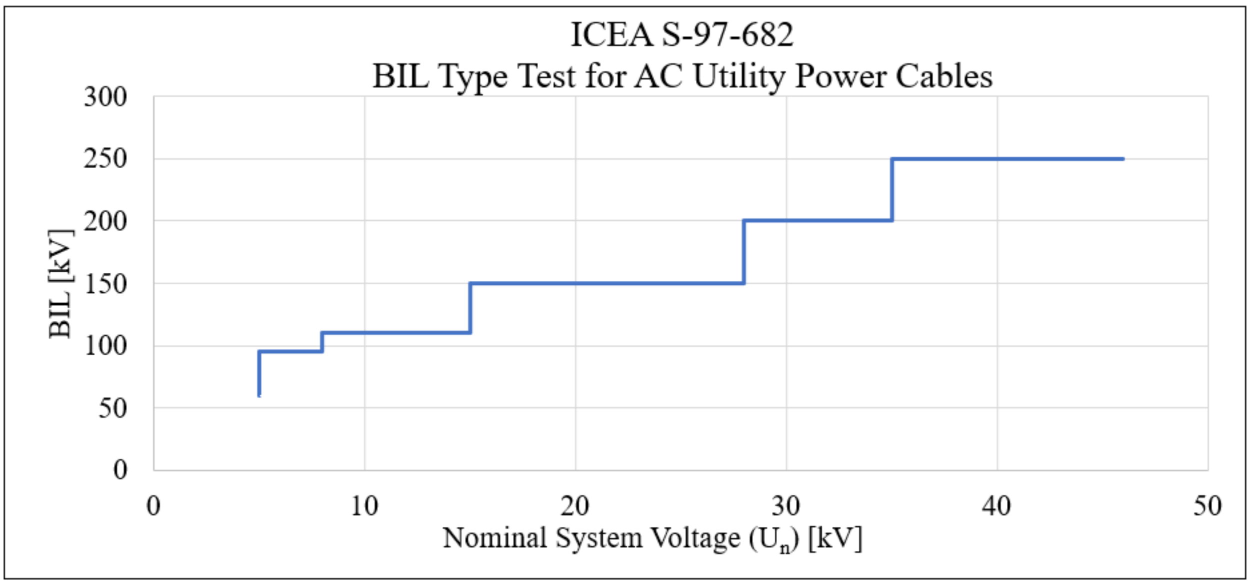


Figure 13: ICEA BIL Type Test vs. U_n, 10 Impulses of Each Polarity on a Heated 2.7 [m] Cable Sample

Cable Rating kV	BIL kV
5	60
8	95
15*	110
25	150
28	150
35	200
46	250

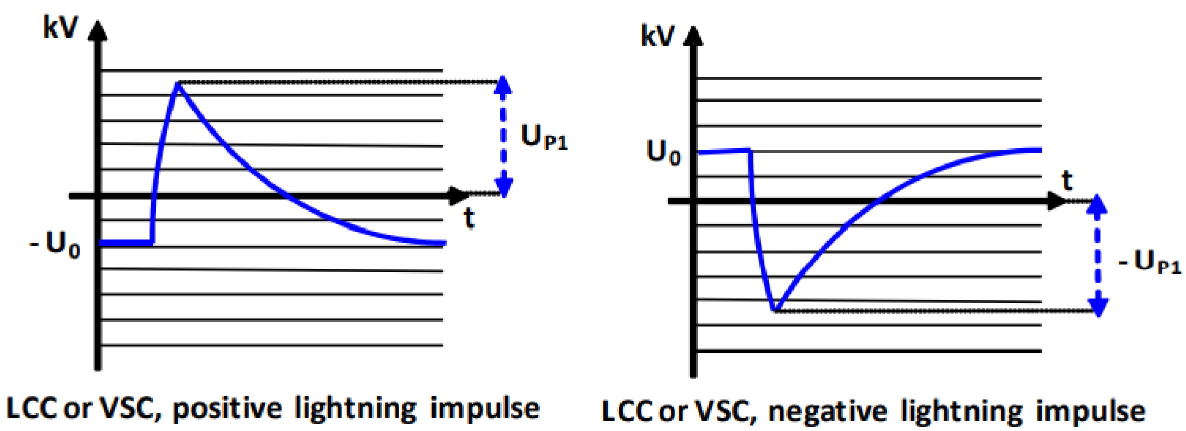
Figure 14: ICEA BIL for a Given Nominal System Voltage (U_n), Applicable to AC Utility Power Cables [35]

4.1.5 HVDC Standards and Recommendations

The high voltage direct current (HVDC) recommendations cover systems with a Nominal System Voltage (U_n) less than 500 [kV], with corresponding BIL values in the range of 0-525 [kV]. The recommendations presented is applicable to Land-Based and submarine HVDC power cables. The HVDC recommendations call for the cable being tested to have an operational voltage applied during testing and the BIL impulse to be superimposed on top of this voltage, an important distinction for DC cable recommendations from AC.

CIGRE Technical Brochure 496 and IEC Std. 62895 specify recommended tests for HVDC power cables up to and including 500 [kV] / 320 [kV] respectively. While these references are intended for HVDC power transmission systems, the MVDC range of interest is covered and thus they were considered for this study. CIGRE TB 496 was published in 2012, after which IEC Std. 62895 was published in 2017 containing identical guidance [37] [38]. §4.4.3.4 of CIGRE TB 496 and §12.4.5.4 of IEC Std. 62895 call for a sample cable length greater than 10 [m] to be heated to its max rated temperature and to have a positive Cable Nominal Voltage (U_o) applied for 10 hours before 10 superimposed negative impulses are applied [37] [38]. This process is then repeated with the opposite polarity and concluded with the application of a positive 1.85xU_o for 2 hours. The BIL is given as U_{P1} shown in Figure 15, with a magnitude of 2.1 times U_o of the opposite polarity [37]. BIL based on these recommendations versus U_o is plotted in Figure 16, with IEC Std. 62895 only being applicable up to a U_o of 160 [kV].

These recommendations apply to system voltages up to 500 [kV], high voltage systems are generally considered to be systems with voltages greater than 69 [kV] U_n. To properly portray this, the Withstand Voltage versus U_o shown in Figure 16 is dashed for U_o less than 34.5 [kV] (corresponding to 69 [kV] U_n).



$$U_{P1} = 2.1 \times U_0$$

Note: This U_{P1} definition means that the delta of the impulse itself is 3.1 U_o total, with an absolute magnitude of 2.1 U_o

Figure 15: CIGRE/IEC Std. 62895 Recommended BIL magnitude [37]

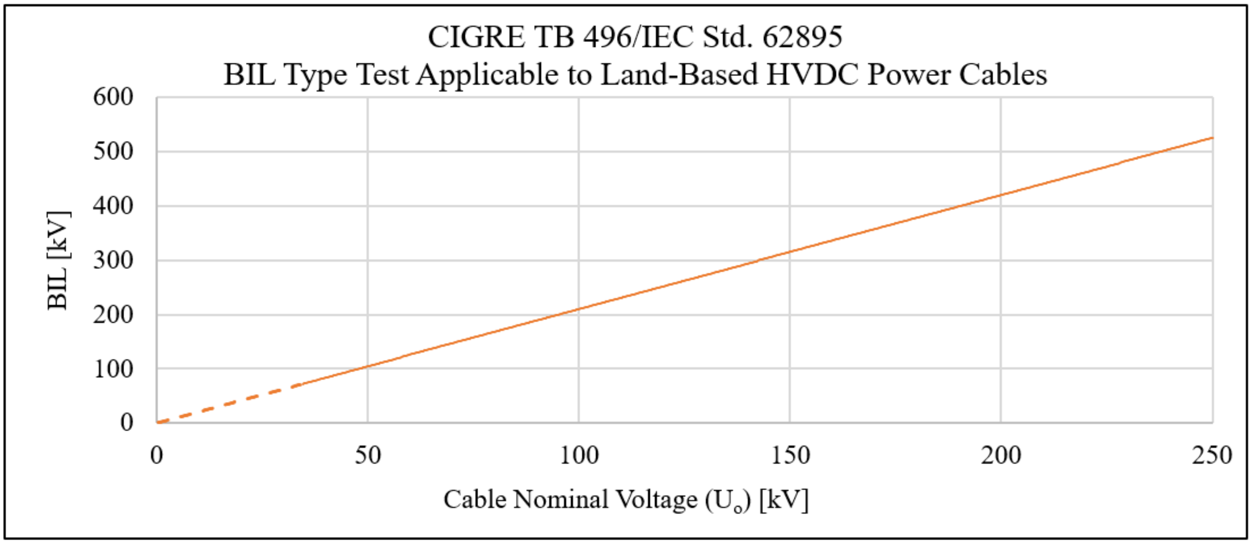


Figure 16: CIGRE TB 496/IEC Std. 62895 BIL Type Test vs. U_o, 10 Superimposed Impulses of Each Polarity on a >10 [m] Cable Sample while Heated

4.1.6 USN Requirements

The USN does not appear to have any guiding doctrine specifying BIL for power cables. An interview with a representative from Naval Surface Warfare Center Philadelphia Division yielded that currently the most common ship power system is 5 [kV] U_n AC, with a corresponding BIL of 65 [kV]. Additionally, there are some commissioned vessels with a 15 [kV] U_n AC power distribution system, and a BIL of 95 [kV]. These two data points are shown in Figure 17, and are used as references points for the comparisons and evaluations of this study.

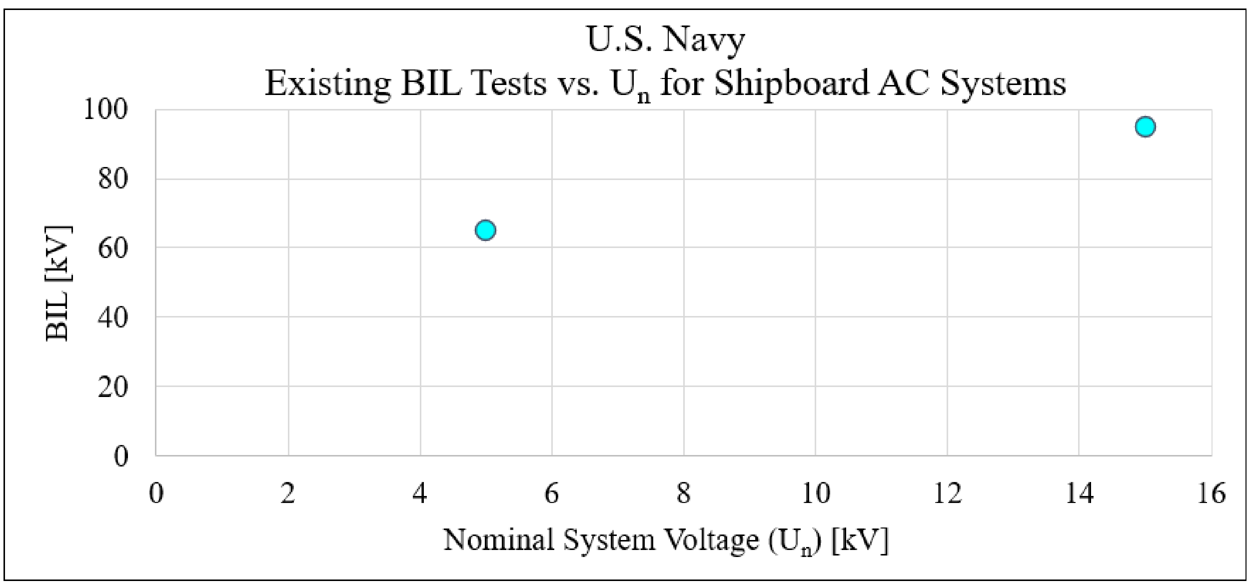


Figure 17: USN Existing AC Power Systems BIL vs. U_n, Applicable to Shipboard AC

4.2 Consolidation of Reference Data

The intent of this section is to examine the data gathered from the preceding section's references in comparable terms. This is accomplished through the following actions:

1. Plotting each reference's BIL voltages versus Nominal System Voltage (U_n) by converting the compared cable or system voltage appropriately. If this is required, it is explained in the paragraph introducing the reference's modified figure.
2. Generating continuous trendline approximations from original step-curve defined by each reference. Most references provide BIL that make a step-change of varying amounts, with the steps at varying voltages, which makes it difficult to directly compare the standards. This study visualizes the step-nature of these curves by converting them into an equivalent polynomial trendline using least squares regression on the centers of the horizontal and vertical portions of each step. For references that provide guidance beyond 35 [kV] U_n, data points up to 90 [kV] U_n are used to ensure the form of the curve accurately represented the reference. Some references provide BIL with a linear equation based on a system voltage. Continuous trendlines are not generated for these references. The generated trendlines are represented as dashed lines, with the points used to fit the lines marked with an "x" on the respective figure. All trendline equations are displayed on the figures. Each manipulated reference was plotted with similar bounds for BIL and U_n for ease of visual comparison.
3. Calculating trendlines for BIL versus Cable Nominal Voltage (U_o) and Nominal Peak Cable Voltage (U_p) by dividing U_n by √(3) and then multiplying by √(2), respectively. These trendlines for each reference, as well as BIL versus U_n, are given in §4.2.5 Table 2.

4.2.1 IEC Standards

IEC Stds. 60502-2/60092-350 outline BIL for given systems based on the Nominal System Voltage, U_n. The graphed BIL vs. U_n with polynomial trendline is shown in Figure 18.

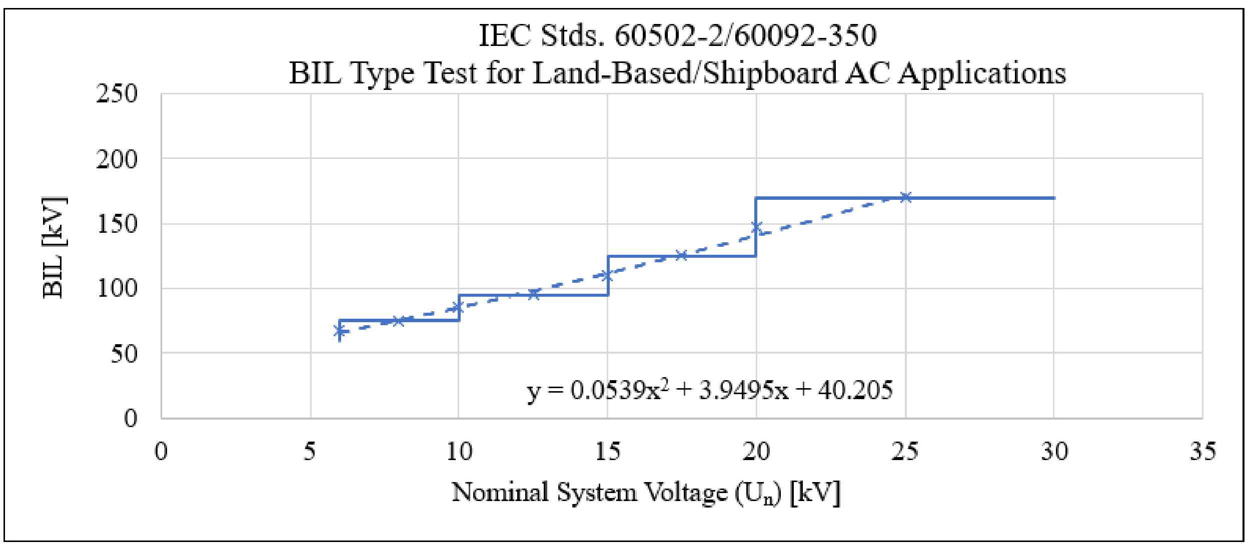


Figure 18: IEC Std. 60502-2/60092-350 BIL Type Test vs. U_n, 10 Impulses of Each Polarity on a 10-15 [m] Sample of Cable while Heated, with Trendline

The IEC Stds. 60071-1/2 outline BIL for given systems based on the Highest Voltage for Equipment, U_m. A chart from within the standard relating a U_n for each U_m is shown in Figure 19. The remaining values of U_n (20 and 30 [kV]) corresponding to U_m of 24 and 36 [kV] are found in IEC Std. 60038 [26]. For a given range of U_n the lower value is used and is shown in Figure 20, and a second order polynomial fit to both the upper and lower bound BIL.

Nominal system voltage[a] kV	**Nominal frequency** Hz	**Highest voltage for equipment** kV
3		3,6
3,3		3,6
6		7,2
6,6	50 or 60	7,2
10		12
11		12
15		17,5

[a] The values are voltages between phases.

Figure 19: Corresponding U_n and U_m within IEC Std. 60092-503 [39]

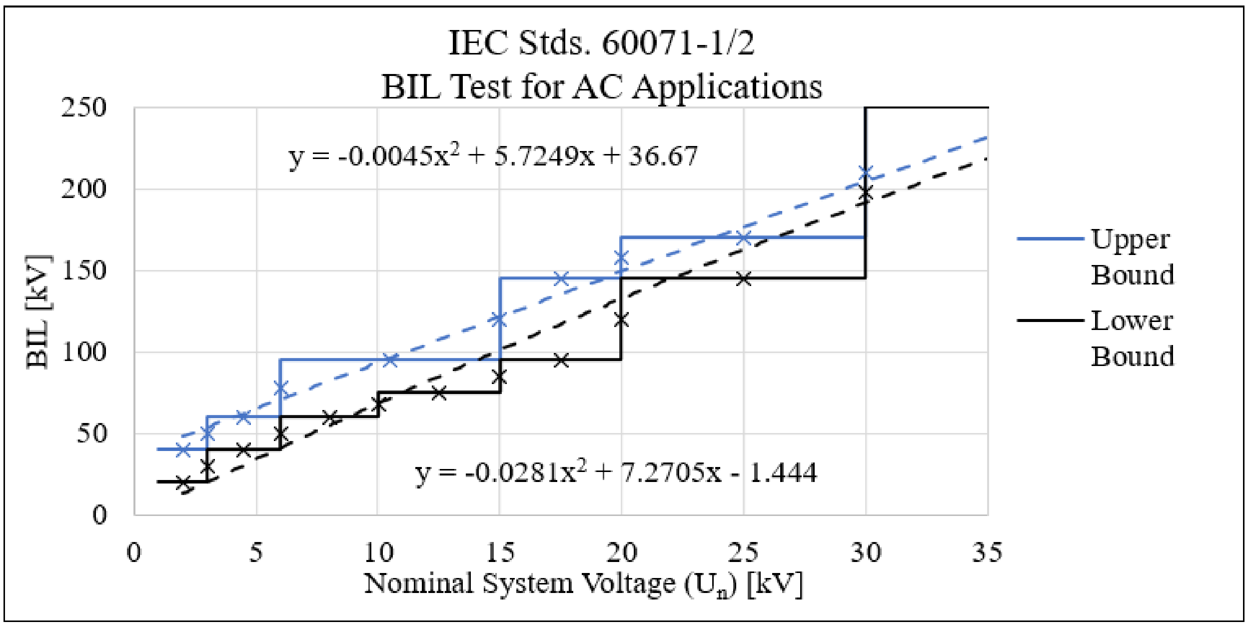


Figure 20: IEC Std. 60071-1/2 BIL vs. U_n, 3 Impulses of Each Polarity, with Trendlines

4.2.2 IEEE Standards

IEEE Stds. 400.1/82 outline BIL for given systems based on the Nominal System Voltage, U_n. The graphed BIL vs. U_n with polynomial trendline is shown in Figure 21, truncated to the region of interest.

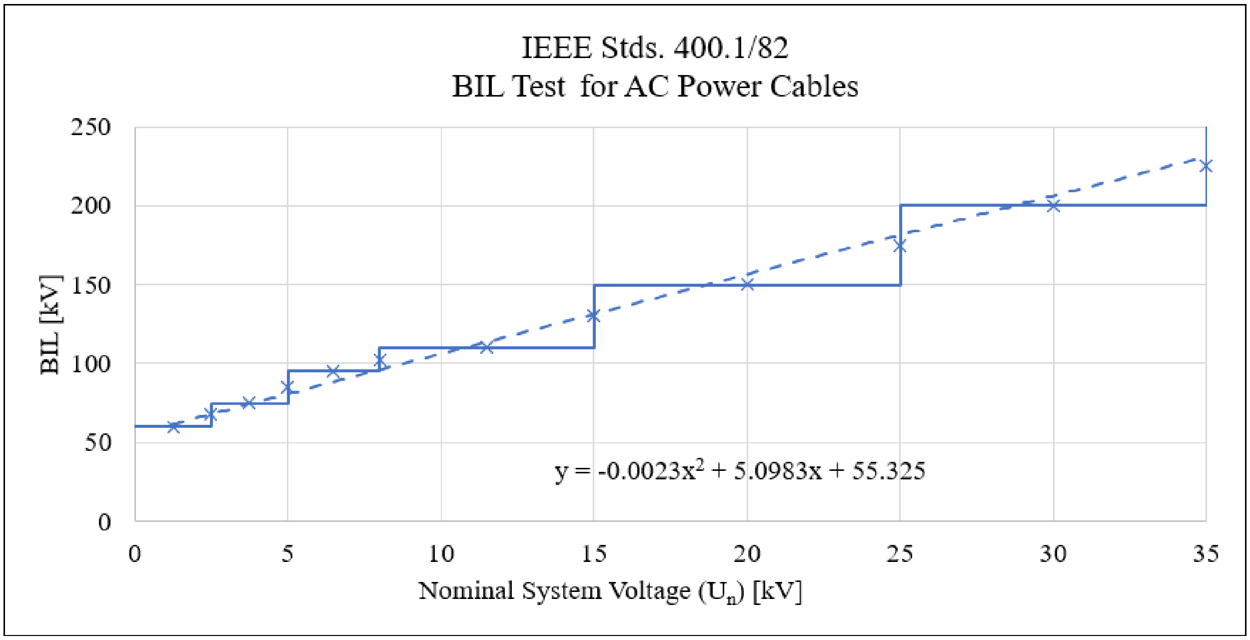


Figure 21: IEEE Stds. 400.1/82 BIL vs. U_n, 10 Impulses of Each Polarity on a ≥ 9 [m] Sample of Cable while Heated, with Trendline

IEEE Std. 1709 outlines a recommended BIL test for DC systems based on the Nominal System Voltage, U_n. The graphed BIL versus U_n with polynomial trendline is shown in Figure 22.

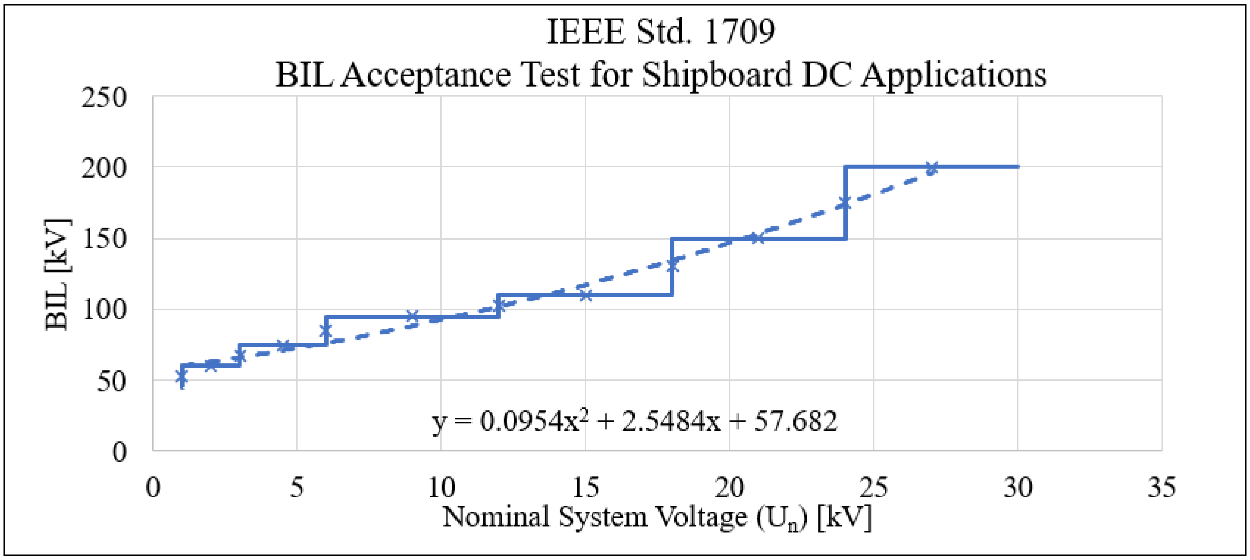


Figure 22: IEEE Std. 1709 Acceptance BIL vs. U_n, 3 Impulses of Each Polarity on the Entire Cable, with Trendline

4.2.3 American Bureau of Shipping Requirements

The ABS Steel Vessel Requirements Part 4 specifies MVAC system BIL based on the Nominal System Voltage (U_n). The graphed BIL vs. U_n with polynomial trendline is shown in Figure 23.

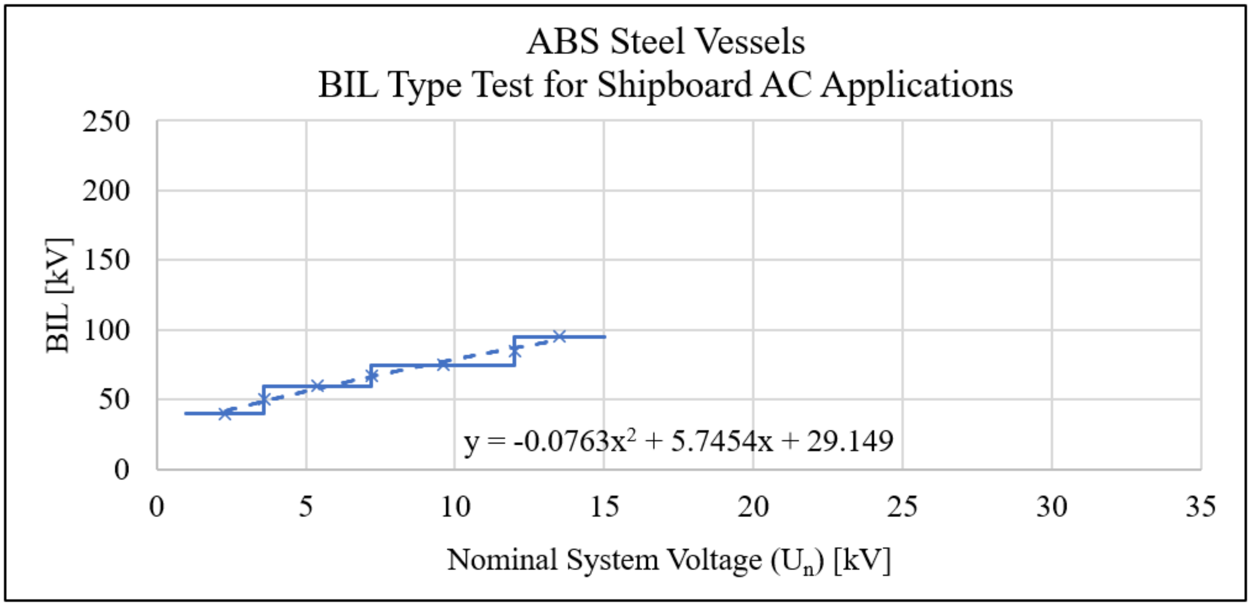


Figure 23: ABS BIL Type Test vs. U_n, 3 Impulses of Each Polarity on the Entire Cable, with Trendline

4.2.4 ICEA Standard

ICEA S-97-682 specifies MVAC system BIL based on the Nominal System Voltage (U_n). The graphed BIL vs. U_n with polynomial trendline is shown in Figure 24.

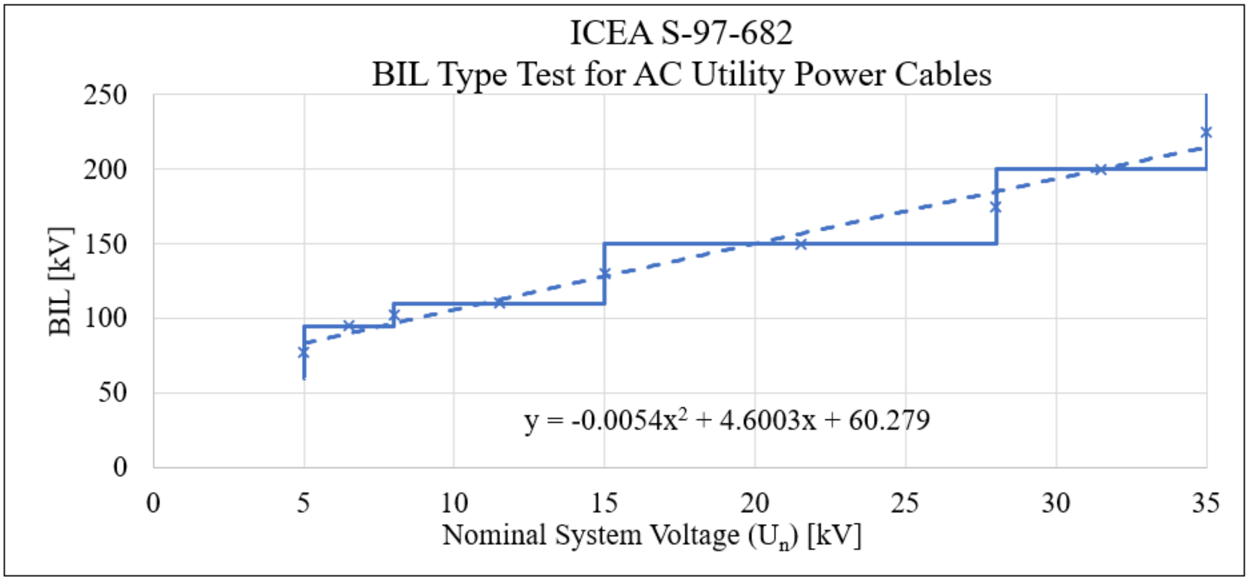


Figure 24: ICEA BIL Test vs. U_n, 10 Impulses of Each Polarity on a Heated 2.7 [m] Cable Sample, with Trendline

4.2.5 HVDC Standards and Recommendations

CIGRE TB 496 and IEC Std. 62895 base their BIL recommendations on the Cable Nominal Voltage (U_o). The voltages were converted into U_n by multiplying U_o by √(3). The graphed BIL vs. U_n with trendline equation is shown in Figure 25, truncated to the region of interest. These recommendations are purely linear in nature, and so a second order polynomial is not used. As these references are intended for HVDC power cables, BIL corresponding to U_n below 69 [kV] are shown with a dashed line (this covers the entire region of interest). Based on the applicability of this reference to HV systems and the large differential of BIL in the area of interest for this study, this reference will not be used for BIL discussion henceforth.

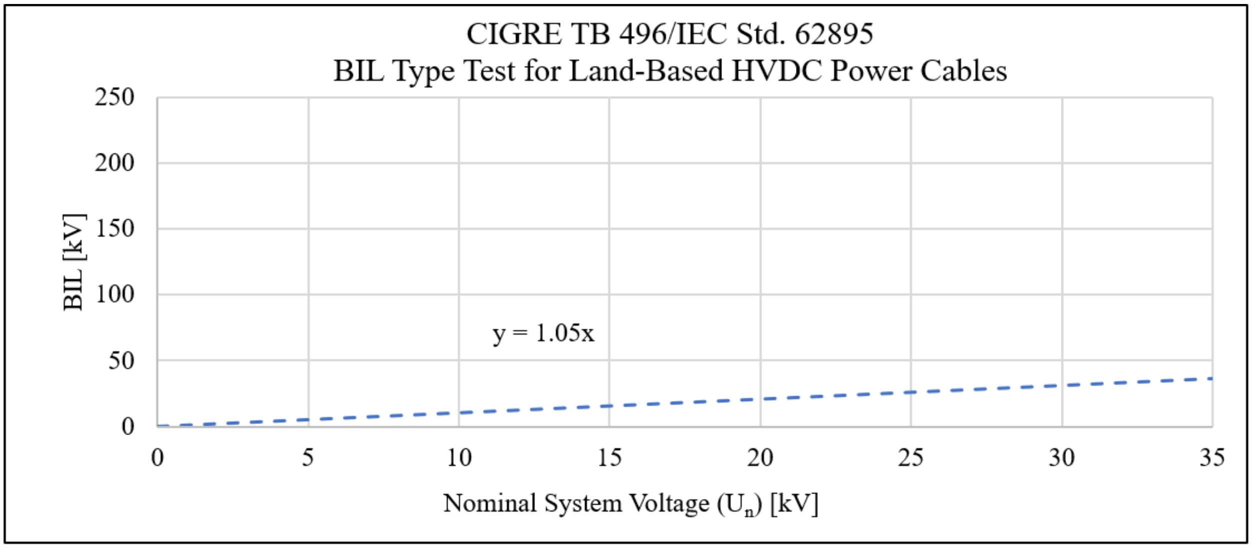


Figure 25: CIGRE TB 496/IEC Std. 62895 BIL Type Test vs. U_n, 10 Superimposed Impulses of Each Polarity on a >10 [m] Cable Sample while Heated, with Trendline

4.2.6 Table of Polynomials

Polynomials for Withstand Tests compared to the Nominal System Voltage (U_n), Cable Nominal Voltage (U_o) and Nominal Peak Cable Voltage (U_p) were calculated and given in Table 2. Each equation is given in the form of U_w as a f(x), with x being the respective voltage.

Reference	BIL vs. U_n	BIL vs. U_o	BIL vs. U_p
IEC Stds. 60502-2/60092-350	$0.0539x^2+3.9495x+40.205$	$0.0936x^2+7.6417x+36.678$[a]	$0.0468x^2+5.4035x+36.678$[a]
IEEE Stds. 400.1/82	$-0.0023x^2+5.0983x+55.325$	$-0.0069x^2+8.8306x+55.325$	$-0.0034x^2+6.2441x+55.325$
IEEE Std. 1709	$0.0954x^2+2.5484x+57.682$	$0.3817x^2+5.0968x+57.682$	N/A
ABS Steel Vessels	$-0.0763x^2+5.7454x+29.149$	$-0.2289x^2+9.9513x+29.149$	$-0.1144x^2+7.0367x+29.149$
ICEA S-97-682	$-0.0054x^2+4.6003x+60.279$	$-0.0161x^2+7.968x+60.279$	$-0.008x^2+5.6342x+60.279$

[a] The IEC standard provides U_o values corresponding to U_n values that does not exactly correspond to the mathematical calculation of U_o form U_n. This different results in the y intercept of BIL vs. U_o and BIL vs. U_p being different from that of BIL vs. U_n.

Table 2: Trendline Polynomials for BIL vs. Respective Voltages

4.3 Comparison of Standards and Recommended Practices BIL

The next step in determining prospective design and test values for MVDC shipboard systems is to compare the BILs from all references. Each BIL (excluding the HVDC references, explained in §4.2.5) are plotted vs. U_n on a single graph, Figure 27. This comparison shows the range of BIL for a given U_n that are acceptable for cables in accordance with the references evaluated.

The legend of Figure 27, and the rest of the figures in this subsection, contain each BIL test's relevant parameters discussed in §4.0. The reference title, applicability (land-based or shipboard), system voltage type (AC or DC), number of impulses per polarity, test category (type, acceptance, or unspecified test), length of cable being tested, and the temperature of the cable during the test are shown in the legends of the following figures in the format shown in Figure 26. All references that required the cable to heated called for the cable to be +5 / -0 [°C] of the maximum rated operating temperature of the insulation, and so the temperature will be referred to as either 'heated' or 'ambient'.

Format:	Reference (Applicability(System Voltage Type), # impulses per polarity, Test Category, Cable length, Temperature)						
Options:	All Refs.	Land or Ship	AC or DC	#	Type or Acceptance or Unspecified	Entire Cable or Sample or Unspecified	Heated or Ambient or Unspecified
Example:	IEEE Std. 1709 (Ship(DC), 3, Accept., Entire Cable, Amb.)						

Figure 26: Key for Legends in §4.3

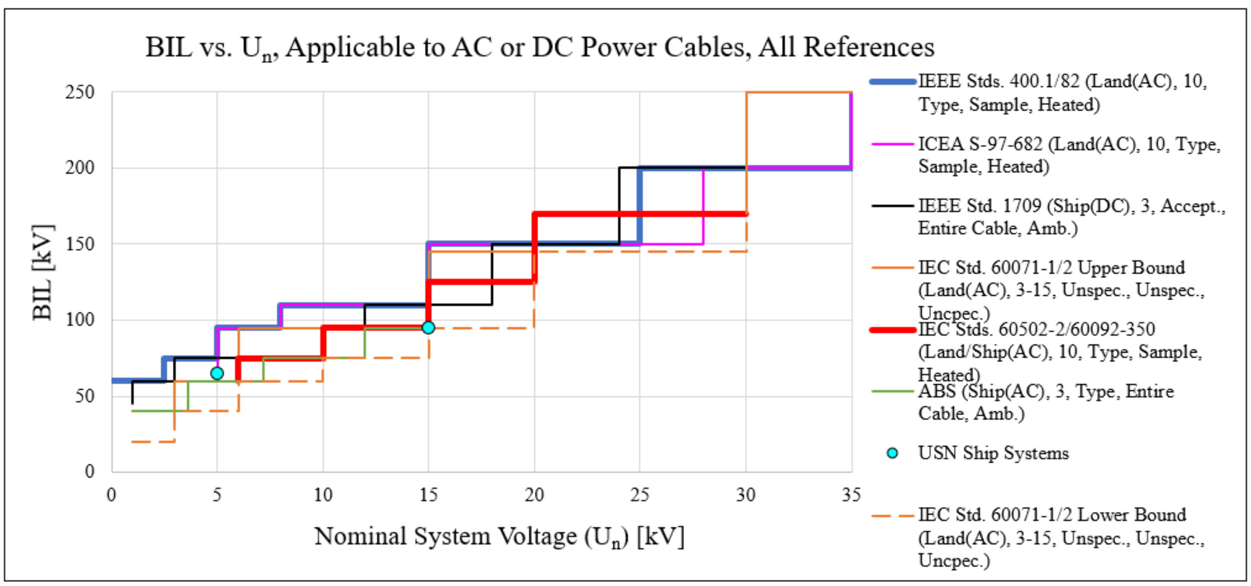


Figure 27: Comparison of BIL vs. U_n for All References in §4.1

Reference	Coordinates (U_n [kV], BIL [kV])								
IEEE Stds. 400.1/82 [33] [34]	2.5,60	2.5,75	5,75	5,95	8,95	8,110	15,110	15,150	25,150
	25,200	35,200	35,250						
ICEA S-97-682 [35]	5,60	5,95	8,95	8,110	15,110	15,150	28,150	28,200	35,200
	35,250								
IEEE Std. 1709 [2]	1,45	1,60	3,60	3,75	6,75	6,95	12,95	12,110	18,110
	18,150	24,150	24,200	30,200					
IEC Std. 60071-1/2 Upper Bound [4] [32]	3,40	3,60	6,60	6,95	15,95	15,145	20,145	20,170	30,170
	30,250								
IEC Stds. 60502-2/60092-350 [30] [31]	6,60	6,75	10,75	10,95	15,95	15,125	20,125	20,170	30,170
ABS [36]	1,40	3.6,40	3.6,60	7.2,60	7.2,75	12,75	12,95	15,95	
USN Ship Systems	5,65	15,95							
IEC Std. 60071-1/2 Lower Bound [4] [32]	3,20	3,40	6,40	6,60	15,60	10,75	15,75	15,95	20,95
	20,145	30,145	30,250						

Table 3: Coordinates of Step-Functions in Figure 27

The trendlines generated for each reference's BIL vs. U_n in §4.2 were plotted as a function of U_n in Figure 28. This figure illustrates a relatively constant range of BIL for any U_n.

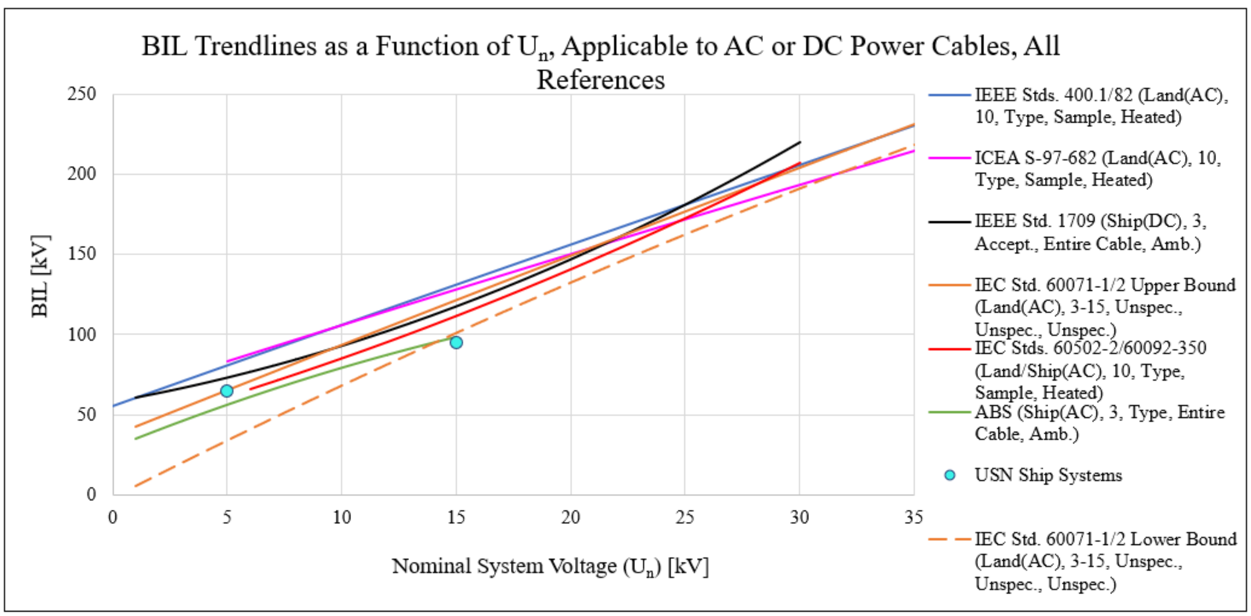


Figure 28: Comparison of BIL Trendlines vs. U_n for All References in §4.1

The above process is repeated with only shipboard-applicable references outlined in §4.1, shown in Figure 29 and Figure 30. The juxtaposition of Figure 29 and Figure 30 show that at 12 [kV] U_n while there is a large range of BIL in accordance with the standards as defined (35 [kV]), the range of the trendlines is significantly smaller (14.9 [kV]).

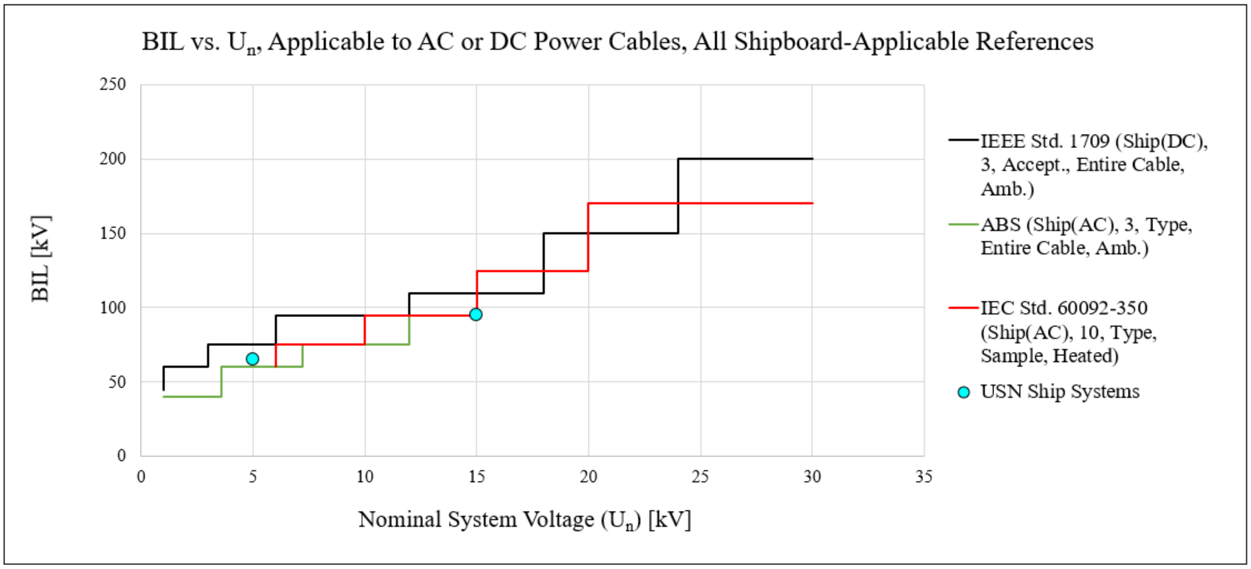


Figure 29: Comparison of BIL vs. U_n for All Shipboard-Applicable References in §4.1

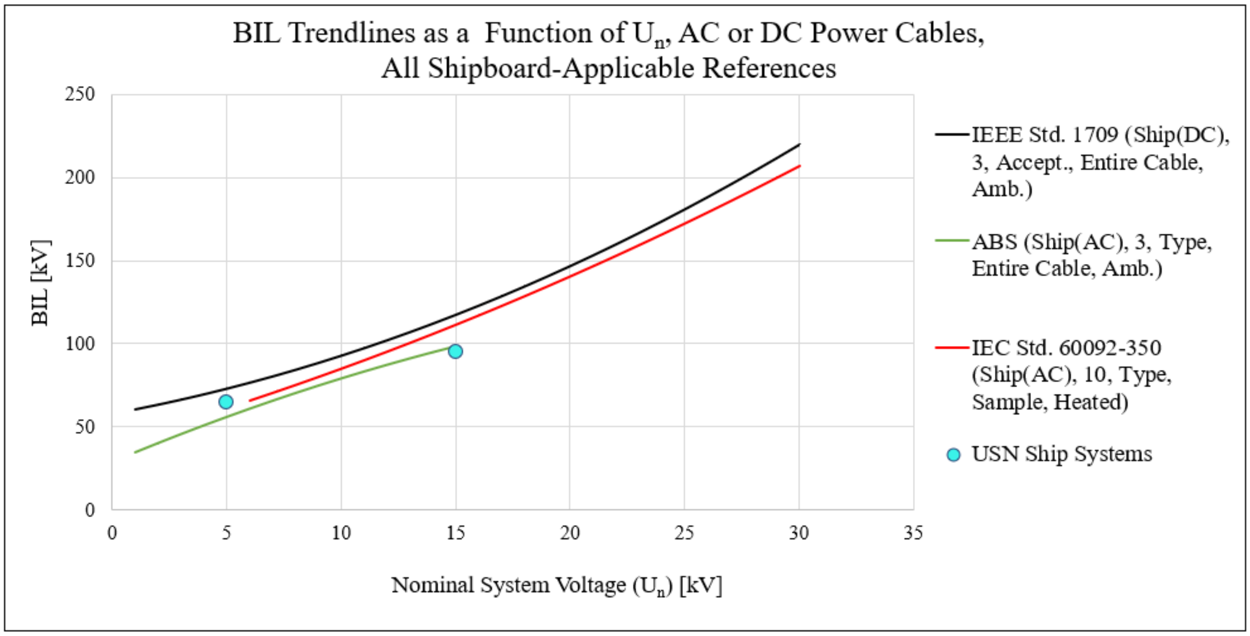


Figure 30: Comparison of BIL Trendlines vs. U_n for All Shipboard-Applicable References in §4.1

5.0 Withstand Test Analysis

This section concerns the tests established in the evaluated references for Withstand Voltage Tests based on a system voltage. Withstand Voltage Tests are compiled and compared to establish the range of Withstand Test Voltages (U_w) deemed acceptable for a given Nominal System Voltage by the various international committees. Additionally, this study aims to determine if MV cable sizes are influenced by the BIL and U_w through required insulation thicknesses. Of note, no evaluated reference provides an insulation thickness based on the U_w, indicating that insulation thickness is not necessarily dependent on U_w. However, the standards imply a linkage between U_w and the insulation thickness, as the prescribed increases of insulation thickness and test voltage levels occur at the same Nominal System Voltage.

The parameters for the Withstand Voltage Test are outlined in §3.7. Of these parameters, the varying duration of the Withstand Tests are in great contrast with the fixed duration of BIL tests, as the range of the collected reference's Withstand Test durations span three orders of magnitude (1-1440 [min]). Each Withstand Test studied in this work states that the test shall be completed on the entirety of the cable (either the entire completed reel or post-installation) at ambient temperature, and so these parameters were considered constant for this work. The withstand tests employ continuous voltages and hence have both magnitude and duration as variables.

Among the references studied only two are applicable to DC power cables. One of which is intended for high voltage systems (with $U_n \geq 69$ [kV]) and thus not applicable to the area of interest of this study, leaving IEEE Std. 1709 to be the sole reference applicable to MVDC. The following section compares the recommended Withstand Test of this reference with the well-established standards and recommendations for MVAC power cable Withstand Tests. This is accomplished through the following three subsections:

1. Standards and Recommended Practices. Presented data for Withstand Tests exactly as they appear in the corresponding reference.
2. Consolidation of Reference Data. Presented each reference U_w compared to a common voltage type, along with generated continuous polynomial trendlines approximating Withstand Voltage levels as a function of system voltage.
3. Comparison of Standards and Recommended Practices. Using the common system voltage presentation of the references and the generated polynomial trendlines presented in section §5.2, and further comparison based on test duration, the references for Withstand Test duration and levels were compared and discussed.

5.1 Standards and Recommended Practices

The standards and recommendations in this section state a system voltage with a corresponding Withstand Test category, withstand voltage (U_w), test duration, and a frequency for the applied voltage (if U_w is AC). U_w is defined as the phase-to-ground RMS voltage for AC tests and line-to-ground voltage for DC tests [4]. It is stated in some standards, and is the expected practice, that if the desired system voltage is in-between given classes cables are to be tested to the next higher given class impulse rating. This results in a step-function nature for all figures of U_w compared to system voltage. The references and corresponding information are shown in Table 4. Each reference's applicability covers the equipment of interest for this study, power cables.

Source	Applicability	Test Voltage Type	Test Duration [min]	Test Category
IEC Std. 60092-503 [39]	**Equipment: Power Supply Systems** **System Type: Shipboard** **Voltage Level: 1-15 [kV] U_n** **Voltage Type:** AC	**DC**	**15**	**Post-Installation**
IEC Std. 60502-2/60092-350 [30] [31]	**Equipment: Power Cables** **System Type: Land/Shipboard** **Voltage Level: 6-30 [kV] U_n** **Voltage Type:** AC	**AC**	**5**	**Acceptance**
IEC Std. 60071-1/2 [4] [32]	**Equip.: Power Supply Systems** **System Type: Land** **Volt. Level: 1-1000 [kV] U_n** **Volt. Type: AC**	**AC**	**1**	**Unspecified**
IEEE Std. 1580 [28]	**Equipment: Power Cables** **System Type: Shipboard and Fixed or Floating Facilities** **Voltage Level: 0.3-35 [kV] U_n** **Voltage Type:** AC	**AC**	**5**	**Acceptance**
IEEE Std. 1709 [2]	**Equipment: Power Supply Systems** **System Type: Shipboard** **Voltage Level: 1-35 [kV] U_n** **Voltage Type:** DC	**DC**	**1**	**Acceptance**
IEEE Std. 400.1 [33]	**Equipment: Power Supply Systems** **System Type: Land** **Voltage Level: 5-500 [kV] U_n** **Voltage Type:** AC	**DC**	**15**	**Post-Installation**
IEEE Std. 400.2 [43]	**Equipment: Power Supply Systems** **System Type: Land** **Voltage Level: 5-69 [kV]** **Voltage Type:** AC	**AC**	**15**	**Post-Installation**
IEEE Std. 400.4 [43]	**Equipment: Power Supply Systems** **System Type: Land** **Voltage Level: 5-69 [kV]** **Voltage Type: AC**	**AC**	**~15**	**Post-Installation**
ABS Steel Vessels Part 4 [36]	**Equipment: Power Supply Systems and Machinery** **System Type: Shipboard** **Voltage Level: 1-15 [kV] U_n** **Voltage Type:** AC	**AC & DC**	**5&1440 (AC), 15 (DC)**	**Post-Installation**
CIGRE TB 496/IEC Std. 62895 [37]	**Equipment: Power Cables** **System Type: Land or Submarine** **Voltage Level: ≤ 500 [kV] U_n** **Voltage Type:** DC	**DC**	**60**	**Acceptance**
MIL-DTL-917F [44]	**Equipment: Power Supply Systems** **System Type: Naval Shipboard Electric Power Equipment** **Voltage Level: 0-15 [kV] U_n** **Voltage Type: AC**	**AC**	**1**	**Acceptance**
MIL-DTL-915G [45]	**Equipment: Power Cables** **System Type: Navy Shipboard Cable** **Voltage Level: 1-5 [kV] U_n** **Voltage Type: AC**	**AC**	**1.5**	**Acceptance**

Table 4: Sources and Scopes for Withstand Test Standards and Recommended Practices

5.1.1 IEC Standards

This IEC standards cover systems with a Nominal System Voltage (U_n) ≤220 [kV]. The corresponding AC Withstand Voltage (U_w) values are in the range of 1.5-460 [kV], for a duration range of 1-15 [min] and frequencies in the range of 48-62 [Hz]. The corresponding DC Withstand Voltage (U_w) values are in the range of 3.6-52.8 [kV] for a duration of 5 [min].

Four standards within the IEC regulate Withstand Tests for shipboard MVAC power cables: Std. 60092-503, 60092-354, 60092-350, and 60502-2. IEC Std. 60092-503 provides guidance for shipboard AC power supply systems with 1-15 [kV] U_n, including cables. §5.5.5 specifies a Withstand Voltage Test after installation for cables. This section calls for a DC voltage of at least $4xU_o$ to be applied to the cable for 15 [min] [39]. Cable Nominal Voltage (U_o) is the phase-to-ground RMS Voltage for an AC system, and the line-to-ground voltage for a DC system. This results in a minimum U_w based on the system U_o, as shown in Figure 31.

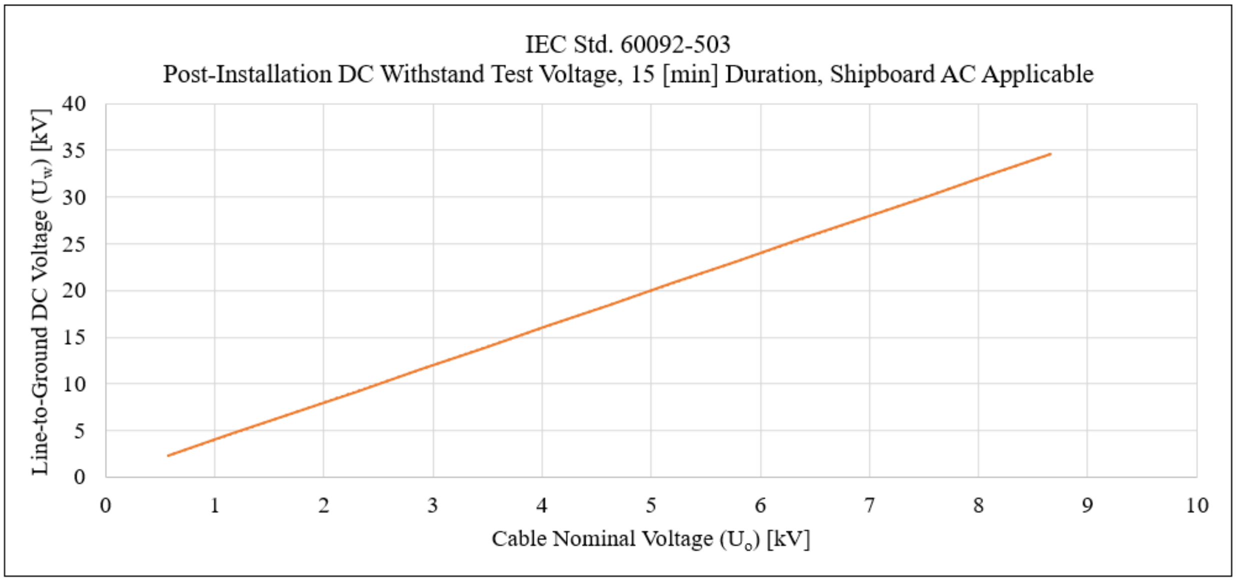


Figure 31: IEC Std. 60092-503 15 [min] Post-Installation DC Withstand Test Voltage (U_w) vs. U_o

Additionally, within IEC Std. 60092-503 §5.5.1 states cables in the medium voltage range of this study shall generally be in accordance with the relevant parts of IEC Stds. 60502, 60092-350, 60092-351, and 60092-354. IEC Std. 60092-351 applies to systems with a nominal system voltage in the range of 1-3 [kV] therefore is not considered for this study as it only covers a small fraction of the lower end of the MV spectrum. IEC Std. 60092-354 directs you to IEC Std. 60092-350 for voltage tests of shipboard AC systems, which contains Withstand Voltage Test guidance within the voltage range of ≤ 30 [kV] U_n. IEC Std. 60502-2 contains Withstand Voltage Test guidelines for land-based AC systems within the voltage range of 6-30 [kV] U_n.

IEC Std. 60092-354 covers shipboard power cables with a 6-30 [kV] U_n and directs you to IEC Std. 60092-350 for voltage tests [40]. IEC Std. 60092-350 covers general construction and testing requirements for electrical installations in ships, intended for AC power systems up to 30 [kV] U_n [31]. This standard specifies an acceptance AC and DC U_w for a given U_o/U_n plotted in Figure 32 and the table shown in Table 5. Test specifications are given in §10.3 of IEC Std. 60092-350. The duration of both the AC and DC Withstand Tests is 5 [min], with a frequency of 49-61 [Hz] for the AC test [31]. However, the DC U_w is stated to be not recommended for systems with > 3 [kV] U_n, and thus are not considered for this study. IEC Std. 60502-2, a standard applicable to land-based applications, contains identical guidance for acceptance BIL tests as IEC Std. 60092-350, limited to the range of 6-30 [kV] Nominal System Voltages [30]. For this study, these standards are presented together and limited to the range of 6-30 [kV] U_n.

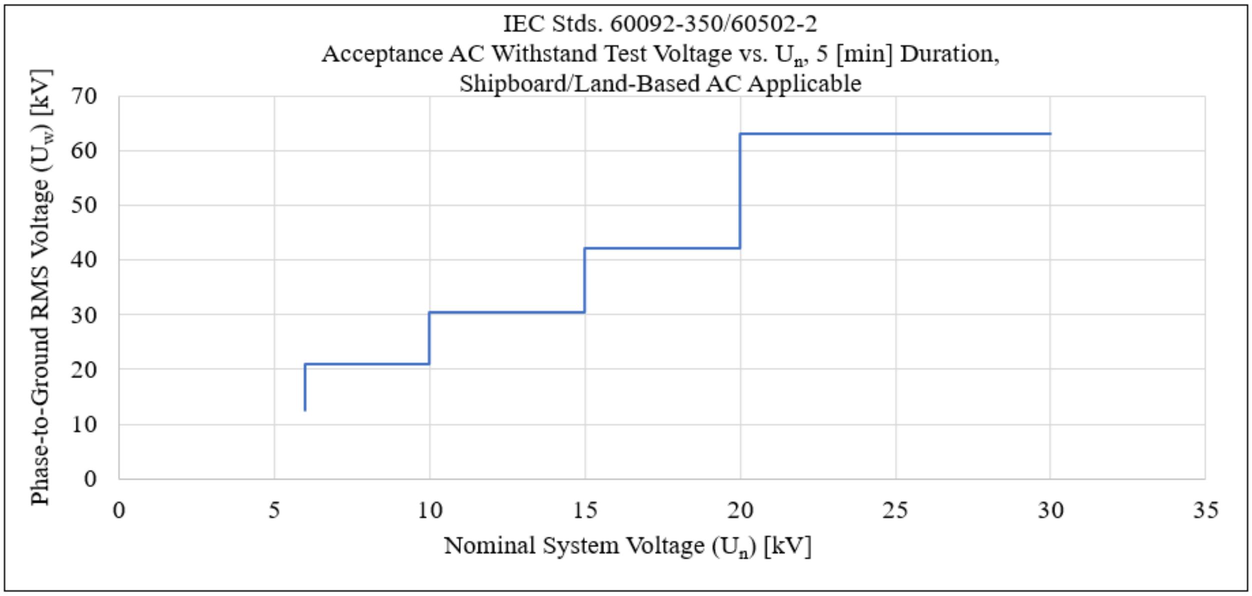


Figure 32: IEC Stds. 60092-350/60502-2 5 [min] Acceptance AC Withstand Test Voltage (U_w) vs. U_n

Rated voltage of cable U_o/U_n kV	Test voltage for 5 min Alternating current (AC) kV
3,6/6	12,5
6/10	21
8,7/15	30,5
12/20	42
18/30	63

Table 5: IEC Stds. 60092-350/60502-2 U_w for a Given U_o/U_n,
Applicable to Shipboard/Land-Based AC [31]

IEC Std. 60092-503 also states in §4.4 that "the conditions on board ships may require certain equipment having an insulation level higher than that of the nominal voltage of the system, see IEC 60071-1 and IEC 60071-2" [39]. IEC Stds. 60071-1/2 cover insulation coordination, specifying the procedure for selecting appropriate insulation design levels for three phase AC systems [4]. Withstand voltage levels are specified in §5.10 of IEC Std. 60071-1 for corresponding Highest Voltage for Equipment (U_m), but it does not explicitly state if the tests are acceptance or post-installation Withstand Tests. The values of the unspecified type of test are plotted in Figure 33 and shown in Figure 34 [4]. These references outline a 1 [min] Withstand Test duration at 48-62 [Hz], described in §6.2 of IEC 60071-1 [4]. Aside from the magnitude of U_w, duration, and frequency, these standards do not specify any other test parameters. These parameters are left to be "specified by the relevant apparatus committees" [4]. The range of U_w for high U_m is addressed in §5.1 of IEC Std. 60071-2, stating the selection level should "take into account the insulation characteristics of the particular equipment being considered" [32]. There is no range of U_w within the area of interest for this study.

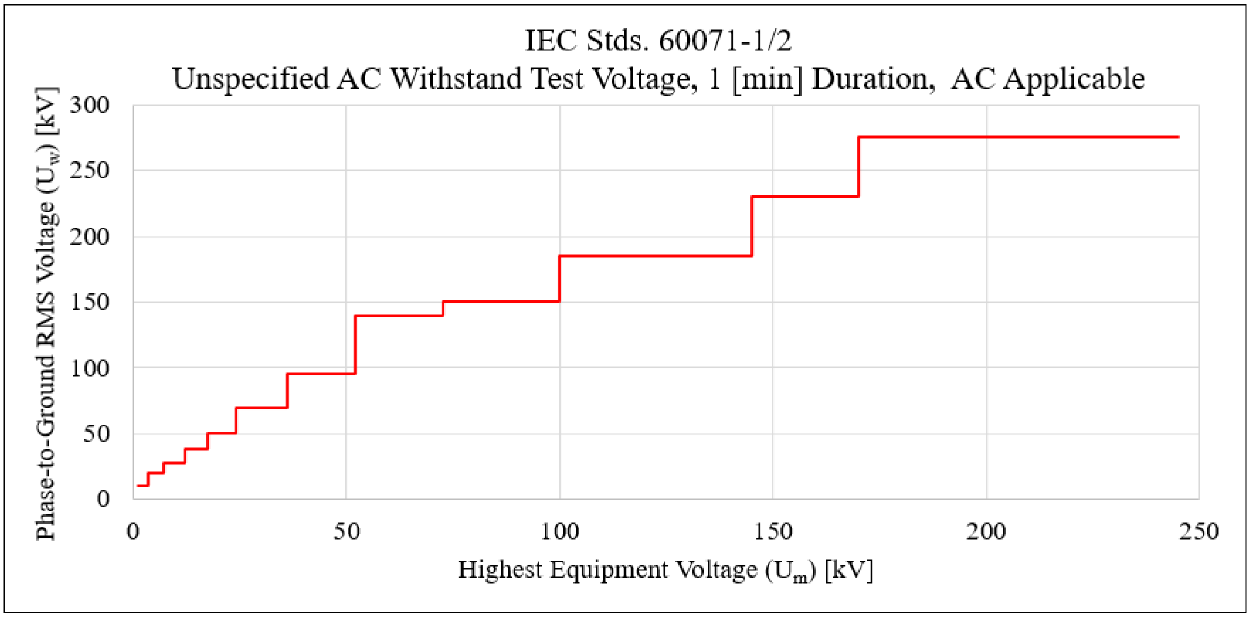


Figure 33: IEC Stds. 60071-1/2 1 [min] Unspecified AC Withstand Test Voltage (U_w) vs. U_m

Highest voltage for equipment, U_m kV (RMS value)	Standard rated short-duration power-frequency withstand voltage kV (RMS value)
3,6	10
7,2	20
12	28
17,5 [a]	38
24	50
36	70
52 [a]	95
72,5	140
100 [b]	(150)
	185
123	(185)
	230
145	(185)
	230
	275
170 [a]	(230)
	275
	325
245	(275)
	(325)
	360
	395
	460

Figure 34: IEC Std. 60071-1 Withstand Voltage (U_w) for a Given Highest Voltage for Equipment (U_m), Applicable to Shipboard AC [kV] [4]

Another applicable standard within IEC is Std. 62895, covering HVDC cables up to 320 [kV]. This standard is evaluated in §5.1.5 of this study.

5.1.2 IEEE Standard and Recommendations

This section evaluates systems with a Nominal System Voltage (U_n) in the range of 1-500 [kV]. The corresponding AC Withstand Test Voltage (U_w) values are in the range of 6-254 [kV], for a duration range of 5-30 [min], and a frequency range of 0.1-62 [Hz]. The corresponding DC Withstand Voltage (U_w) values in the range of 10-838 [kV] for a duration of 1-15 [min].

Five standards within the IEEE regulate Withstand Tests for MV power cables: 1580, 1709, 400.1, 400.2, and 400.3. IEEE Std. 1580 covers recommended practices for marine cables in AC systems with U_n between 0.3 and 35 [kV] [28]. This standard specifies acceptance Withstand Voltage (U_w) for cables based on conductor size and Nominal System Voltage (U_n) between 2 and 35 [kV] in §5.17.1 [28]. This standard specifies two different U_w, one for 100% and 133% insulation levels. Cables with 100% insulation are intended for use in systems where ground faults are cleared in less than 1 [min], while 133% insulation level cables are intended for systems where ground faults are cleared between 1-60 [min] [29]. IEEE Std. 1580 also specifies a 173% insulation level for systems where the fault clearing times exceed 1 [hr] but does not provide these values of U_w [28]. The AC Withstand Tests outlined by IEEE Std. 1580 have a 5 [min] duration, with a frequency of 48-62 [Hz] [28] [46]. Figure 35 shows the plotted levels of U_w for both the 100% and 133% insulation levels, which are given in Figure 36.

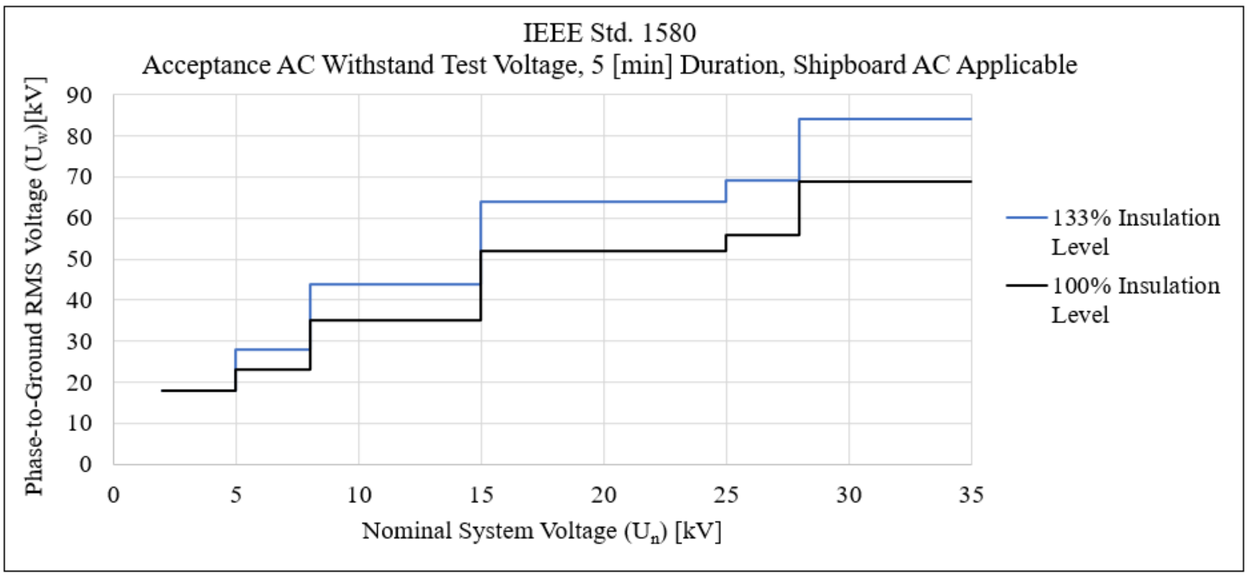


Figure 35: IEEE Std. 1580 5 [min] Acceptance AC Withstand Test Voltages (U_w) vs. U_n

Rated circuit voltage phase to phase	Conductor size	100% insulation level (grounded neutral)	133% insulation level (ungrounded neutral)
2001 – 5000	8 AWG – 1111 kcmil	18	18
5001 – 8000	6 AWG – 1111 kcmil	23	28
8001 – 15000	2 AWG – 1111 kcmil	35	44
15001 – 25000	1 AWG – 1111 kcmil	52	64
25001 – 28000	1 AWG – 1111 kcmil	56	69
28001 – 35000	1/0 AWG – 1111 kcmil	69	84

Figure 36: IEEE Std. 1580 Acceptance AC Withstand Voltage (U_w) for a Given Nominal System Voltage (U_n), Applicable to Shipboard AC [28]

IEEE Std. 1709 applies to 1-35 [kV] shipboard MVDC power systems [2]. This standard outlines an acceptance Withstand Voltage Test with DC U_w levels for a given U_n in §5.2.3, plotted in Figure 37. These DC U_w are to be applied for a duration of 1 [min] for each test and are given in Figure 38 [2].

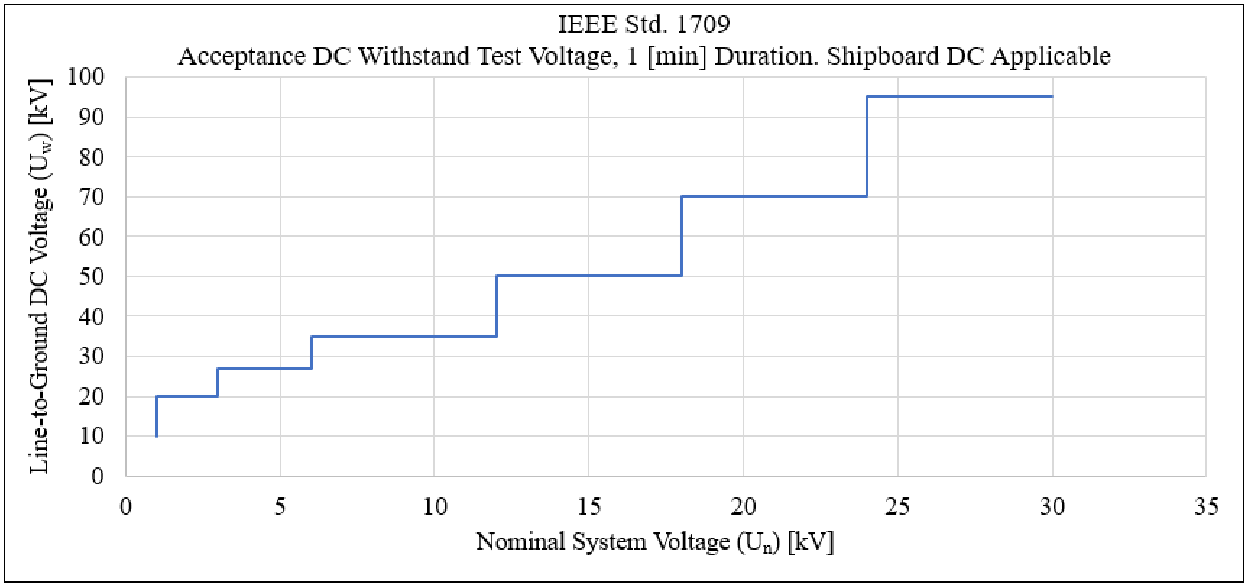


Figure 37: IEEE Std. 1709 1 [min] Acceptance DC Withstand Test Voltage (U_w) vs. U_n

MVDC class	Rated short-duration withstand voltage to ground U_d kV for 1 min
1	10
3	20
6	27
12	35
18	50
24	70
30	95

Figure 38: IEEE Std. 1709 Acceptance DC Withstand Voltage (U_w) for a Given Nominal System Voltage (U_n), Applicable to Shipboard DC [2]

The IEEE Std. 400 series contains parts 1-4 (400.1-400.4) guiding field testing and evaluation for the insulation of land-based AC power transmission cable systems rated 5 [kV] and above [33]. Parts 1, 2, and 4 contain Withstand Tests using different types of applied voltages and are evaluated in this section [33] [43] [47]. Part 3 covers only a partial discharge test and was not evaluated for this study [48].

IEEE Std. 400.1 outlines a 15 [min] post-installation DC Withstand Test. §4 of this reference provides the test procedures and magnitude of U_w based on U_n. The upper and lower bounds of this reference are plotted versus U_n in Figure 39. The values of these withstand voltages are given in Figure 40 [33]. Of note, this standard uses the term “acceptance test” as the test applied to a cable after it is installed but before it is put into service, which corresponds to this study’s post-installation test. The standard also gives U_w values for and maintenance tests, which were not evaluated in this study.

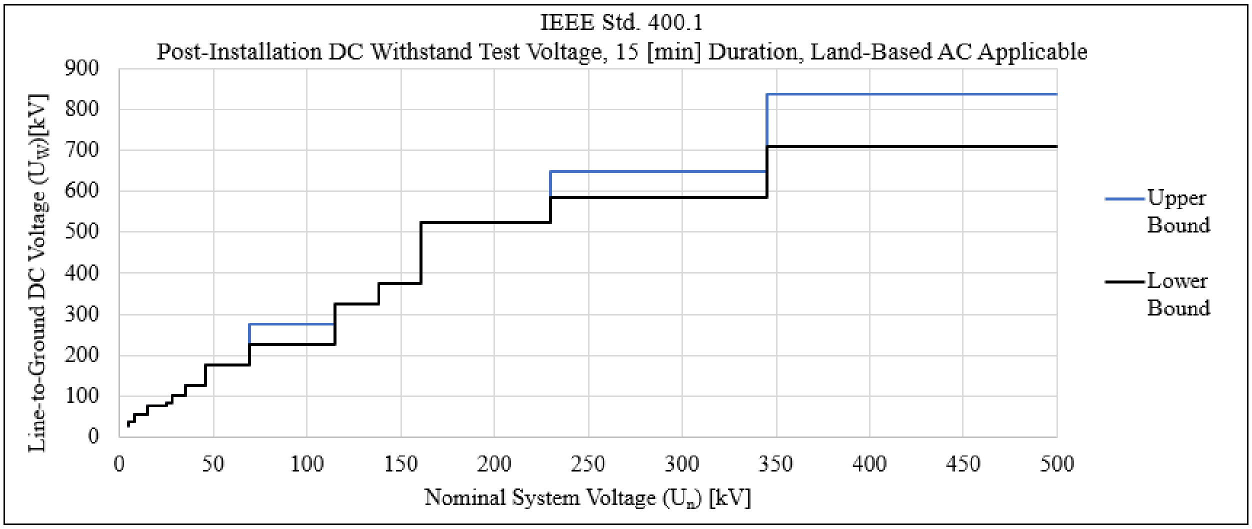


Figure 39: IEEE Std. 400.1 15 [min] Post-Installation DC Withstand Test Voltages (U_w) vs. U_n

System voltage, kV rms, phase-to-phase	System BIL, kV crest	Acceptance test, kV dc, phase-to-ground	Maintenance test, kV dc, phase-to-ground
5	75	28	23
8	95	36	29
15	110	56	46
25	150	75	61
28	170	85	68
35	200	100	75
46	250	125	95
69	350	175	130
115	450	225	170
115	550	275	205
138	650	325	245
161	750	375	280
230	1050	525	395
345	1175	585	440
345	1300	650	488
500	1425	710	535
500	1550	775	580
500	1675	838	629

Figure 40: IEEE 400.1 BIL and Withstand Voltage (U_w) for a Given Nominal System Voltage (U_n), Applicable to Land-Based AC [33]

IEEE Std. 400.2 contains recommendations for VLF (0.1 [Hz]) AC Acceptance Withstand Test specifications in §5 [43]. Table 3 from the standard, shown in Figure 42, contains both acceptance test levels and installation test levels, however, their definitions differ from this study [43]. In IEEE 400.2 an acceptance test occurs after cable system installation but before normal service, while an installation test occurs after installation but before jointing or terminating the cable into the system [43]. The IEEE Std. 400.2 acceptance test matches this study's post-installation test and will be displayed as such henceforth in this document. The acceptance column (post-installation for this study) of Figure 42 contains U_w for an post-installation test corresponding to U_n, with a recommended duration of at least 30 [min], plotted in Figure 41 [43]. U_w for maintenance tests were also given but were not considered for this study.

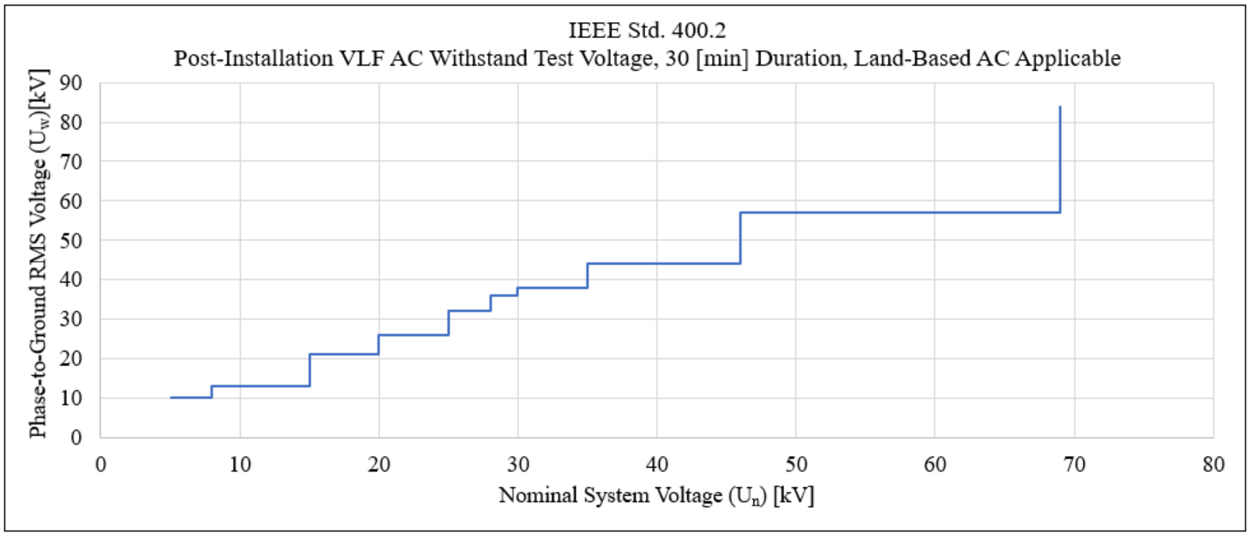


Figure 41: IEEE Std. 400.2 30 [min] Post-Installation VLF AC Withstand Test Voltage (U_w) vs. U_n

Waveform	Cable system rating (phase to phase) [kV]	Installation (phase to ground)		Acceptance (phase to ground)		Maintenance[2] (phase to ground) (see Note 2)	
		[kV rms]	[kV peak]	[kV rms]	[kV peak]	[kV rms]	[kV peak]
Sinusoidal	5	9	13	10	14	7	10
	8	11	16	13	18	10	14
	15	19	27	21	30	16	22
	20	24 (Note 3)	34 (Note 3)	26	37	20	28
	25	29 (Note 3)	41 (Note 3)	32	45	24 (Note 3)	34 (Note 3)
	28	32	45	36 (Note 3)	51 (Note 3)	27	38
	30	34	48	38	54	29 (Note 3)	41 (Note 3)
	35	39	55	44	62	33	47
	46	51	72	57	81	43	61
	69	75	106	84	119	63	89

Figure 42: IEEE 400.2 VLF Withstand Voltage (U_w) for a Given Nominal System Voltage (U_n), Applicable to Land-Based AC [43]

Finally, IEEE Std. 400.4 contains recommendations for damped AC (DAC) Withstand Test specifications in §5.2 [43]. IEEE Std. 400.4 is the only standard within this study that was found to have a DAC

Withstand Test. Table A.1 from the standard is shown in Figure 45 containing U_w (shown as V_T) for a Withstand Test corresponding to U_n and U_o. This standard calls for 50 pulses of DAC to be applied to the cable for the post-installation Withstand Test. The form of these pulses is shown in Figure 43 with the following parameters: V_T being the U_w maximum voltage, the charging time being on the order of tens of seconds, and the discharge time on the order of milliseconds [47]. 50 pulses of this DAC leads to a duration between 8.3 and 16.6 [min], assuming a charging time of 10-20 [s]. For this study a duration of ~15 [min] will be used. Figure 44 shows the plotted U_w compared to U_n, with the lower value of U_n used for the defined ranges in Figure 45. IEEE Std. 400.4 also outlines a maintenance Withstand Voltage Test, but it is not considered for this study.

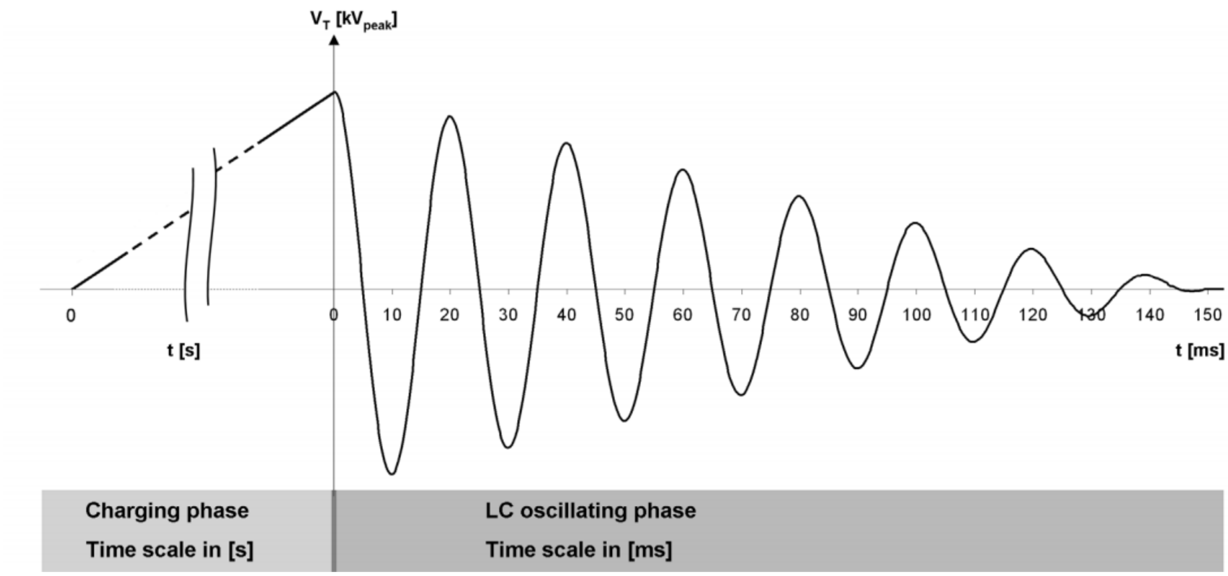


Figure 43: IEEE Std. 400.4 Characteristics of DAC Pulses [47]

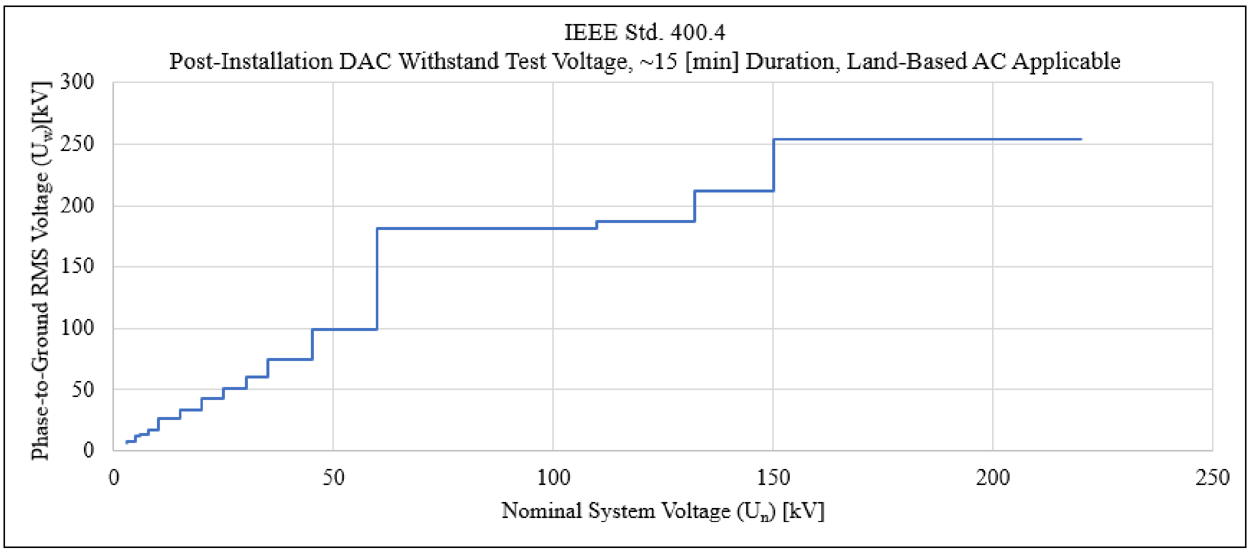


Figure 44: IEEE Std. 400.4 ~15 [min] Post-Installation DAC Withstand Test Voltage (U_w) vs. U_n

Power cable rated voltage U [kV] phase-to-phase	U_0 [kV]	DAC test voltage level V_T [kV_{peak}] phase-to-ground
3	2	6
5	3	8
6	4	12
8	5	14
10	6	17
15	9	26
20	12	34
25	15	43
30	18	51
35	21	60
45–47	26	74
60–69	35	99
110–115	64	181
132–138	77	187
150–161	87	212
220–230	127	254

Figure 45: IEEE 400.2 DAC Withstand Voltage (U_w) for a Given Nominal System Voltage (U_n), Applicable to Land-Based AC [47]

5.1.3 American Bureau of Shipping Requirements

These requirements cover systems with a Nominal System Voltage (U_n) in the range of 1-15 [kV]. The corresponding AC Withstand Voltage (U_w) values are in the range of 1.7-20 [kV], for a duration range of 5-1440 [min], with an unspecified frequency. The corresponding DC Withstand Voltage (U_w) values in the range of 7.2-48 [kV] for a duration of 15 [min].

In accordance with ABS Steel Vessel Requirements Part 4 §3.13.3, each completed cable and its accessories that will be used in a system with a $U_n > 3$ [kV] shall have a post-installation Withstand test conducted to the levels specified in §3.9.6 [36]. One of the following tests methods may be used:

1. An AC test voltage applied for 5 [min] with U_n applied between the conductor and the metallic screen/sheath.
2. An AC voltage test for 24 [hr] at the phase-to-ground RMS voltage (U_o) for the completed system.
3. A DC test voltage equal to 4 times the minimum rated voltage of the cable for 15 [min].

The ABS defines cable ratings by set levels of U_n, and provides corresponding parameters for highest system voltage (U_m in this reference) and minimum rated cable voltage (U_o), shown in Figure 47 [36]. Values corresponding to a maximum of 15 [kV] U_n are used for evaluation in this study, as the ABS states this limit for shipboard use. Of note, the U_o used by the ABS is different than the U_o of this study. The ABS U_o is a minimum rated phase-to-ground RMS voltage required for a cable to be used in a system with voltage U_n as a safety factor. This value is greater than U_o used in this study, which is the nominal phase-to-ground RMS voltage ($U_n/\sqrt{(3)}$). For clarity this study will refer to the ABS voltage as "minimum rated voltage of cable" henceforth.

The first allowable withstand test from the ABS is an AC phase-to-ground RMS voltage at the level of U_n applied for 5 [min]. The lower values of the U_n ranges provided in Figure 47 were used for this study. The relationship of the testing voltage with the system voltage as is shown in Figure 46.

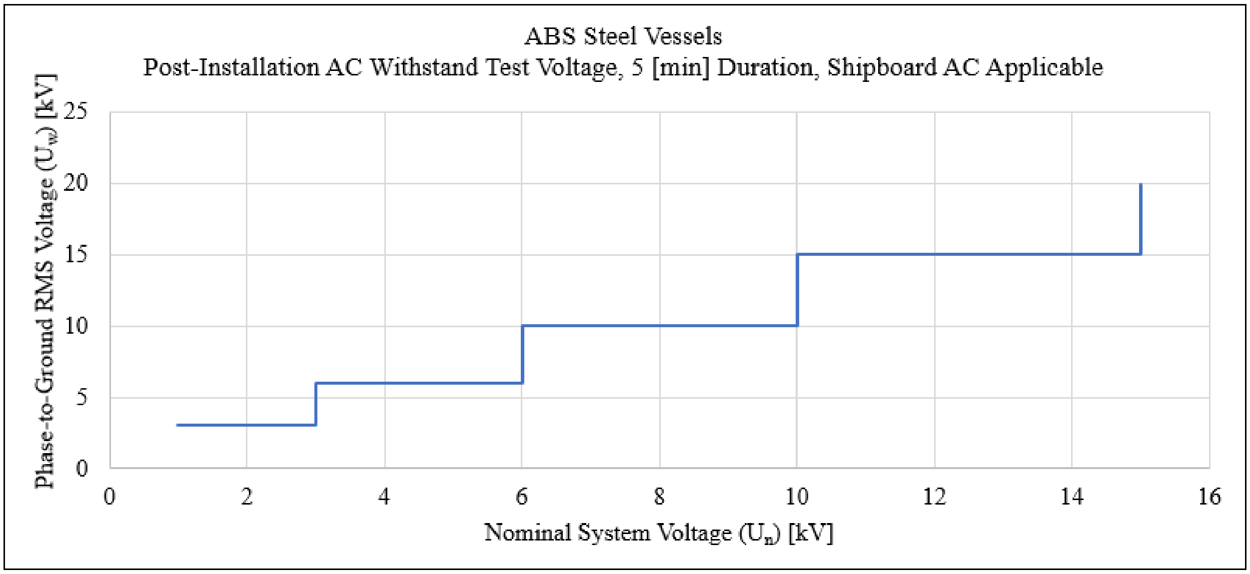


Figure 46: ABS Test 1, 5 [min] Post-Installation AC Withstand Test Voltage (U_w) vs. U_n

Nominal System Voltage (U_n) (kV)	*Highest System Voltage (U_m) (kV)*	*Minimum Rated Voltage of Cable (U_o/U) (kV)*	
		Systems with Automatic Disconnection Upon Detection of an Earth Fault	*Systems without Automatic Disconnection Upon Detection of an Earth Fault*
3.0/3.3	3.6	1.8/3.0	3.6/6.0
6.0/6.6	7.2	3.6/6.0	6.0/10.0
10.0/11.0	12.0	6.0/10.0	8.7/15.0
15.0/16.5	17.5	8.7/15.0	12.0/20.0
20.0/22.0	24.0	12.0/20.0	18.0/30.0

Figure 47: ABS Cable Rating Guidelines [36]

The second withstand test outlined by the ABS calls for a cable to be tested at the normal operating voltage, U_o for a single cable, for 24 [hr]. This U_w is obtained by dividing the given U_n by √(3). The relationship between U_w and U_n for this withstand test is shown in Figure 48 below.

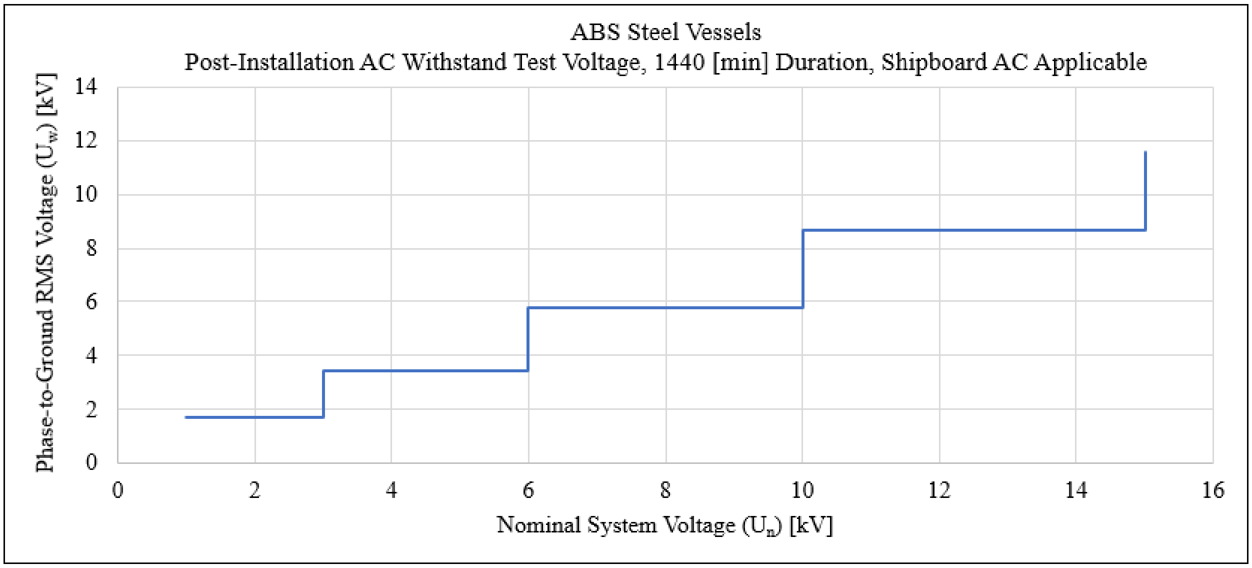


Figure 48: ABS Test 2, 1440 [min] Post-Installation AC Withstand Test Voltage (U_w) vs. U_n

The third and final withstand test defined by the ABS calls for U_w to be a DC voltage at 4 times the minimum rated voltage of cable, applied for 15 [min]. For each U_n and minimum rated voltage of cable range in Figure 47 the lower value is used, up to 15 [kV] due to the applicable shipboard limit. Minimum rated voltages of cables for systems without automatic disconnection were used, as this is the most likely scenario for a warship and a conservative estimate. This relationship between U_w and U_n is shown in Figure 49.

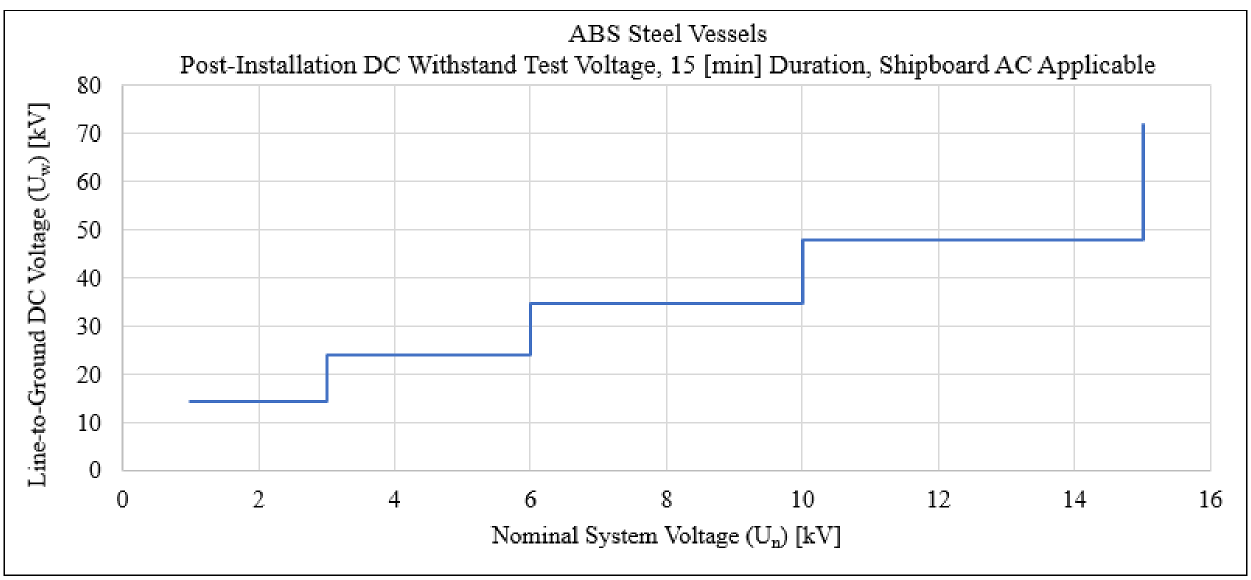


Figure 49: ABS Test 3, 15 [min] Post-Installation DC Withstand Test Voltage (U_w) vs. U_n

5.1.4 ICEA Standard

The Insulated Cable Engineers Association (ICEA) develops cable standards for electric power, control, and telecommunications industries, many of which are approved by the American National Standards Institute (ANSI) [42]. Cable manufacturers around the world use ICEA guidance for the cable design process. The evaluated standard covers systems with a Nominal System Voltages (U_n) 5-46 [kV], with corresponding Acceptance Withstand Test Voltages in the range of 18-150 [kV] for AC U_w, 35-275 [kV] for DC U_w [35]. The standard evaluated is applicable to AC utility power cables.

ICEA S-97-682 outlines an Acceptance Withstand Test with an AC U_w to be conducted at the voltage levels plotted in Figure 50 and shown in Figure 51. The test voltages shall have a frequency of 49-61 [Hz], be conducted at room temperature, and have a duration of 5 [min] [35]. This standard also outlines an optional DC U_w Withstand Test, with the values plotted in Figure 52 and shown in Figure 53, for a duration of 15 [min] [35]. Note that both the AC and DC U_w have 100%, 133%, and 173% levels corresponding to the percent insulation level of the system. Additionally, the voltage levels are dependent on the conductor size. For this study, conductors with the range of AWG 1/0 and 1000 [kcmil] will be evaluated. Within this range of conductor size, the U_w outlined by the ICEA is independent of conductor size. However, the lower limit on conductor size from this ICEA standard is AWG 0 (53.5 [mm^2]) for 28-35 [kV] U_n systems, and AWG 4/0 (107 [mm^2]) for 35-46 [kV] U_n systems [35].

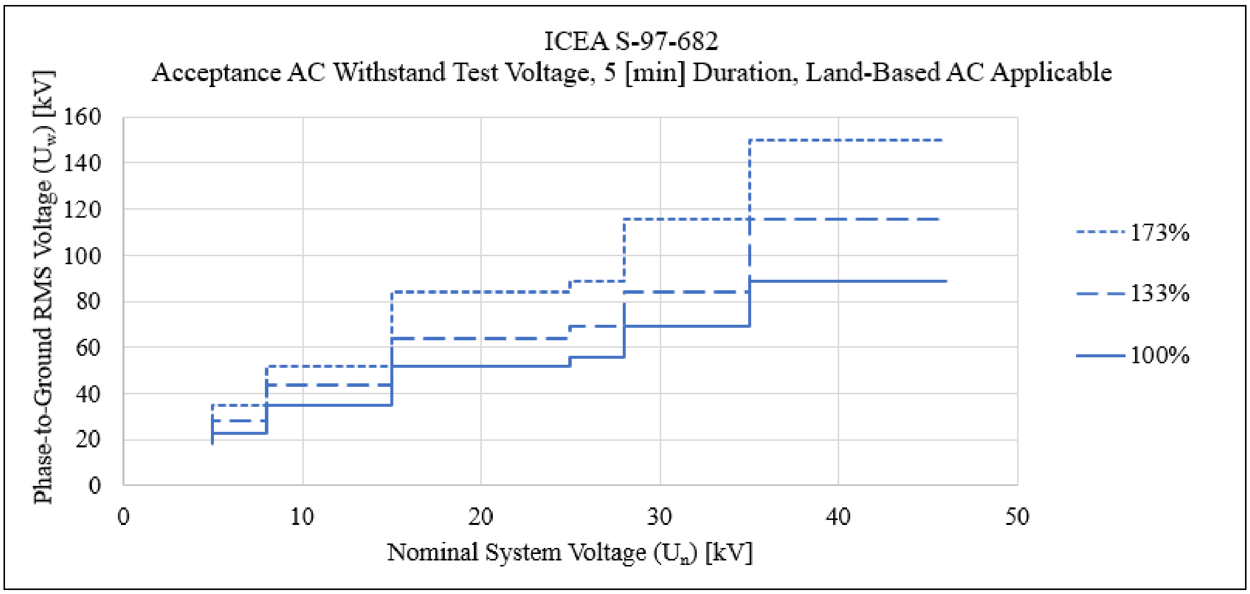


Figure 50: ICEA 5 [min] Acceptance AC Withstand Test Voltages (U_w) vs. U_n

Rated Phase-to-Phase Circuit Voltage[a]	Conductor Size, (AWG or kcmil)[b]	Insulation Thickness (mils)						a-c Test Voltage, kV[d]		
		100 Percent Level[c]		133 Percent Level[c]		173 Percent Level[c]		Insulation Level		
		Min	Max	Min	Max	Min	Max	100%	133%	173%
2001-5000	8-1000[e]	85	120	110	145	135	170	18	23	28
	1001-3000	135	170	135	170	135	170	28	28	28
5001-8000	6-1000	110	145	135	170	165	205	23	28	35
	1001-3000	165	205	165	205	210	250	35	35	44
8001-15000	2-1000	165	205	210	250	245	290	35	44	52
	1001-3000	210	250	210	250	245	290	44	44	52
15001-25000	1-3000	245	290	305	350	400	450	52	64	84
25001-28000	1-3000	265	310	330	375	425	495	56	69	89
28001-35000	1/0-3000	330	375	400	460	550	630	69	84	116
35001-46000	4/0-3000	425	495	550	630	*	*	89	116	150

Figure 51: ICEA Acceptance AC Withstand Test Voltages (U_w) for a Given Nominal System Voltage (U_n) [35]

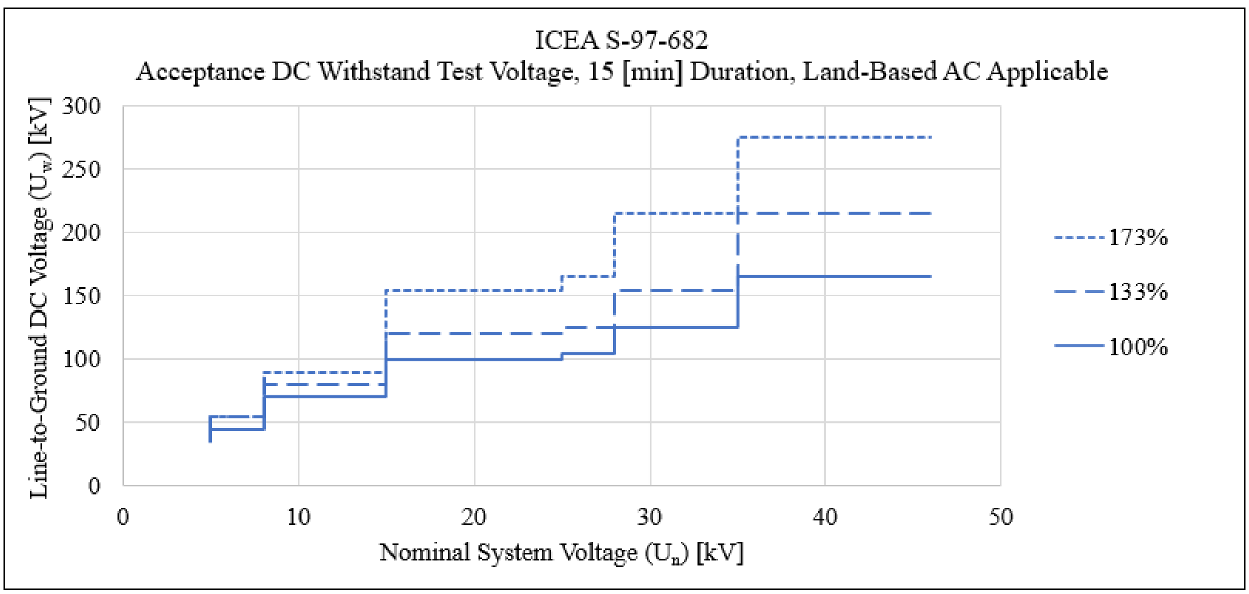


Figure 52: ICEA 15 [min] Acceptance DC Withstand Test Voltages (U_w) vs. U_n

Rated Phase-to-Phase Circuit Voltage	Conductor Size, AWG or kcmil (mm^2)	Insulation Thickness mils (mm)						dc Test Voltage, kV		
		100 Percent Level		133 Percent Level		173 Percent Level		Insulation Level		
		Min	Max	Min	Max	Min	Max	100%	133%	173%
2001-5000	8-1000 (8.37-506.7)	85 (2.16)	120 (3.05)	110 (2.79)	145 (3.68)	135 (3.43)	170 (4.32)	35	45	45
	1001-3000 (506.8-1520)	135 (3.43)	170 (4.32)	135 (3.43)	170 (4.32)	135 (3.43)	170 (4.32)	35	45	45
5001-8000	6-1000 (13.3-506.7)	110 (2.79)	145 (3.68)	135 (3.43)	170 (4.32)	165 (4.19)	205 (5.21)	45	55	55
	1001-3000 (506.8-1520)	165 (4.19)	205 (5.21)	165 (4.19)	205 (5.21)	210 (5.33)	250 (6.35)	45	55	70
8001-15000	2-1000 (33.6-506.7)	165 (4.19)	205 (5.21)	210 (5.33)	250 (6.35)	245 (6.22)	290 (7.37)	70	80	90
	1001-3000 (506.8-1520)	210 (5.33)	250 (6.35)	210 (5.33)	250 (6.35)	245 (6.22)	290 (7.37)	70	80	90
15001-25000	1-3000 (42.4-1520)	245 (6.22)	290 (7.37)	305 (7.75)	350 (8.89)	400 (10.2)	450 (11.4)	100	120	155
25001-28000	1-3000 (42.4-1520)	265 (6.73)	310 (7.87)	330 (8.38)	375 (9.53)	425 (10.8)	495 (12.6)	105	125	165
28001-35000	1/0-3000 (53.5-1520)	330 (8.38)	375 (9.53)	400 (10.2)	460 (11.7)	550 (14.0)	630 (16.0)	125	155	215
35001-46000	4/0-3000 (107.2-1520)	425 (10.8)	495 (12.6)	550 (14.0)	630 (16.0)	*	*	165	215	275

Figure 53: ICEA Acceptance DC Withstand Test Voltages (U_w) for a Given Nominal System Voltage (U_n) [35]

This standard also describes post-installation and maintenance DC Withstand Tests, with 15 [min] and 5 [min] respective durations [35]. The voltages of these tests are plotted in Figure 54 and shown in Figure 55. As with the acceptance test, the U_w outlined by the ICEA is dependent on conductor size. However, within the range of conductor size evaluated within this study the U_w is independent of conductor size. Maintenance Withstand Tests are not included within this study.

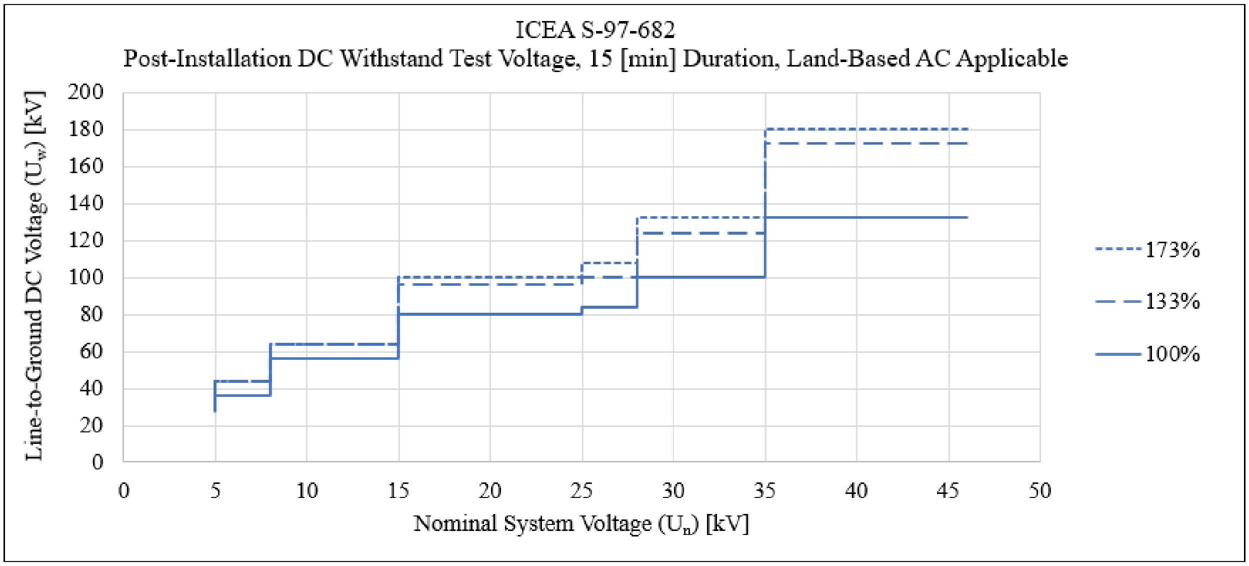


Figure 54: ICEA 15 [min] Post-Installation DC Withstand Test Voltages (U_w) vs. U_n

Rated Phase to Phase Circuit Voltage	Conductor Size AWG or kcmil (mm²)	Maximum dc Field Test Voltages-kV					
		During/After Installation			First 5 Years		
		Insulation Level			Insulation Level		
		100%	133%	173%	100%	133%	173%
2001-5000	8-1000 (8.4-507) Above 1000 (507)	28 28	36 36	36 36	9 9	11 11	11 11
5001-8000	6-1000 (13.3-507) Above 1000 (507)	36 36	44 44	44 56	11 11	14 14	14 14
8001-15000	2-1000 (33.6)-507) Above 1000 (507)	56 56	64 64	64 64	18 18	20 20	20 20
15001-25000	1-2000 (42.4-1013)	80	96	100	25	30	31
25001-28000	1-2000 (42.4-1013)	84	100	108	26	31	33
28001-35000	1/0-2000 (53.5-1013)	100	124	132	31	39	41
35001-46000	4/0-2000 (107.2-1013)	132	172	180	41	54	56

Figure 55: ICEA Post-Installation and Maintenance DC Withstand Test Voltages (U_w) for a Given Nominal System Voltage (U_n) [35]

5.1.5 HVDC Standards and Recommendations

The HVDC standards and recommendations cover systems with a Nominal System Voltages (U_n) ≤500 [kV], with corresponding Withstand Test levels up to 462.5 [kV]. The references presented are applicable to terrestrial and submarine DC systems.

CIGRE Technical Brochure 496 and IEC Std. 62895 specify recommended tests for HVDC power cables up to and including 500 [kV] / 320 [kV] respectively. While these references are intended for HVDC power transmission systems, the MVDC range of interest is covered and thus they were considered for this study. CIGRE TB 496 was published in 2012, after which IEC Std. 62895 was published in 2017 containing identical guidance [37] [38]. The acceptance Withstand Test Voltage (U_w) magnitude and duration are outlined in §5.1 of CIGRE TB 496 and §9.2 of IEC Std. 62895, is 1.85xU_o, to be applied between the conductor and ground for 1 [hr] [37] [38]. While these recommendations apply to system voltages up to 500/320 [kV] respectively, high voltage systems are generally considered to be systems with voltages greater than 69 [kV] U_n. To properly portray this, the Withstand Voltage versus U_o shown in Figure 56 is dashed for U_o less than 34.5 [kV] (corresponding to 69 [kV] U_n).

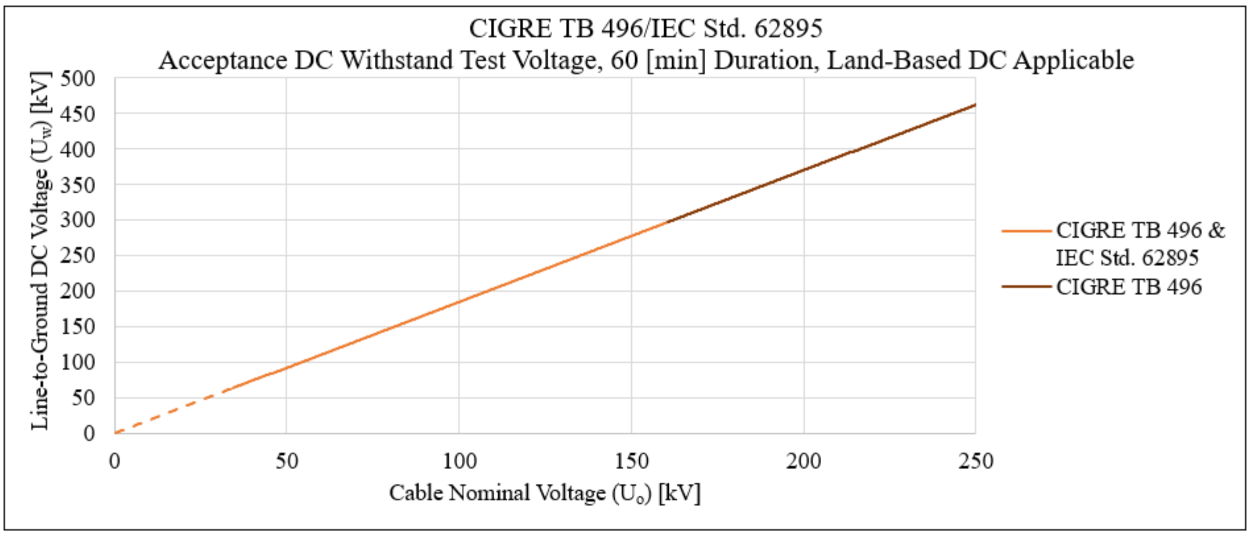


Figure 56: CIGRE TB 496/IEC Std. 62895 60 [min] Acceptance DC Withstand Test Voltage (U_w) vs. U_o

5.1.6 USN Requirements

This section's references are detail specifications that are applicable to shipboard systems with a Nominal System Voltage (U_n) in the range of 0-15 [kV], with corresponding Withstand Test levels in the range of 1-31 [kV] for a duration range of 1-1.5 [min].

MIL-DTL-917F provides basic requirements for USN shipboard electric power equipment, to include the Withstand Test. The detail specification sheet states that it is applicable for systems up to 0.45 [kV] AC or 1 [kV] DC unless otherwise specified, however, for the Withstand Test, AC systems up to 15 [kV] are specified [44]. The test calls to have 2 times U_n + 1[kV] at 60 [hz] for no less than 1 [min] applied to the test cable between the conductor and ground, following the procedure outlined by Method 301 of MIL-STD-202 for an acceptance test [44]. This relationship between U_w and U_n is shown in Figure 57.

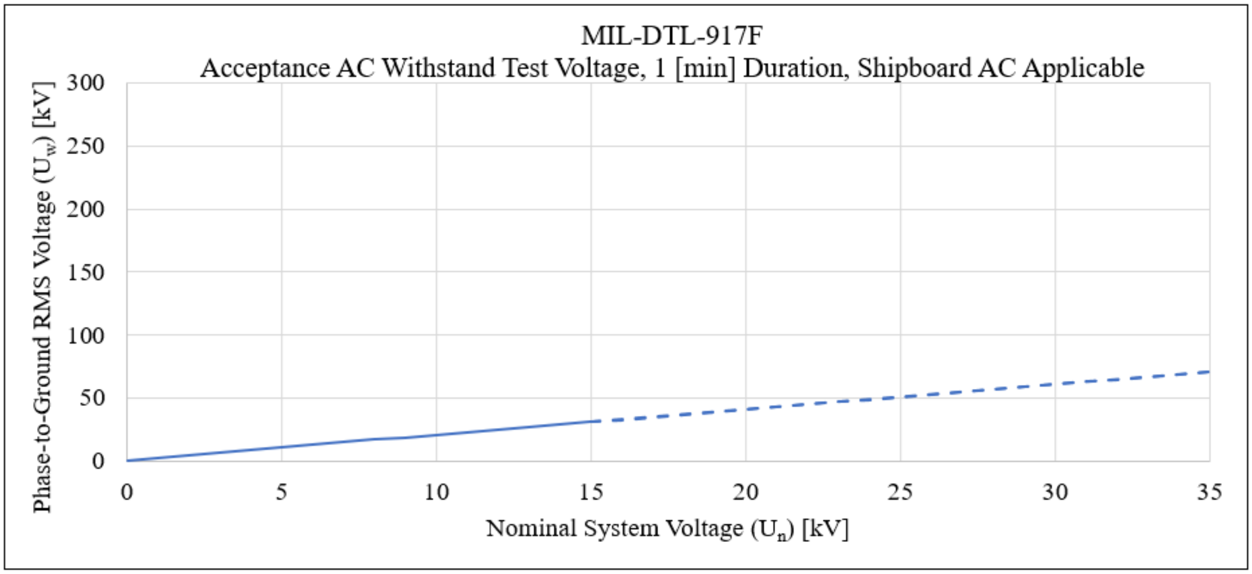


Figure 57: MIL-DTL-917F 1 [min] Acceptance AC Withstand Test Voltage (U_w) vs. U_n

MIL-DTL-915G also provides guidance for electrical cables for Navy shipboard applications and gives specific guidance for AC Withstand Tests in §4.6.5 [45]. This detail specification calls for the applied voltage to be at less than 100 [Hz], for no less than 1.5 [min], and at a U_w given by the cable specification sheet [45]. Cable specifications sheets were gathered for cables prescribed by MIL-DTL-24643B and plotted as data points in Figure 58, and shown in Table 6 [49]. The Withstand Voltages prescribed for a given U_n were given in either phase-to-phase RMS voltage or phase-to-ground RMS voltage.

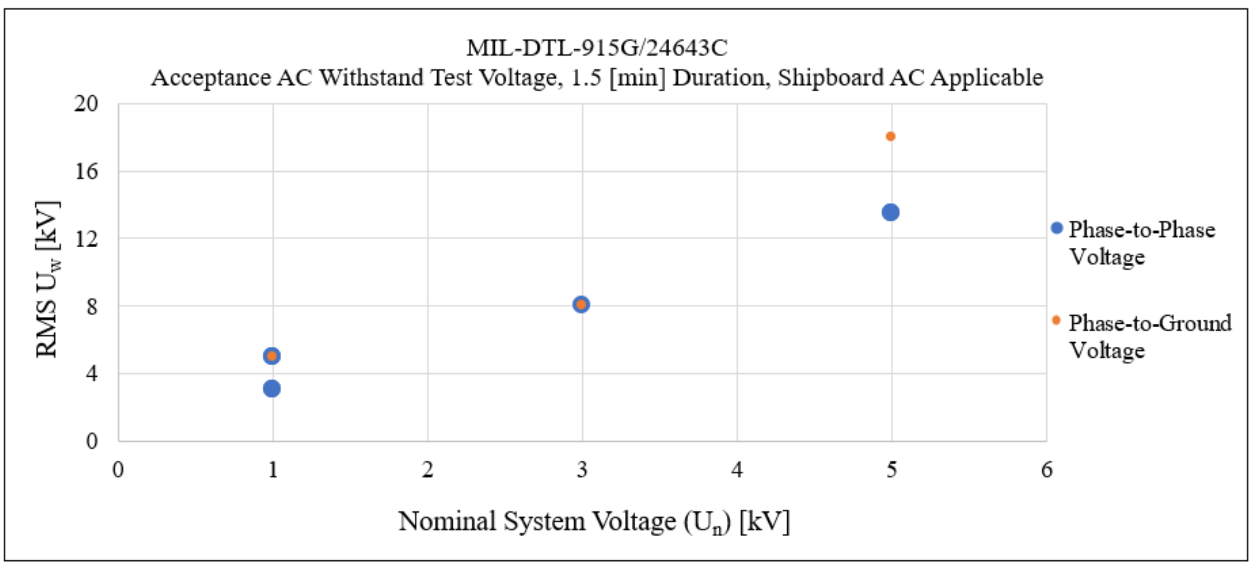


Figure 58: MIL-DTL-915G 1.5 [min] Acceptance AC Withstand Test Voltage (U_w) vs. U_n

MIL-DTL-24643B Spec Sheet [Source]	U_n [kV]	Phase-to-Phase RMS U_w [kV]	Phase-to-Ground RMS U_w [kV]
14F [50]	1	N/A	5
76F (133%) [51]	5	N/A	18
53F [52]	3	8	8
15F, 16F, and 17F (AWG 3-9) [53] [54] [55]	1	3	N/A
15F, and 16F (AWG 14+) [53] [55]	1	5	N/A
17F (AWG 23+) [54]	1	5	N/A
20F [56]	1	3	N/A
22E [57]	5	13.5	N/A
86 [58]	5	13.5	N/A

Table 6: USN (MIL-DTL-915G/MIL-DTL-24643B) Shipboard Cable Withstand Voltage (U_w) for a Given Cable and Nominal System Voltage (U_n)

5.2 Consolidation of Reference Data

The intent of this section is to examine the data gathered from the preceding section's references in comparable terms. This is accomplished through the following actions:

1. Plotting each reference's U_w versus Nominal System Voltage (U_n) by converting the compared cable or system voltage appropriately. If this is required, it is explained in the paragraph introducing the reference's modified figure.
2. Generating continuous trendline approximations from original step-curve defined by each reference. Most references provide U_w that make a step-change of varying amounts, with the steps at varying voltages which made it difficult to directly compare the standards. This study visualizes the step-nature of these curves by converting them into an equivalent polynomial trendline using least squares regression on the centers of the horizontal and vertical portions of each step. For references that provide guidance beyond 35 [kV] U_n, data points up to 90 [kV] U_n are used to ensure the form of the curve accurately represented the reference. Some references provide U_w with a linear equation based on a system voltage, continuous trendlines are not generated for these references. The generated trendlines are represented as dashed lines, with the points used to fit the lines marked with an "x" on the respective figure. All trendline equations are displayed on the figures. Each manipulated reference is plotted with similar bounds for U_w and U_n for ease of visual comparison.
3. Calculating trendlines for U_w versus Cable Nominal Voltage (U_o) and Nominal Peak Cable Voltage (U_p) by dividing U_n by $\sqrt{(3)}$ and then multiplying by $\sqrt{(2)}$, respectively. These trendlines for each reference, as well as the trendline for U_w versus U_n, are shown in §5.2.6 Table 7.

5.2.1 IEC Standards

IEC Std. 60092-503 outlines U_w for given systems based on the Highest Voltage for Equipment, U_m. A chart from within the standard showing corresponding U_n for each U_m is shown in Figure 19. For a given range of U_n the lower value is used for plotting the relationship with U_w, shown in Figure 59.

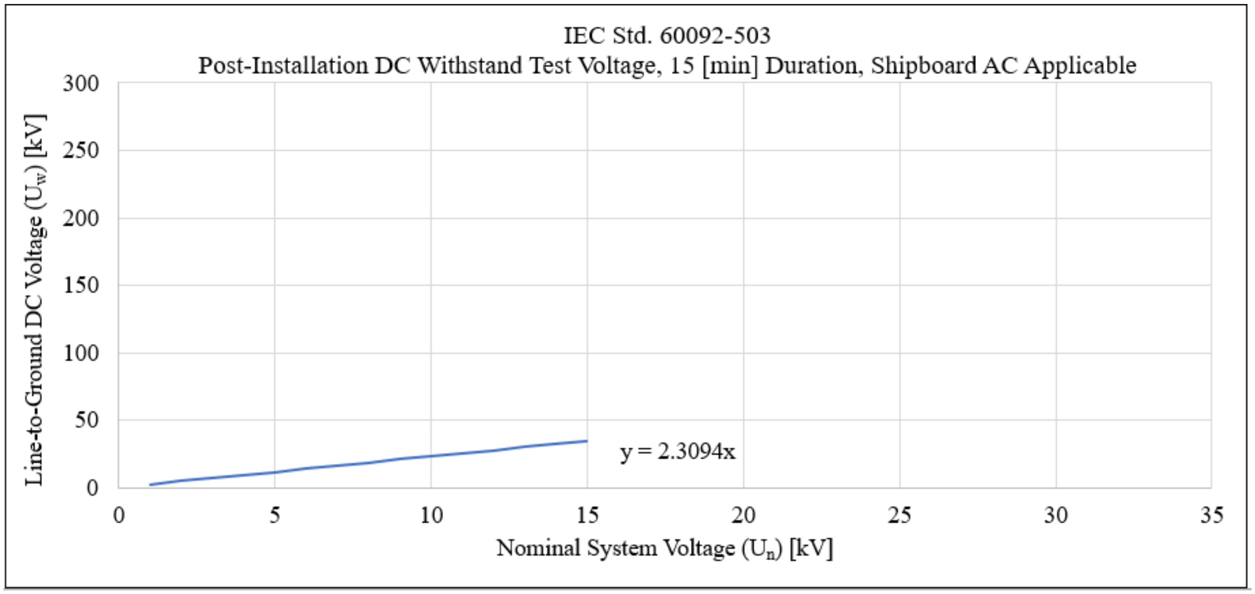


Figure 59: IEC Std. 60092-503 15 [min] Minimum Post-Installation AC Withstand Test Voltage (U_w) vs. U_n, with Trendline

IEC Stds. 60092-350/60502-2 outline U_w for given systems based on the Nominal System Voltage, U_n. The relationship with U_w is shown in Figure 60.

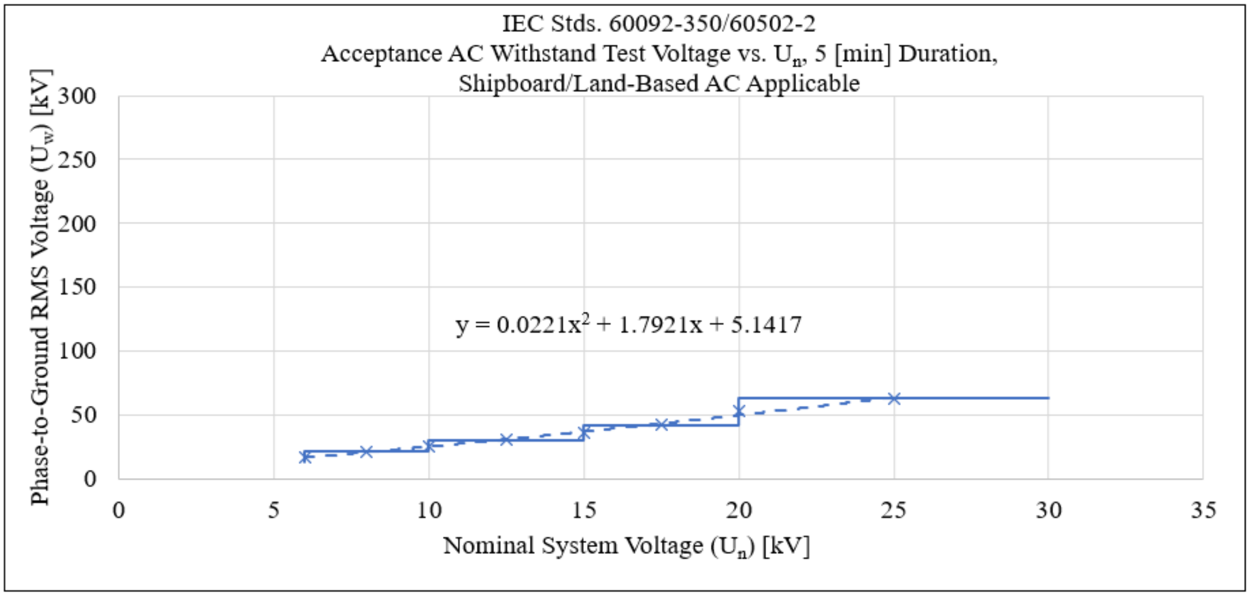


Figure 60: IEC Stds. 60092-350/60502-2 5 [min] Acceptance AC Withstand Test Voltage (U_w) vs. U_n, with Trendline

IEC Stds. 60071-1/2 outline U_w for given systems based on the Highest Voltage for Equipment, U_m. This U_m is converted into U_n using the given corresponding values in IEC Std. 60038 [40]. The relationship with U_w is shown in Figure 61.

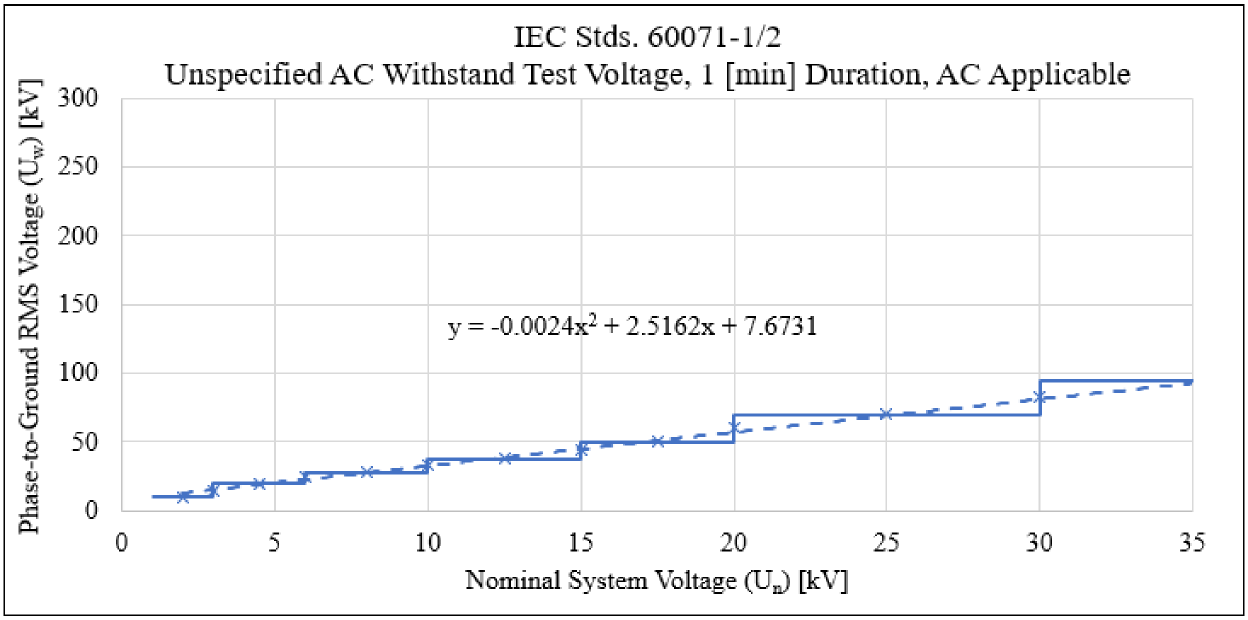


Figure 61: IEC Stds. 60071-1/2 1 [min] Unspecified AC Withstand Test Voltage (U_w) vs. U_n, with Trendline

5.2.2 IEEE Standards and Recommendations

IEEE Std. 1580 outlines recommended AC U_w for given systems based on the Nominal System Voltage (U_n) for both the 100% and the 133% insulation level. The relationships of insulation levels and U_n have been plotted for the AC U_w in Figure 62.

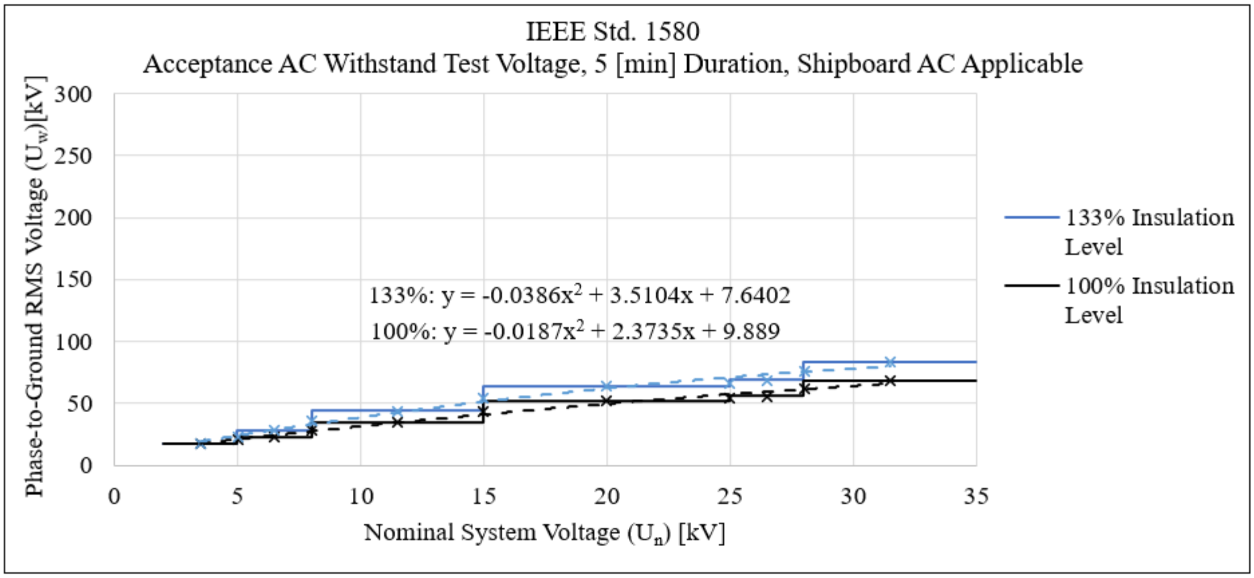


Figure 62: IEEE Std. 1580 5 [min] Acceptance AC Withstand Test Voltages (U_w) vs. U_n, with Trendlines

IEEE Std. 1709 outlines a recommended AC U_w for given systems based on the Nominal System Voltage (U_n) for shipboard MVDC systems. This relationship is shown in Figure 63.

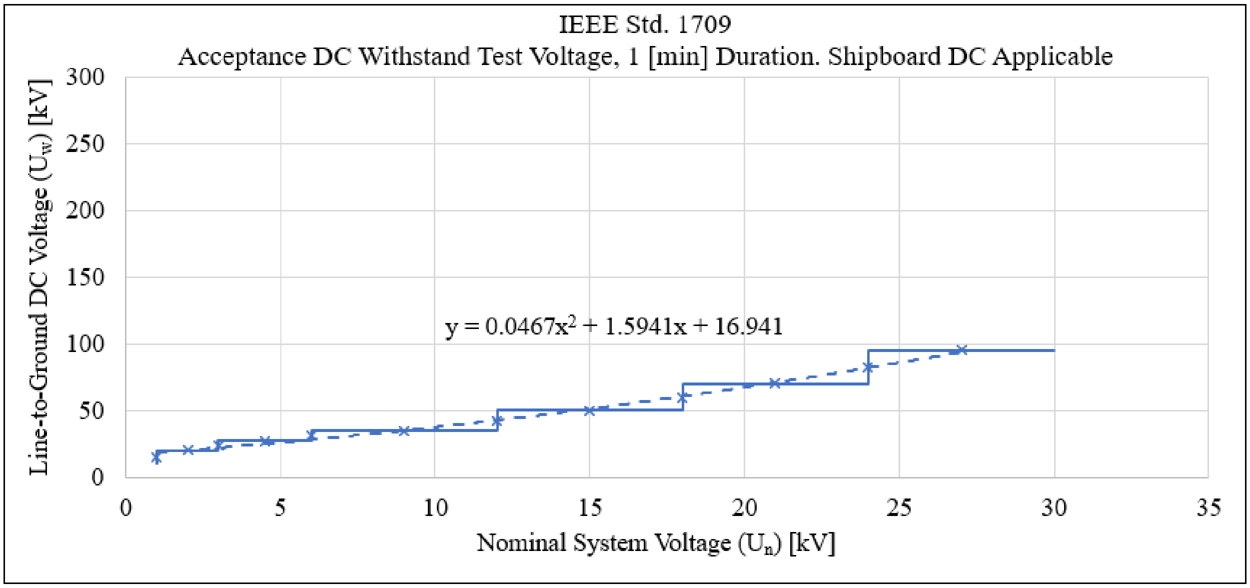


Figure 63: IEEE Std. 1709 1 [min] Acceptance DC Withstand Test Voltage (U_w) vs. U_n, with Trendline

IEEE Stds. 400.1, 400.2, and 400.4 outline recommended DC, VLF AC, and DAC U_w for given systems based on the Nominal System Voltage (U_n) for land-based MVDC systems respectively. These relationships are shown in Figure 64 through Figure 66.

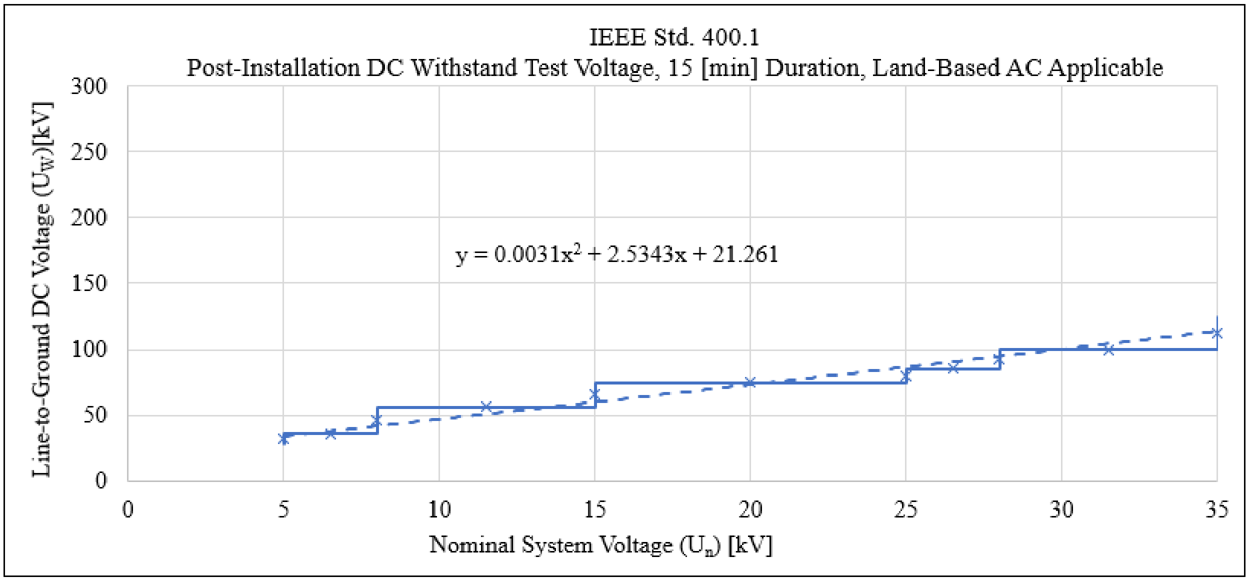


Figure 64: IEEE Std. 400.1 15 [min] Post-Installation DC Withstand Test Voltage (U_w) vs. U_n, with Trendline

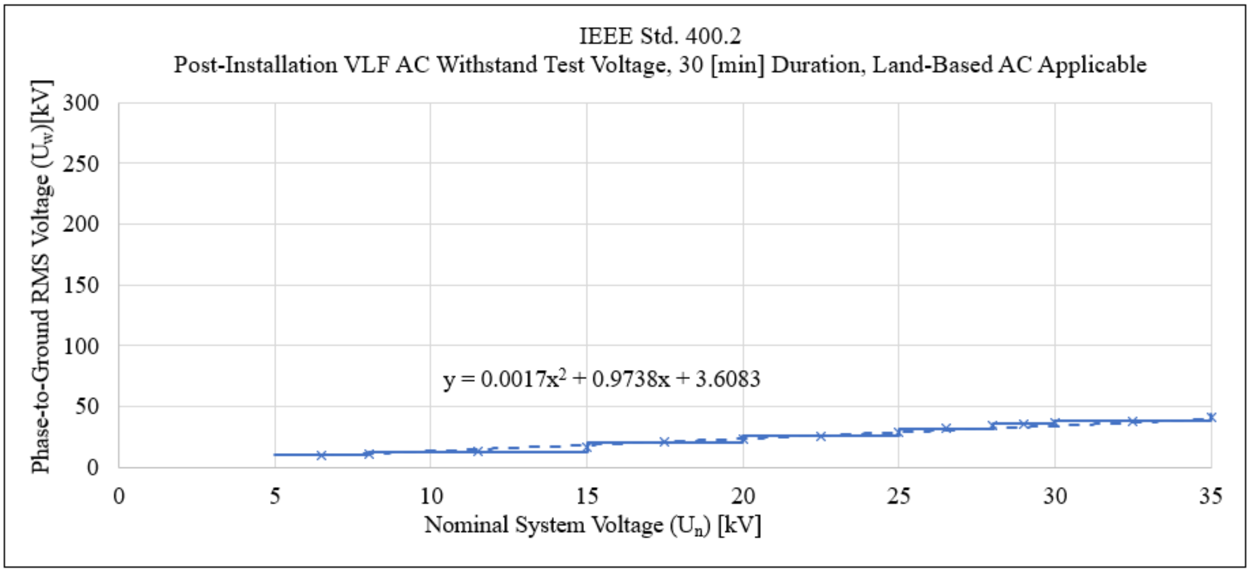


Figure 65: IEEE Std. 400.2 30 [min] Post-Installation VLF AC Withstand Test Voltage (U_w) vs. U_n, with Trendline

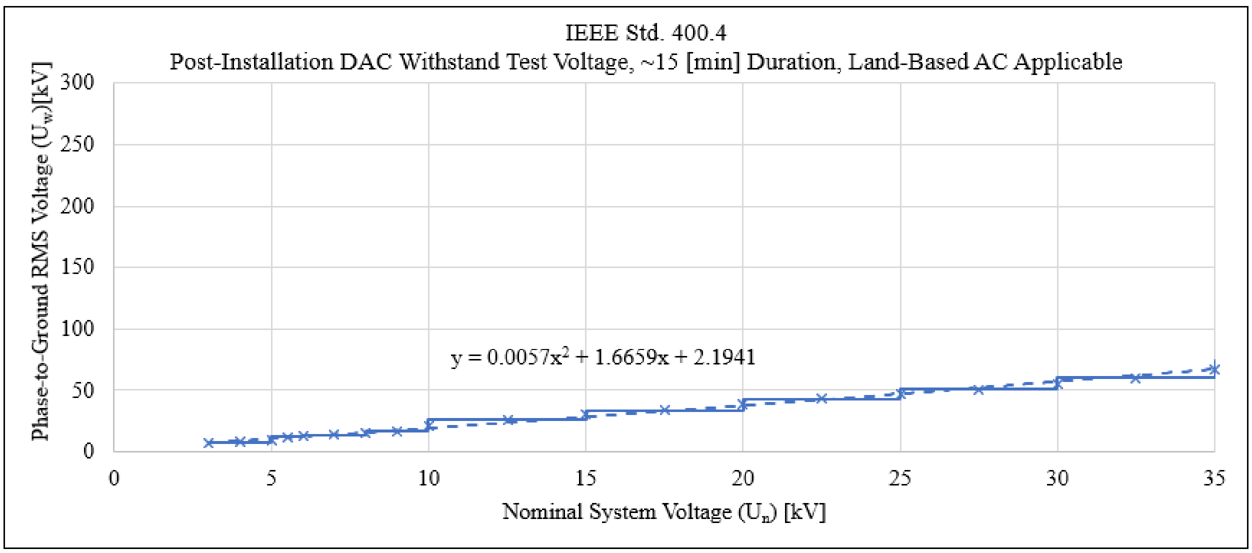


Figure 66: IEEE Std. 400.4 ~15 [min] Post-Installation DAC Withstand Test Voltage (U_w) vs. U_n, with Trendline

5.2.3 American Bureau of Shipping Standard

The three Withstand Test methods outlined by the ABS Steel Vessel Requirements base U_w on the system U_n. The three test methods and their U_w vs. U_n relationships are shown in Figure 67 through Figure 69.

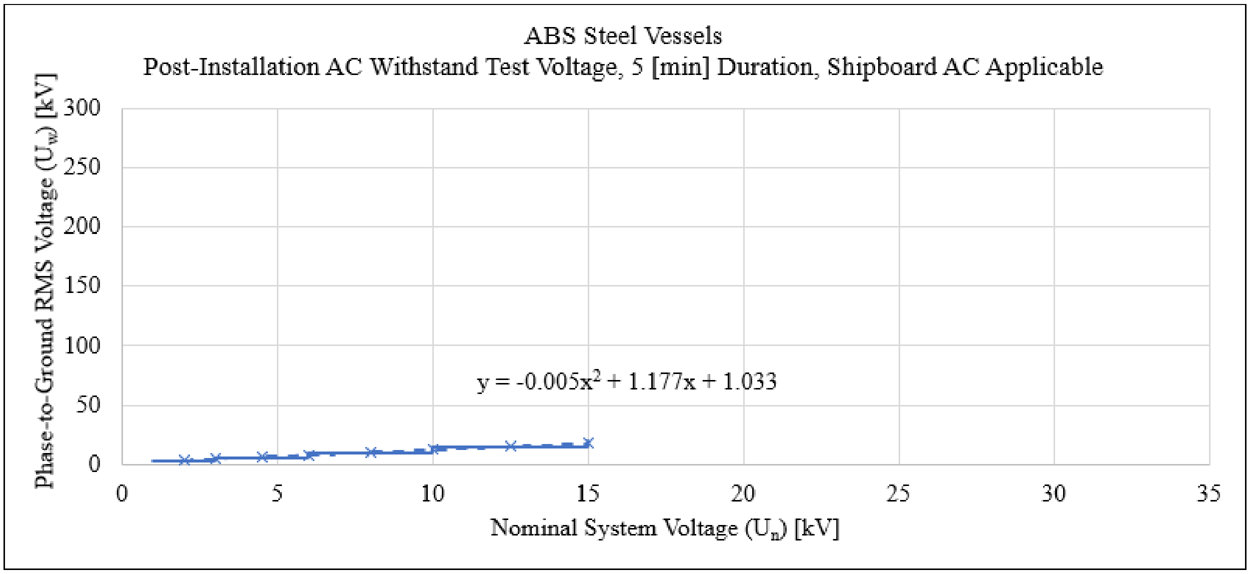


Figure 67: ABS Test 1, 5 [min] Post-Installation AC Withstand Test Voltage (U_w) vs. U_n, with Trendline

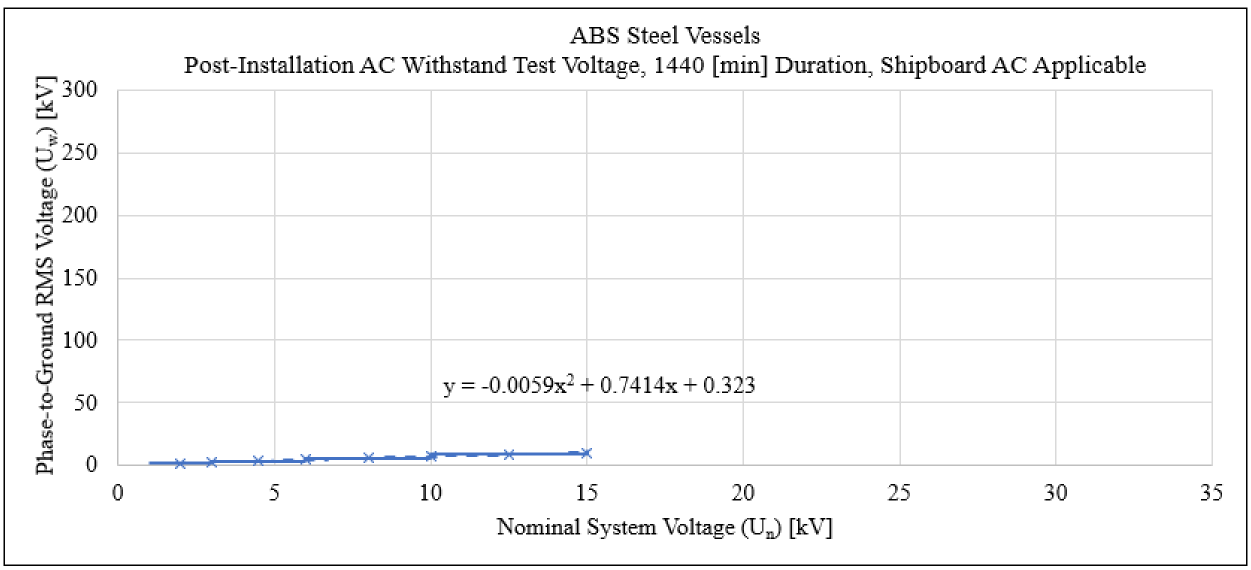


Figure 68: ABS Test 2, 1440 [min] Post-Installation AC Withstand Test Voltage (U_w) vs. U_n, with Trendline

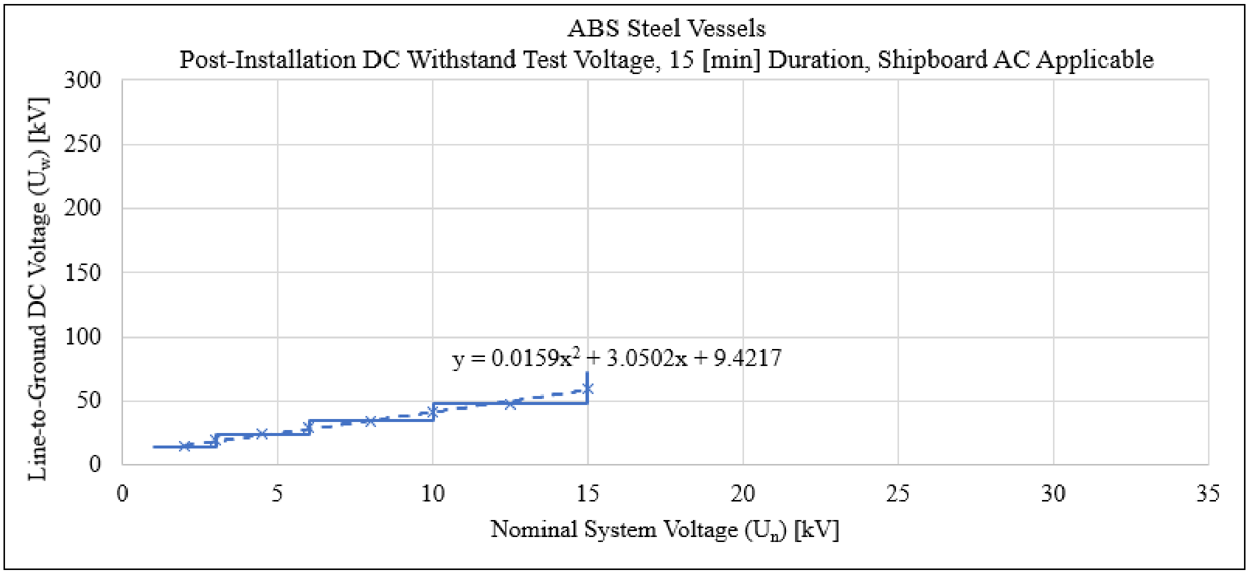


Figure 69: ABS Test 3, 15 [min] Post-Installation DC Withstand Test Voltage (U_w) vs. U_n, with Trendline

5.2.4 ICEA Standard

The AC and DC U_w Withstand Tests outlined by ICEA S-97-682 base U_w on the system U_n for the 100%, 133%, and 173% insulation levels. The relationship of U_w to U_n for these tests are shown in Figure 70 through Figure 72.

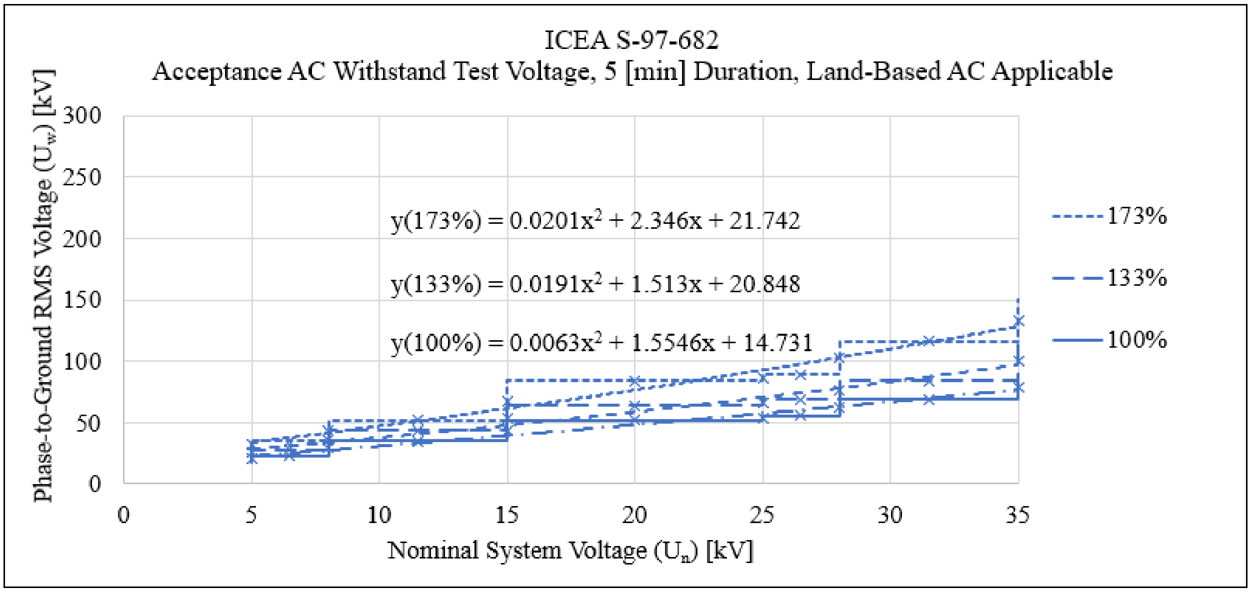


Figure 70: ICEA 5 [min] Acceptance AC Withstand Test Voltages (U_w) vs. U_n, with Trendlines

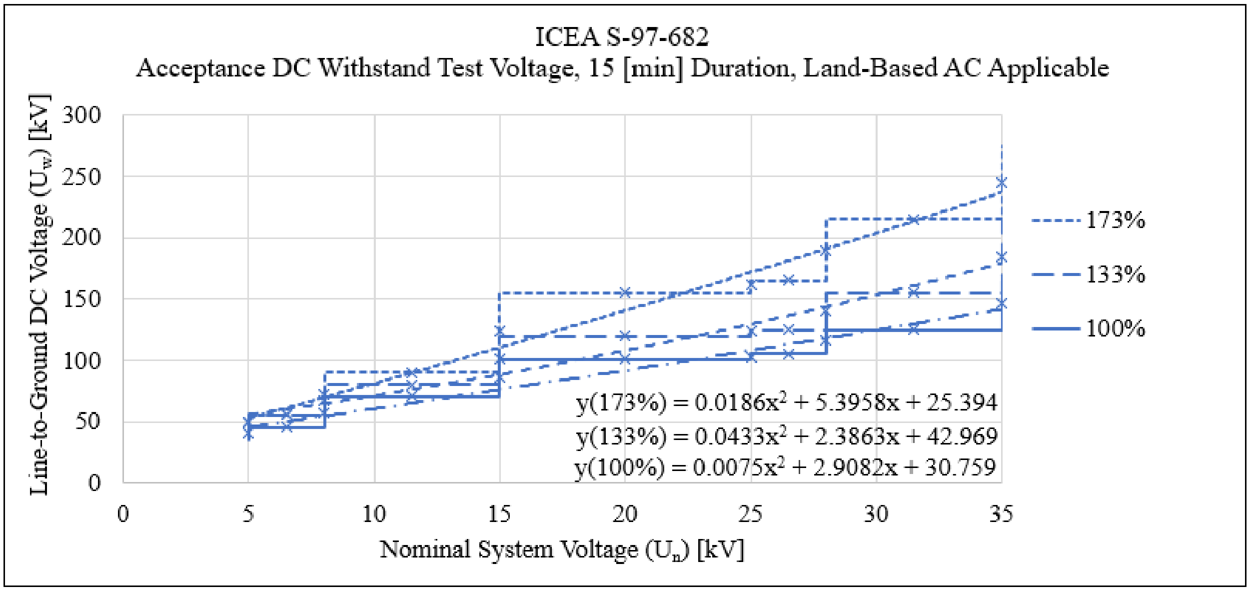


Figure 71: ICEA 15 [min] Acceptance DC Withstand Test Voltages (U_w) vs. U_n, with Trendlines

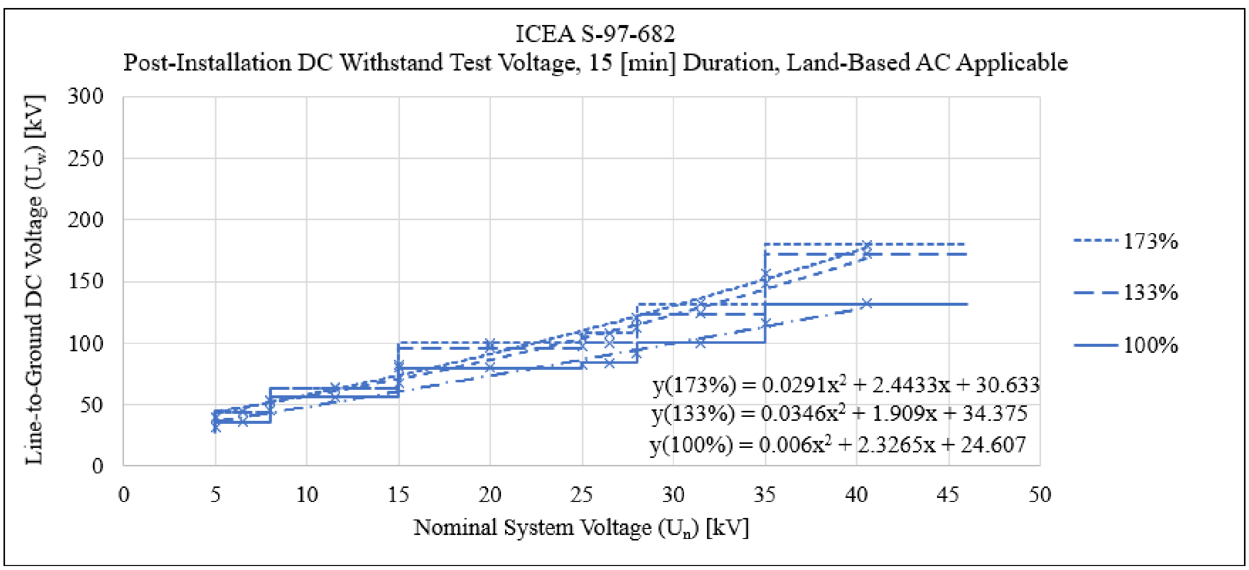


Figure 72: ICEA 15 [min] Post-Installation DC Withstand Test Voltages (U_w) vs. U_n, with Trendlines

5.2.5 HVDC Standards and Recommendations

CIGRE Technical Brochure 496 and IEC Std. 62895 specify U_w for given systems based on the Cable Nominal Voltage, U_o. For DC systems this is converted to U_n by multiplying by 2. The relationship between U_w and U_n is shown in Figure 73. As stated in §5.1.4, while These references are applicable to power cables with a $U_n \leq 500/320$ [kV] respectively, they are intended for HVDC power cables (generally accepted to be ≥69 [kV] U_n), and so these references will not be used for Withstand Test discussion henceforth.

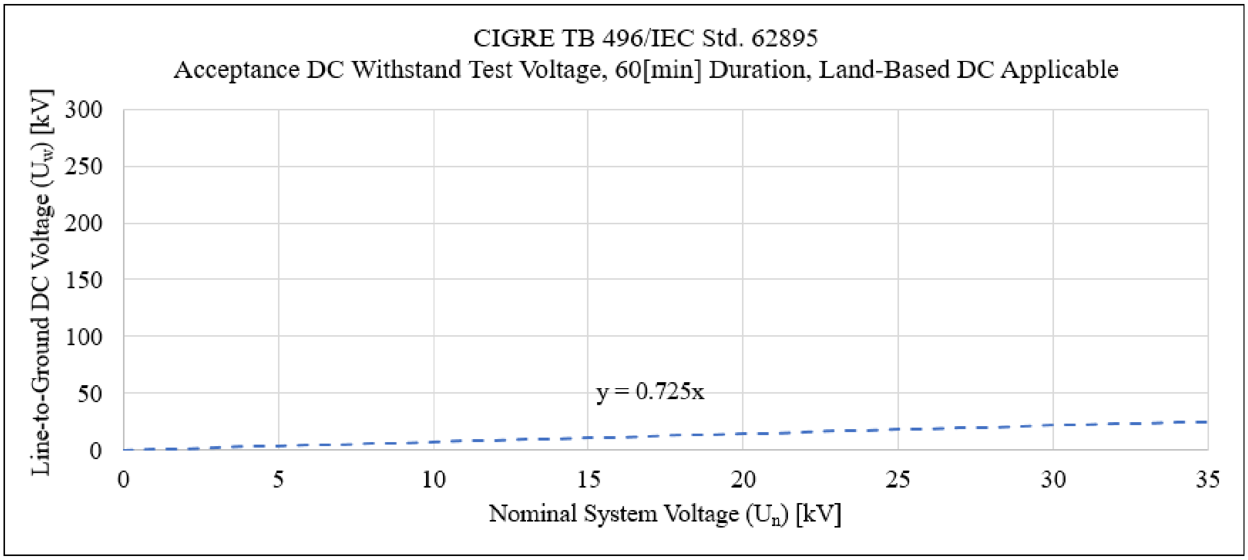


Figure 73: CIGRE TB 496/IEC Std. 62895 60 [min] Acceptance DC Withstand Test Voltage (U_w) vs. U_o

5.2.6 USN Requirements

MIL-DTL-917F requirements for U_w are outlined for a given U_n. This relationship is shown in Figure 74. The highest ship system voltage that has been constructed to date under this reference is currently 15 [kV], systems greater than this are valid for this reference but have not been built to date. These possible systems are shown as a dashed line in Figure 74.

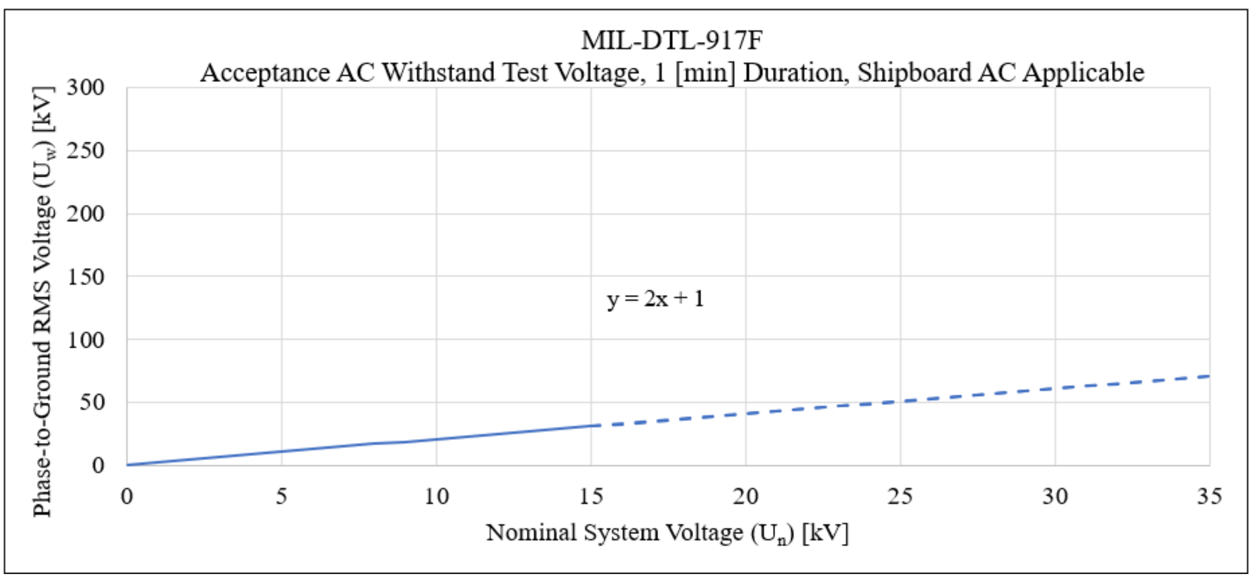


Figure 74: MIL-DTL-917F 1 [min] Acceptance AC Withstand Test Voltage (U_w) vs. U_n

For the USN detail specifications MIL-DTL-915G/MIL-DTL-24643C, the U_w given in Table 6 that were in terms of phase-to-phase voltage were converted to phase-to-neutral RMS by dividing by $\sqrt{(3)}$. Neutral is assumed to be ground for this calculation. These values, and the voltages that were originally phase-to-ground U_w are shown in Figure 75. No trendline is fit to these data points, but rather the points themselves are used for comparison in §5.3.

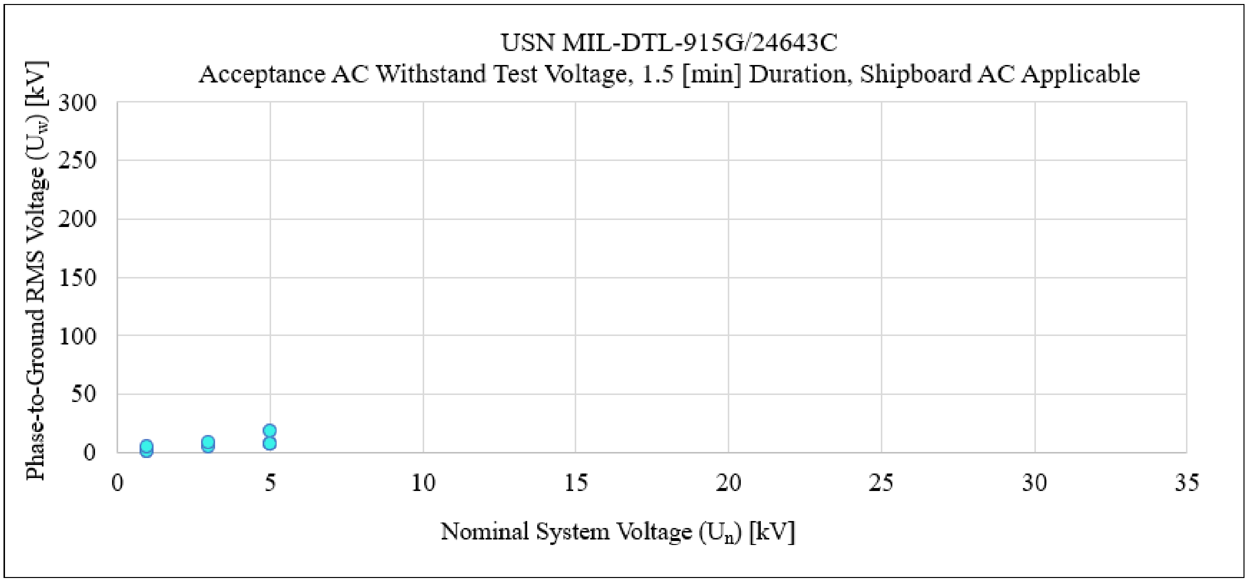


Figure 75: MIL-DTL-915G 1.5 [min] Acceptance AC Withstand Test Voltage (U_w) vs. U_n

5.2.7 Table of Polynomials

Polynomials for Withstand Tests compared to the Nominal System Voltage (U_n), Cable Nominal Voltage (U_o) and Nominal Peak Cable Voltage (U_p) were calculated and given in Table 7 below. Each equation is given in the form of U_w as a f(x), with x being the respective voltage.

Reference	Duration	Frequency	Test Type	U_w vs. U_n	U_w vs. U_o	U_w vs. U_p
IEC Std. 60092-503	15 [min]	N/A (DC)	Post-Installation	$2.3094x$	$4x$	$2.8284x$
IEC Stds. 60502-2/60092-350	240 [min]	49-61 [Hz]	Acceptance	$0.0021x^2 +1.7921x +5.1417$	$0.0373x^2 +3.443x +3.6276$[a]	$0.0187x^2 +2.4345x +3.6276$[a]
IEC Std. 60071-1/2	1 [min]	48-62 [Hz]	Unspecified	$-0.0024x^2 +2.5162x +7.6731$	$-0.0071x^2 +4.3582x+ 7.6731$	$-0.0035x^2 +3.0817x+ 7.6731$
IEEE Std. 1580 100% Insulation	5 [min]	23-62 [Hz]	Acceptance	$-0.0187x^2 +2.3735x +9.889$	$-0.056x^2 +4.1111x+ 9.889$	$-0.028x^2 +2.907x +9.889$
IEEE Std. 1580 133% Insulation	5 [min]	23-62 [Hz]	Acceptance	$-0.0386x^2 +3.5104x +7.6402$	$-0.1159x^2 +6.0802x+ 7.6402$	$-0.0579x^2 +4.2994x +7.6402$
IEEE Std. 1709[b]	1 [min]	N/A (DC)	Acceptance	$0.0467x^2 +1.5941x +16.941$	$0.1869x^2 +3.1882x +16.941$	N/A[b]
IEEE Std. 400.1	15 [min]	N/A (DC)	Post-Installation	$0.0031x^2 +2.5343x +21.261$	$0.0094x^2 +4.3896x +21.261$	$0.0047x^2 +3.1039x +21.261$
IEEE Std. 400.2	30 [min]	0.1 [Hz]	Post-Installation	$0.0017x^2 +0.9738x +3.6083$	$0.0051x^2 +1.6867x +3.0683$	$0.0025x^2 +1.1927x +3.6083$
IEEE Std. 400.4	~15 [min]	20-500 [Hz]	Post-Installation	$0.0057x^2 +1.6659x +2.1941$	$0.0183x^2 +2.8147x +1.4509$[a]	$0.0092x^2 +1.9903x +1.4509$[a]

Reference	Duration	Frequency	Test Type	U_w vs. U_n	U_w vs. U_o	U_w vs. U_p
ABS Test 1	5 [min]	50-60 [Hz]	Post-Installation	$-0.005x^2 +1.177x +1.033$	$-0.0149x^2 +2.0386x +1.033$	$-0.0075x^2 +1.4415x +1.033$
ABS Test 2	24 [hr]	50-60 [Hz]	Post-Installation	$-0.0059x^2 +0.7414x +0.323$	$-0.0178x^2 +1.2842x +0.323$	$-0.0089x^2 +0.908x +0.323$
ABS Test 3	15 [min]	N/A (DC)	Post-Installation	$0.0159x^2 +3.0502x +9.4217$	$0.0477x^2 +5.283x +9.4217$	$0.0238x^2 +3.7357x +9.4217$
ICEA S-97-682 100% Insulation	5 [min]	49-61 [Hz]	Acceptance	$0.0063x^2 +1.5546x +14.731$	$0.0189x^2 +2.6927x +14.731$	$0.0094x^2 +1.904x +14.731$
ICEA S-97-682 133% Insulation	5 [min]	49-61 [Hz]	Acceptance	$0.0191x^2 +1.513x +20.848$	$0.0574x^2 +2.6207x +20.848$	$0.0287x^2 +1.8531x +20.848$
ICEA S-97-682 173% Insulation	5 [min]	49-61 [Hz]	Acceptance	$0.0201x^2 +2.346x +21.742$	$0.0603x^2 +4.0634x +21.742$	$0.0301x^2 +2.8733x +21.742$
ICEA S-97-682 100% Insulation	15 [min]	N/A (DC)	Acceptance	$0.0075x^2 +2.9082x +30.759$	$0.0226x^2 +5.0371x +30.759$	$0.0113x^2 +3.5618x +30.759$
ICEA S-97-682 133% Insulation	15 [min]	N/A (DC)	Acceptance	$0.0433x^2 +2.3862x +42.969$	$0.1299x^2 +4.1331x +42.969$	$0.0649x^2 +2.9225x +42.969$
ICEA S-97-682 173% Insulation	15 [min]	N/A (DC)	Acceptance	$0.0186x^2 +5.3958x +25.394$	$0.0559x^2 +9.3459x +25.394$	$0.028x^2 +6.6085x +25.394$
ICEA S-97-682 100% Insulation	15 [min]	N/A (DC)	Post-Installation	$0.006x^2 +2.3265x +24.607$	$0.0181x^2 +4.0297x +24.607$	$0.009x^2 +2.8494x +24.607$
ICEA S-97-682 133% Insulation	15 [min]	N/A (DC)	Post-Installation	$0.0346x^2 +1.909x +34.375$	$0.1039x^2 +3.3065x +34.375$	$0.0519x^2 +2.338x +34.375$
ICEA S-97-682 173% Insulation	15 [min]	N/A (DC)	Post-Installation	$0.0291x^2 +2.4433x +30.633$	$0.0873x^2 +4.2319x +30.633$	$0.0426x^2 +2.9924x +30.633$
MIL-DTL-917F	1 [min]	60 [Hz]	Acceptance	$2x + 1$	$3.4641x +1$	$2.4495x +1$

[a] The IEC standard provides U_o values corresponding to U_n values that does not exactly correspond to the mathematical calculation of U_o form U_n. This different results in the y intercept of BIL vs. U_o and BIL vs. U_p being different from that of BIL vs. U_n.

[b] This standard applied to MVDC power cables, therefore U_p is equivalent to U_o.

Table 7: Trendline Polynomials for BIL vs. Respective Voltages

5.3 Comparison of Standards and Recommended Practices Withstand Tests

The intention of this section is to compare and gain insight from the well-established standards and recommendations for MVAC systems Withstand Tests to the guidelines within IEEE Std. 1709.

This study separated the reference's Withstand Tests into AC and DC U_w and plotted them versus U_n. Each test's additional information is displayed in the legend, explained further in the next paragraph. Additional figures were created for shipboard-applicable references showing the relationship between the test duration and U_w. U_n is indicated by the marker of these plots, and follow-on figures normalize these U_w by U_n. Finally figures comprising all shipboard AC and DC U_w Withstand tests were created.

The legends of the figures in the following subsections contain each Withstand Voltage Test's relevant parameters. The reference name, applicability (shipboard or land-based), system voltage (AC or DC), test voltage (AC or DC), test duration, and test category are shown in the legend of the following figures in the format shown below in Figure 76.

Format:	Reference (Applicability(System Voltage Type), Test Voltage Type, Test Duration, Test Category					
Options:	All Refs.	Land or Ship	AC or DC	AC or DC	[min]	Post-Installation or Acceptance or Unspecified
Example:	IEEE Std. 1709 (Ship(DC), DC, 1, Accept.)					

Figure 76: Key for Legends in §5.3

It was identified that the waveform of the U_w applied to the power cable being tested does not depend on the waveform of the cable's Nominal System Voltage (U_n). Standards and recommendations examined in §5.1 identified AC and DC U_w applied to cables with an AC or DC U_n. This section compares AC U_w applied to power cables with AC U_n, and DC U_w applied to power cables with DC or AC U_n.

5.3.1 Acceptance (At Factory) Withstand Tests

Figure 77 shows all references that prescribe an AC U_w for an acceptance or unspecified Withstand test. This figure applies to AC power cables.

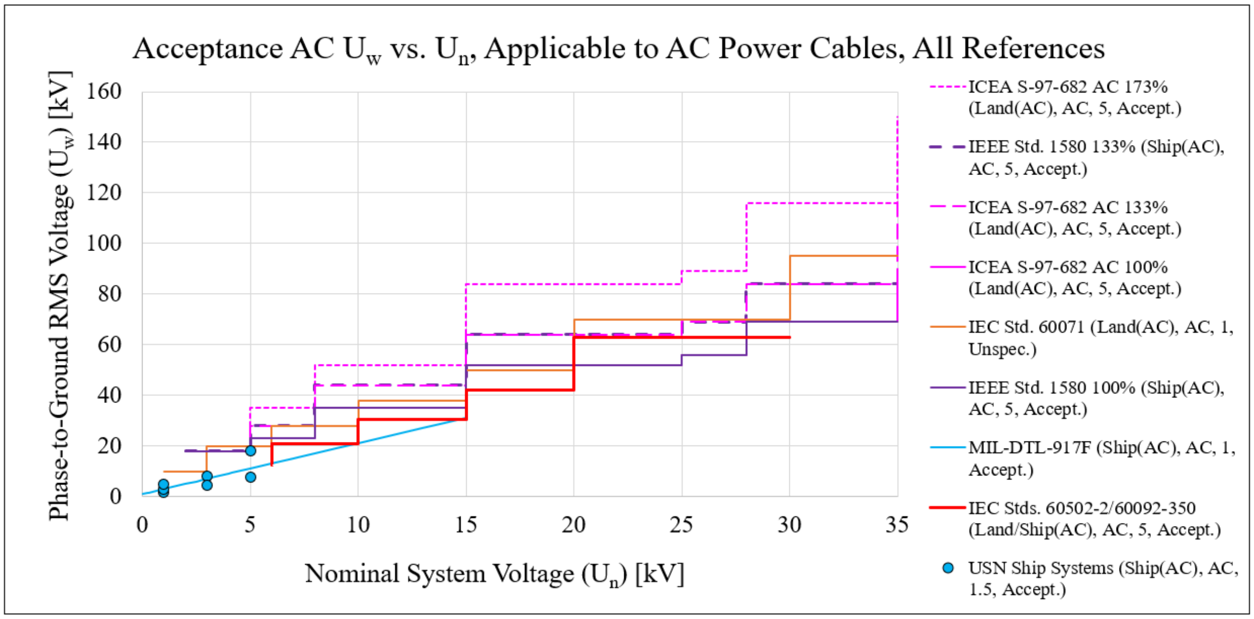


Figure 77: Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. U_n for All References in §5.1

Reference	Coordinates (U_n [kV], Acceptance AC U_w [kV])								
ICEA S-97-682 173% [35]	5,28	5,35	8,35	8,52	15,52	15,84	25,84	25,89	28,89
	28,116	35,116	35,150						
IEEE Std. 1580 133% [28]	2,18	5,18	5,28	8,28	8,44	15,44	15,64	25,64	25,69
	28,69	28,84	35,84						
ICEA S-97-682 133% [35]	5,23	5,28	8,28	8,44	15,44	15,64	25,64	25,69	28,69
	28,84	35,84	35,116						
ICEA S-97-682 100% [35]	5,18	5,23	8,23	8,35	15,35	15,52	25,52	25,56	28,56
	28,69	35,69	35,89						
IEC Std. 60071 [4] [32]	1,10	3,10	3,20	6,20	6,28	10,28	10,38	15,38	15,50
	20,50	20,70	30,70	30,95					
IEEE Std. 1580 100% [28]	2,18	5,18	5,23	8,23	8,35	15,35	15,52	25,52	25,56
	28,56	28,69	35,69						
MIL-DTL-917F [44]	Acceptance AC $U_w = 2 * U_n + 1 \mid \{0 \leq U_n \leq 15 \text{ [kV]}\}$								
IEC Stds. 60502-2/60092-350 [30] [31]	6,12.5	6,21	10,21	10,30.5	15,30.5	15,42	20,42	20,63	30,63
USN Ship Systems (see Table 6)	1,1.73	1,2.89	1,5	3,4.62	5,7.79	5,18			

Table 8: Coordinates of Step-Functions in Figure 77

The trendlines generated for each reference's acceptance test AC U_w vs. U_n in §5.2 were plotted as a function of U_n in Figure 78. This figure illustrates a relatively constant range of U_w for any U_n.

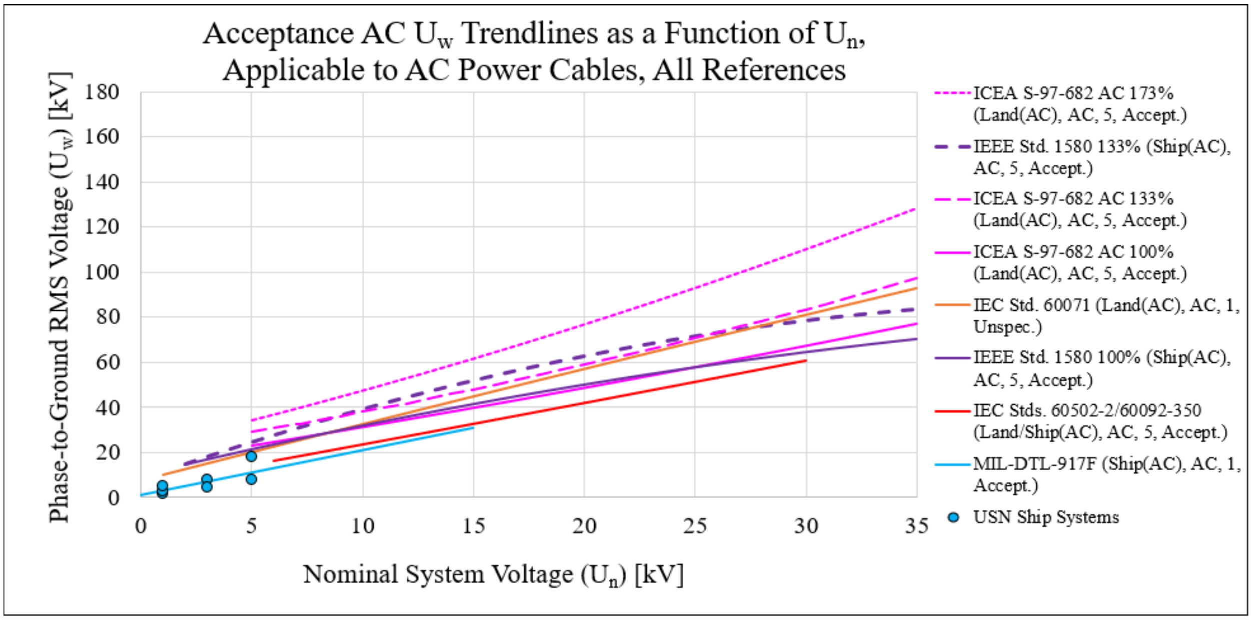


Figure 78: Trendline Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. U_n for All References in §5.1

To visualize the data another way, the phase-to-ground voltage values of Withstand Test Voltage (U_w) were organized into bins based on their applicable Nominal System Voltage (U_n). These bins were created with 5 [kV] intervals as seen in Figure 79. The U_w prescribed for the start of the bin (with 'start' meaning the lowest U_n value of that bin), as well as any increases to U_w within the bin were plotted below in Figure 79. For references specifying linear relationships of U_w with U_n, the Uw at the start and end of each bin is used to keep the information while reducing clutter. Figure 79 displays the log-linear scale of the relationship between duration and U_w, while Figure 80 and Figure 81 show the relationship on a log-log scale and then with inverted axis, respectively. The log-log scale relationship normalized by U_n is shown in Figure 82.

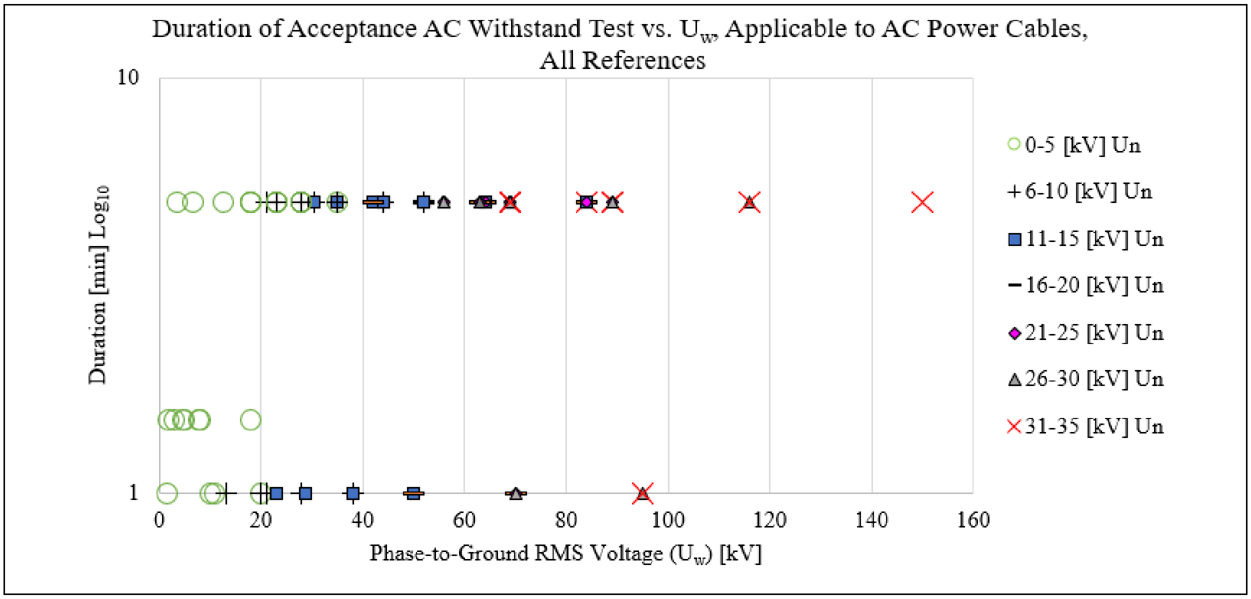


Figure 79: Comparison of Acceptance Withstand Test Duration vs. AC Withstand Voltages (U_w) for All References in §5.1, Log-Linear

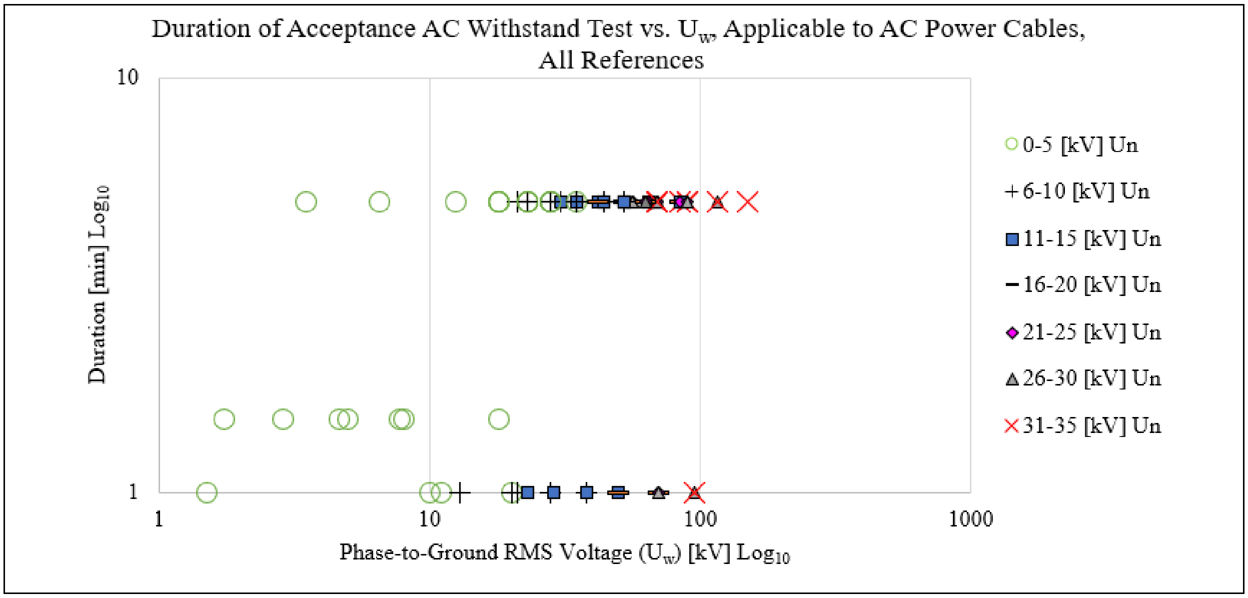


Figure 80: Comparison of Acceptance Withstand Test Duration vs. AC Withstand Voltages (U_w) for All References in §5.1, Log-Log

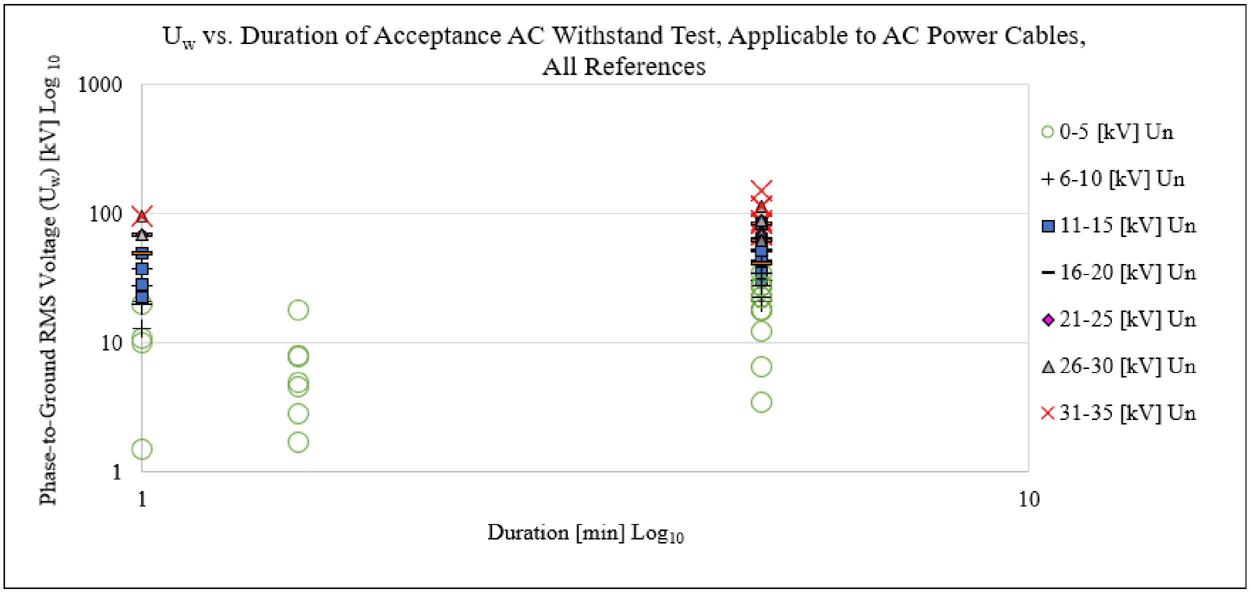


Figure 81: Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. Duration for All References in §5.1, Log-Log

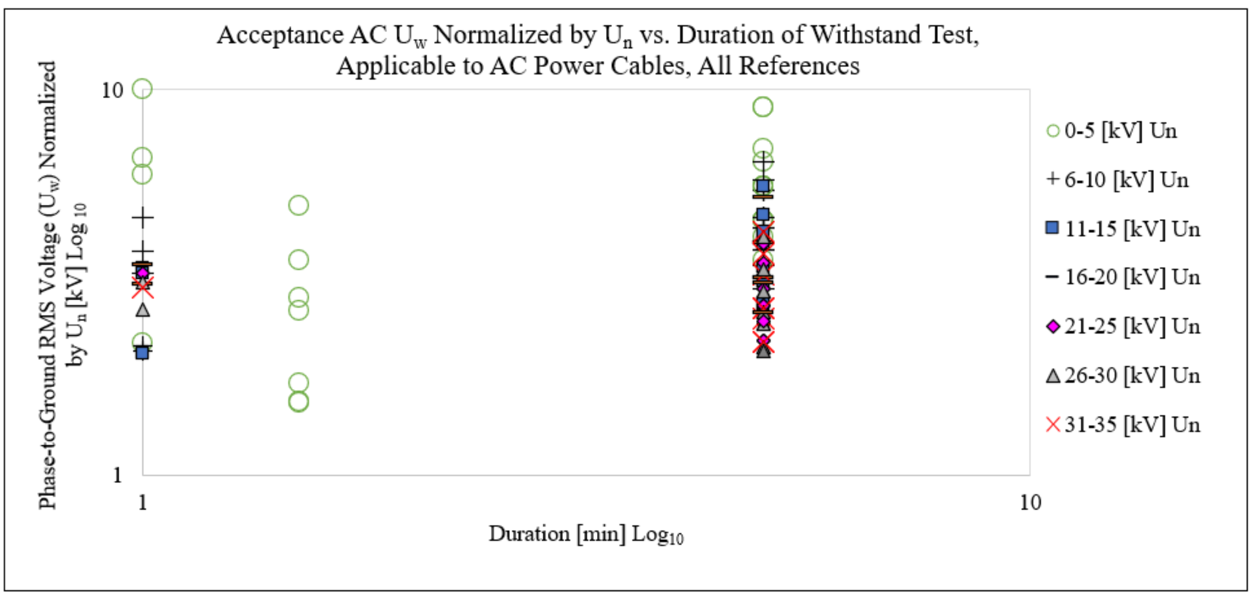


Figure 82: Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

To emphasize the common parameters among the compared Withstand Voltage tests, Figure 83 through Figure 87 display only references that are applicable to shipboard power cables.

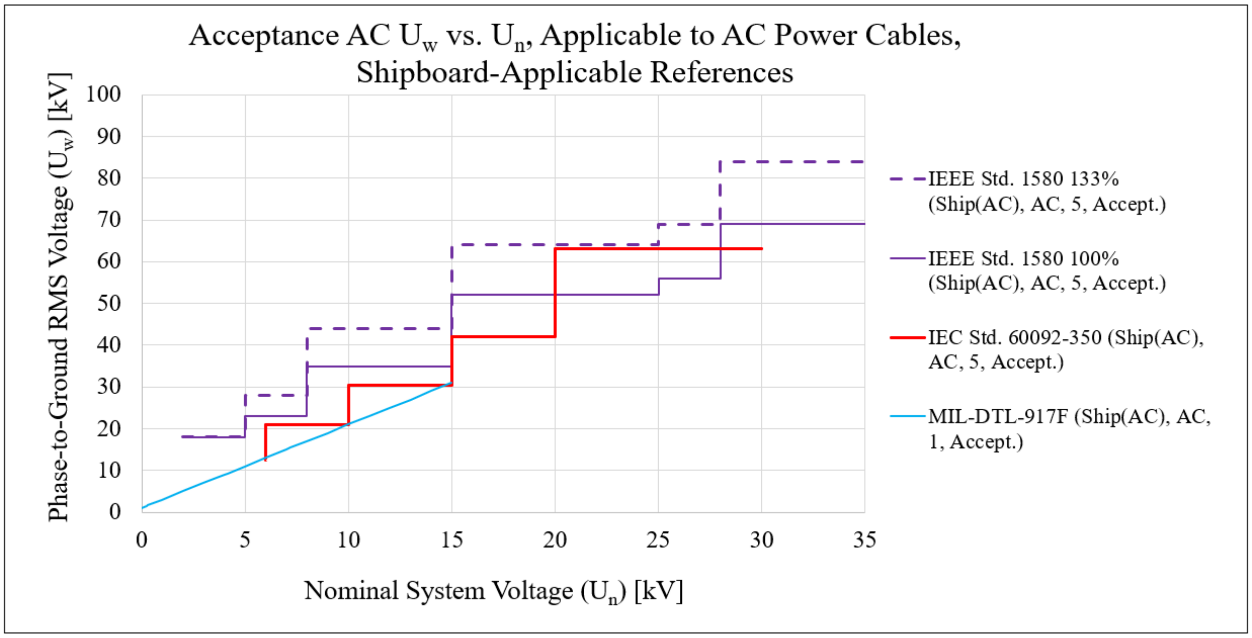


Figure 83: Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. U_n for Shipboard-Applicable References in §5.1

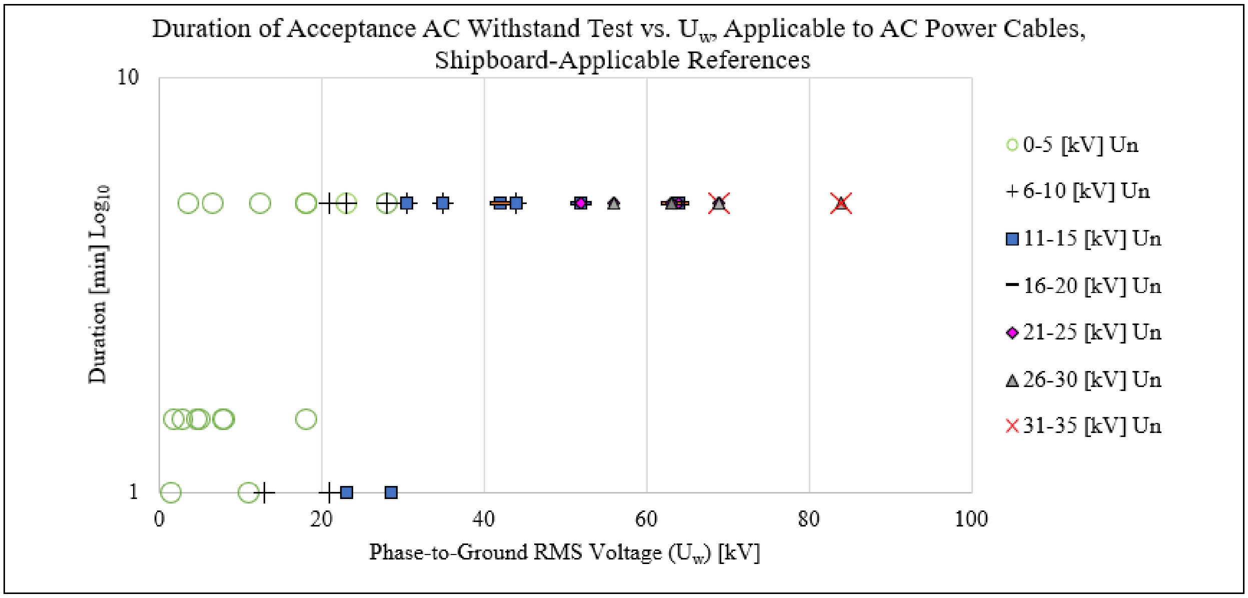


Figure 84: Comparison of Acceptance Withstand Test Duration vs. AC Withstand Voltages (U_w) for Shipboard-Applicable References in §5.1, Log-Linear

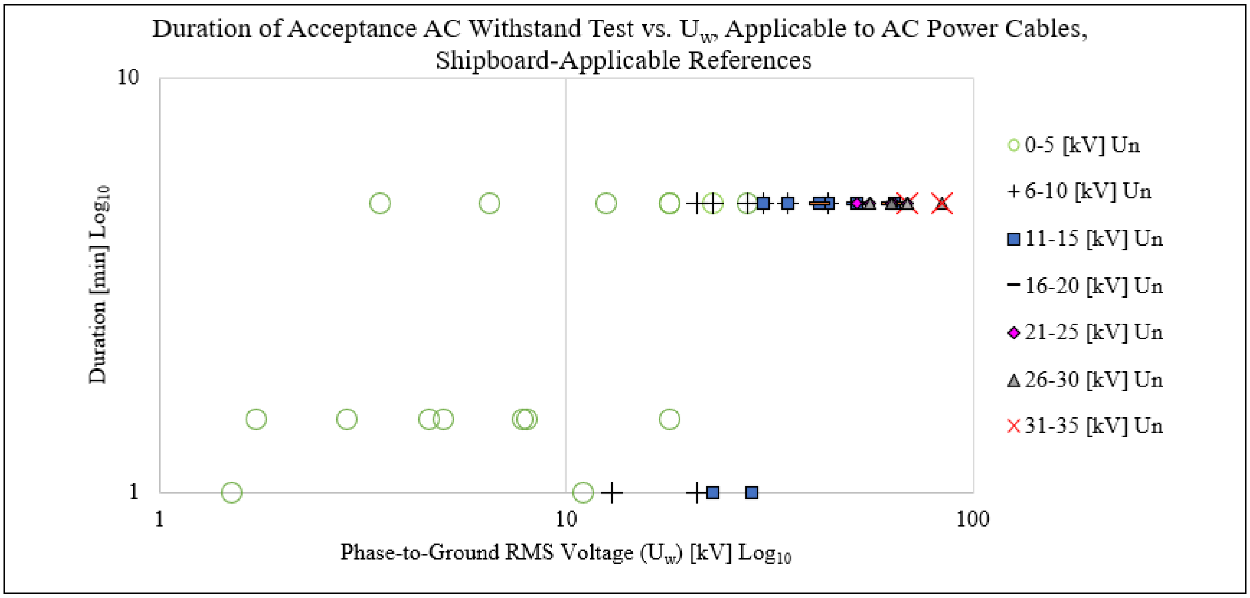


Figure 85: Comparison of Acceptance Withstand Test Duration vs. AC Withstand Voltages (U_w) for Shipboard-Applicable References in §5.1, Log-Log

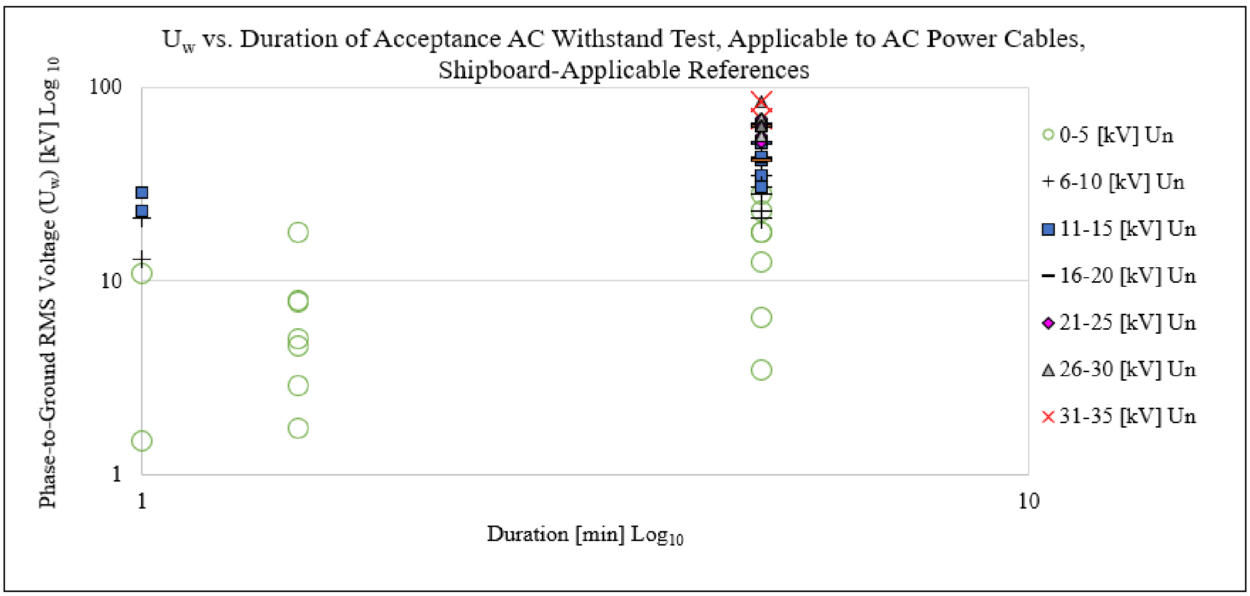


Figure 86: Comparison of AC Withstand Test Voltages (U_w) vs. Duration for Shipboard-Applicable References in §5.1, Log-Log

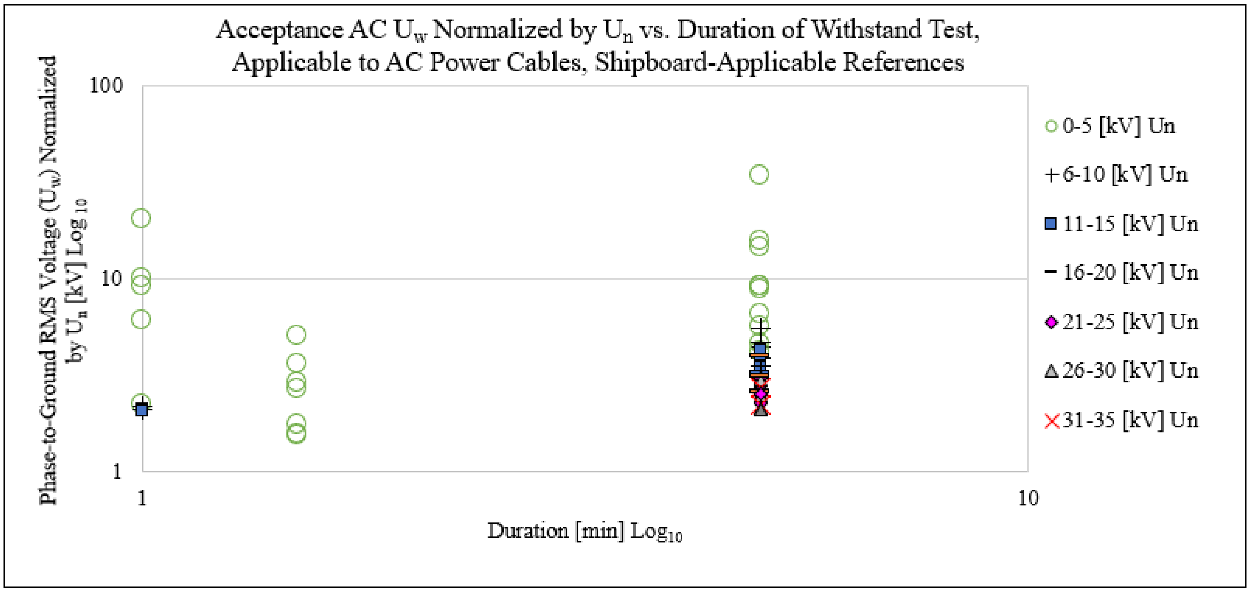


Figure 87: Comparison of AC Withstand Test Voltages (U_w) vs. Duration for Shipboard References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

The most common test duration is 5 [min], and so Figure 88 is made with only the 5 [min] duration tests to show an arguably more comparable range of AC U_w. Considering this limitation, Figure 88 illustrates the large differential of possible AC U_w. For example, the Withstand Voltage Test requirements for a 12 [kV] MVAC shipboard power system has a range from 15-55 [kV] applied for 5 [min] depending on the reference used for testing.

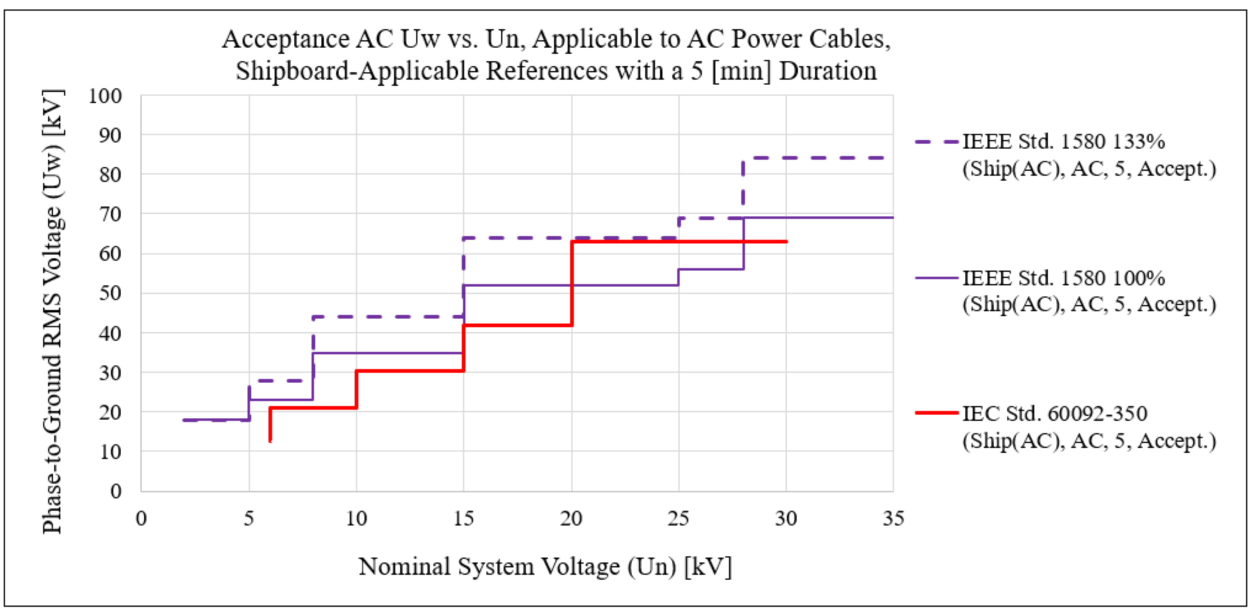


Figure 88: Comparison of AC Withstand Test Voltages (U_w) for Shipboard-Applicable References in §5.1, 5 [min] Duration

The trendlines fit to each shipboard-applicable reference's AC U_w vs. U_n in §5.2 were plotted as a function of U_n in Figure 89, and reduced to the tests with 5 [min] durations for Figure 90. These figures illustrate the divergence of the references as U_n increases.

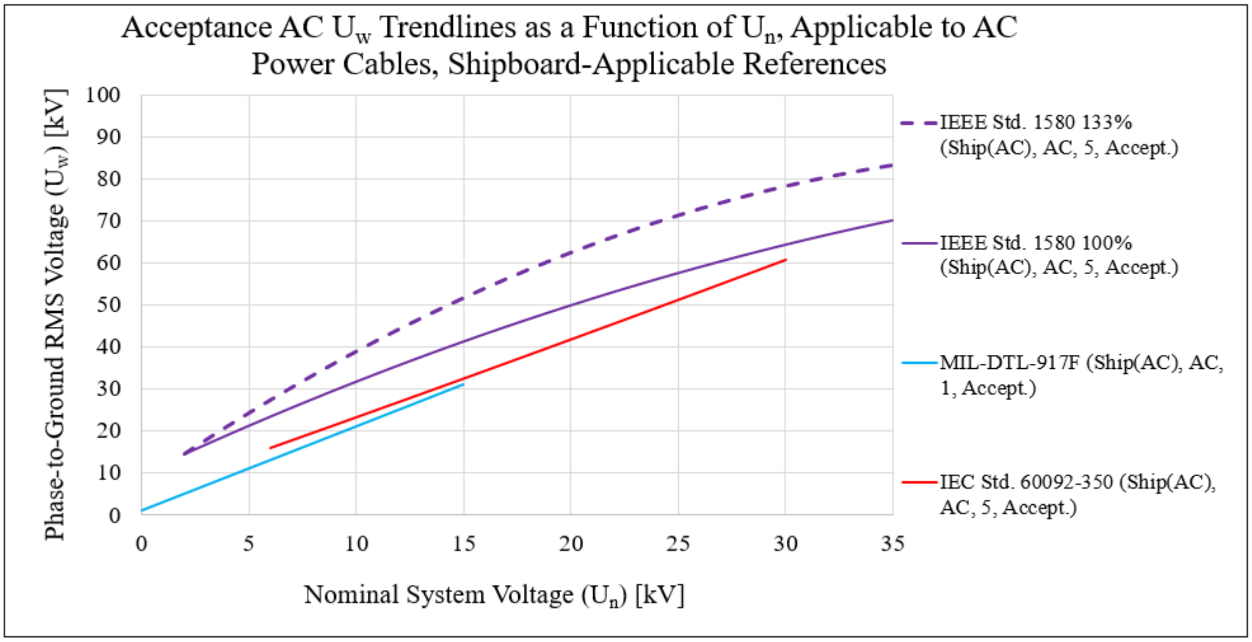


Figure 89: Comparison of AC Withstand Test Voltages (U_w) Trendlines for Shipboard-Applicable References in §5.1

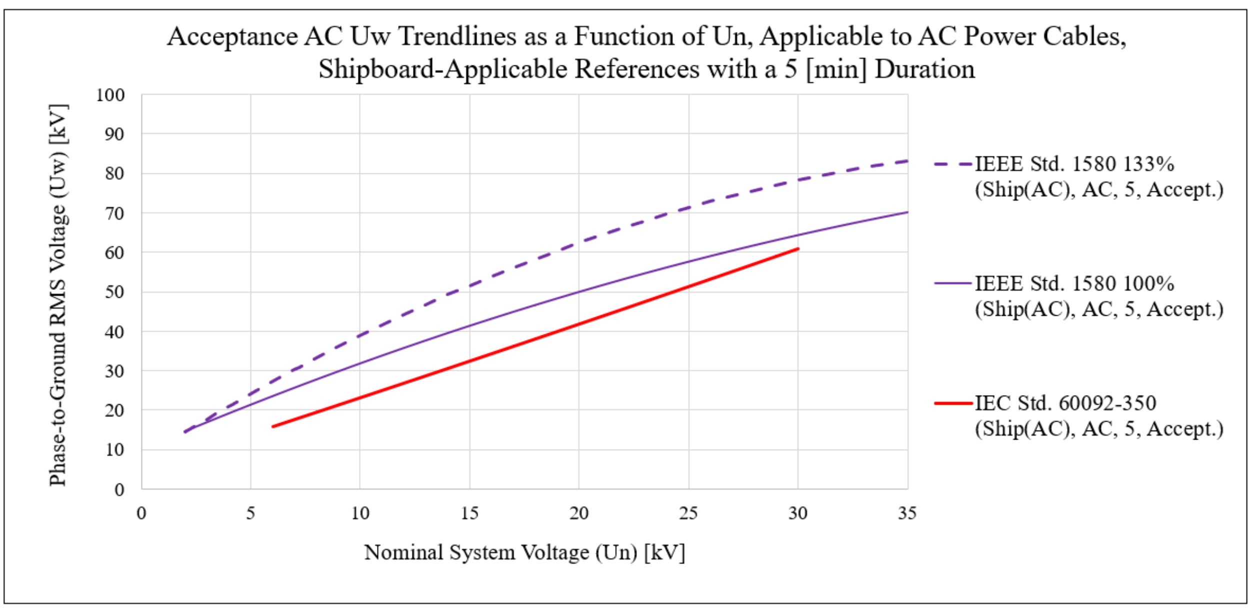


Figure 90: Trendline Comparison of AC Withstand Test Voltages (U_w) for Shipboard-Applicable References in §5.1 - 5 [min] Duration

The above process is repeated for DC U_w, with all references using an DC U_w being plotted vs. U_n on Figure 91. As with the AC U_w, this comparison shows a wide range of U_w corresponding to any U_n, with the number of other parameters applicable to each reference's U_w suggesting that a direct comparison of these values is not necessarily appropriate.

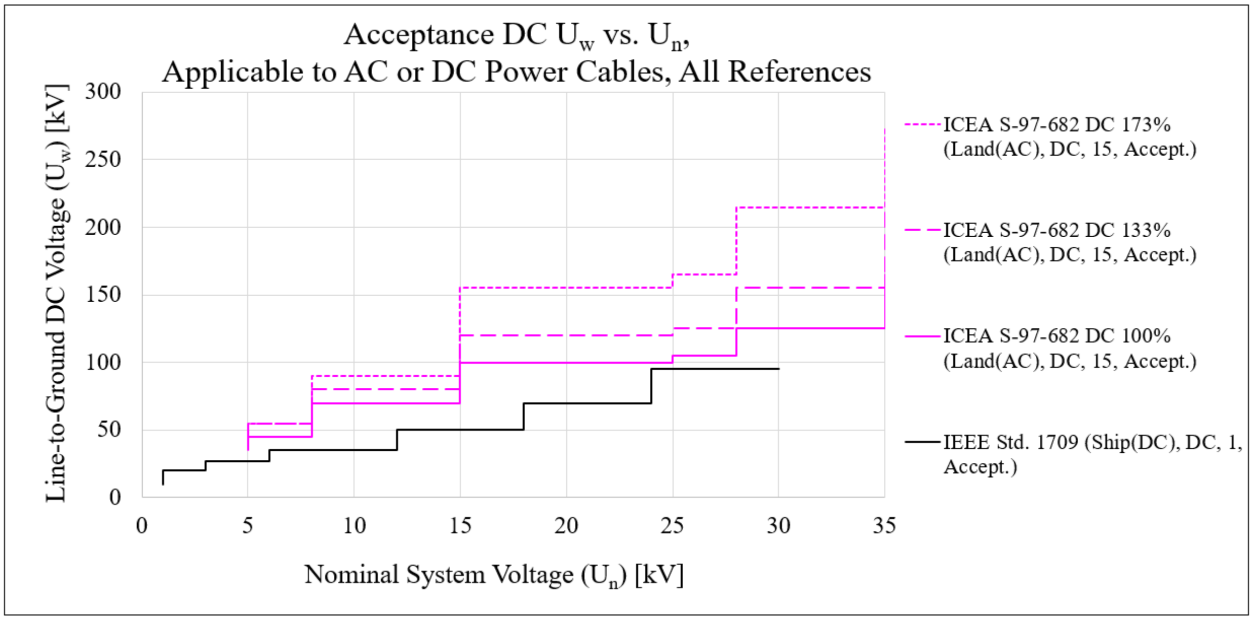


Figure 91: Comparison of DC Withstand Test Voltages (U_w) for All References in §5.1

Reference	Coordinates (U_n [kV], Acceptance DC U_w [kV])								
ICEA S-97-682	5,45	5,55	8,55	8,90	15,90	15,155	25,155	25,165	28,165
173% [35]	28,215	35,215	35,275						
ICEA S-97-682	5,45	5,55	8,55	8,80	15,80	15,120	25,12	25,125	28,125
133% [35]	28,155	35,155	35,215						
ICEA S-97-682	5,35	5,45	8,45	8,70	15,70	15,100	25,100	25,105	28,105
100% [35]	28,125	35,125	35,165						
IEEE Std. 1709	1,10	1,20	3,20	3,27	6,27	6,35	12,35	12,50	18,50
[2]	18,70	24,70	24,95	30,95					

Table 9: Coordinates of Step-Functions in Figure 91

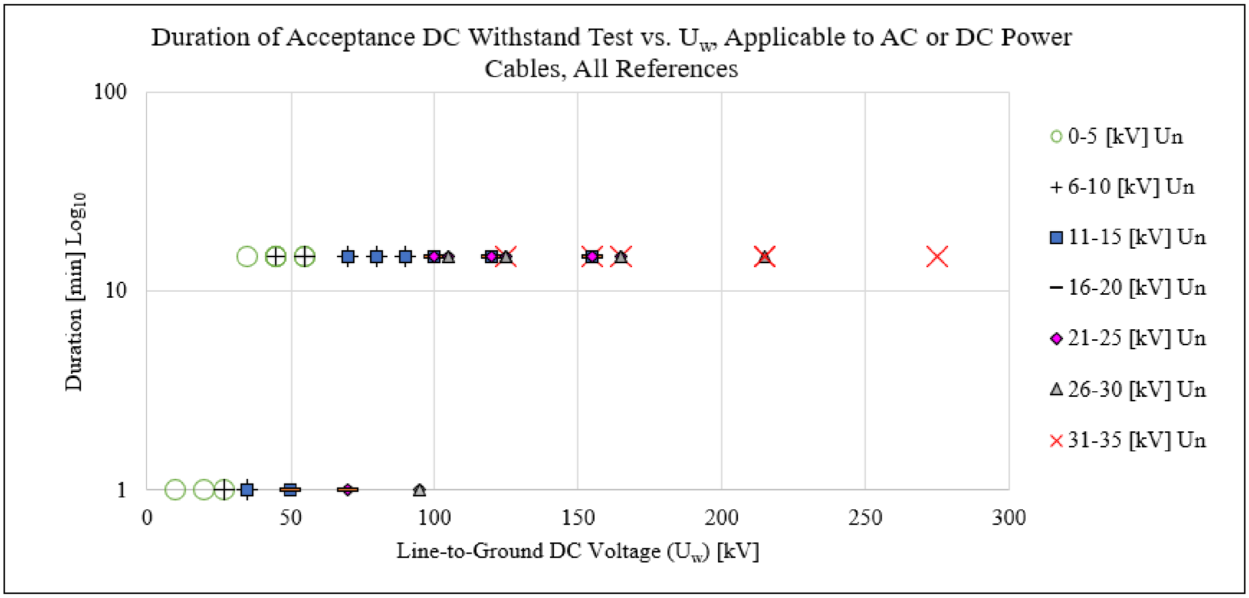


Figure 92: Comparison of Duration vs. DC Withstand Test Voltages (U_w) for All References in §5.1, Log-Linear

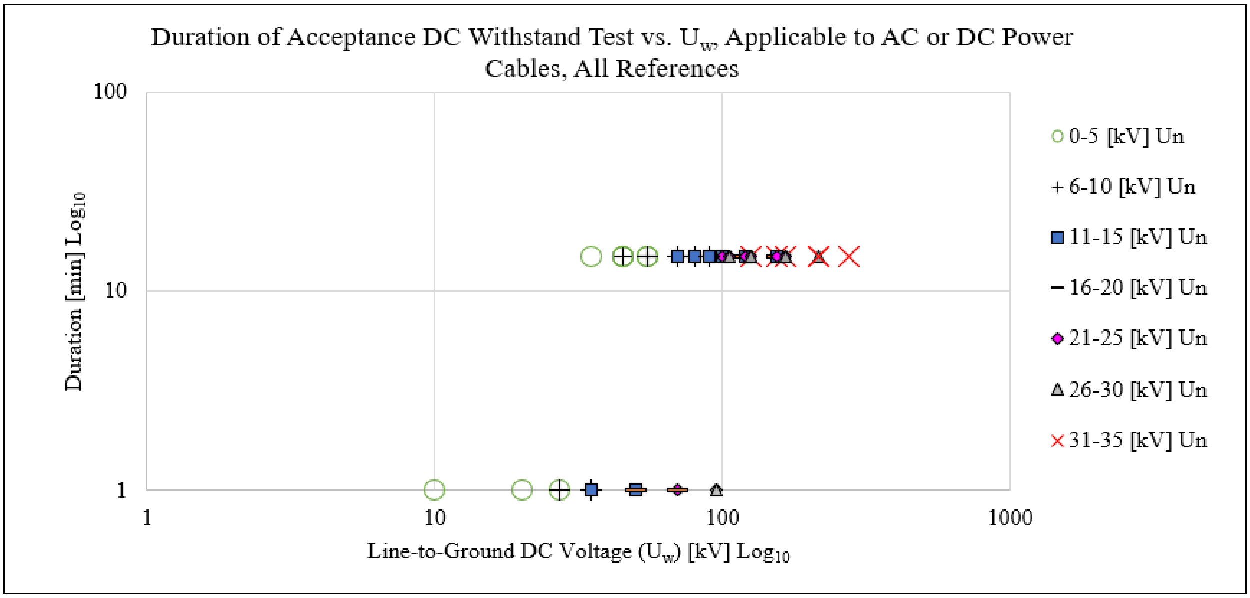


Figure 93: Comparison of Duration vs. DC Withstand Test Voltages (U_w) for All References in §5.1, Log-Log

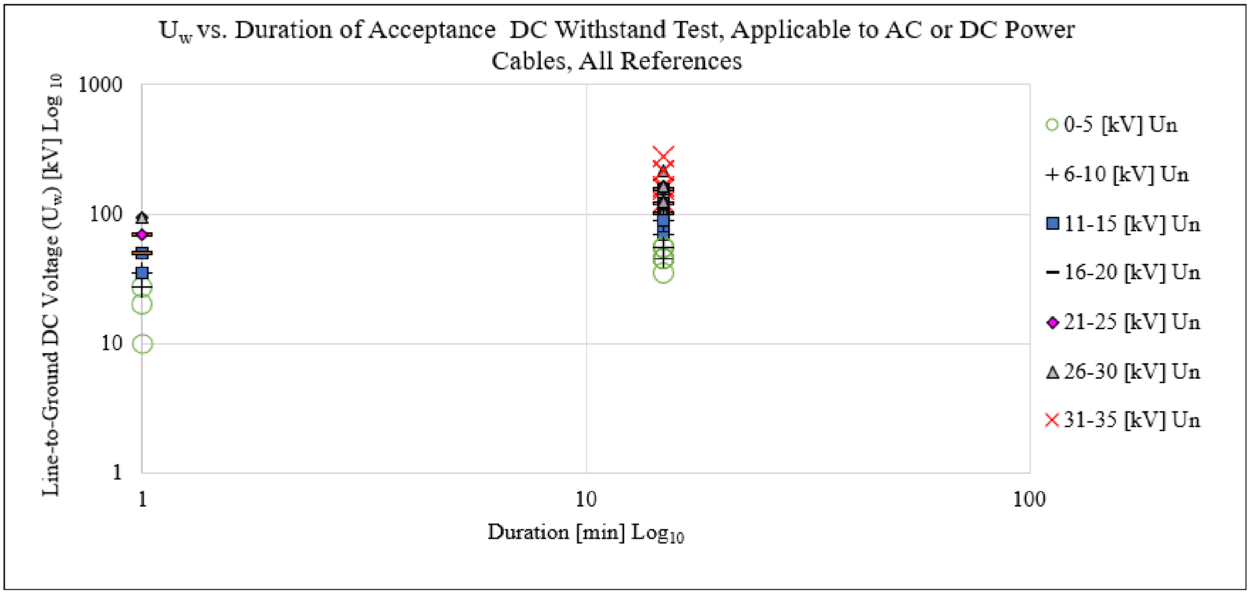


Figure 94: Comparison of DC Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log

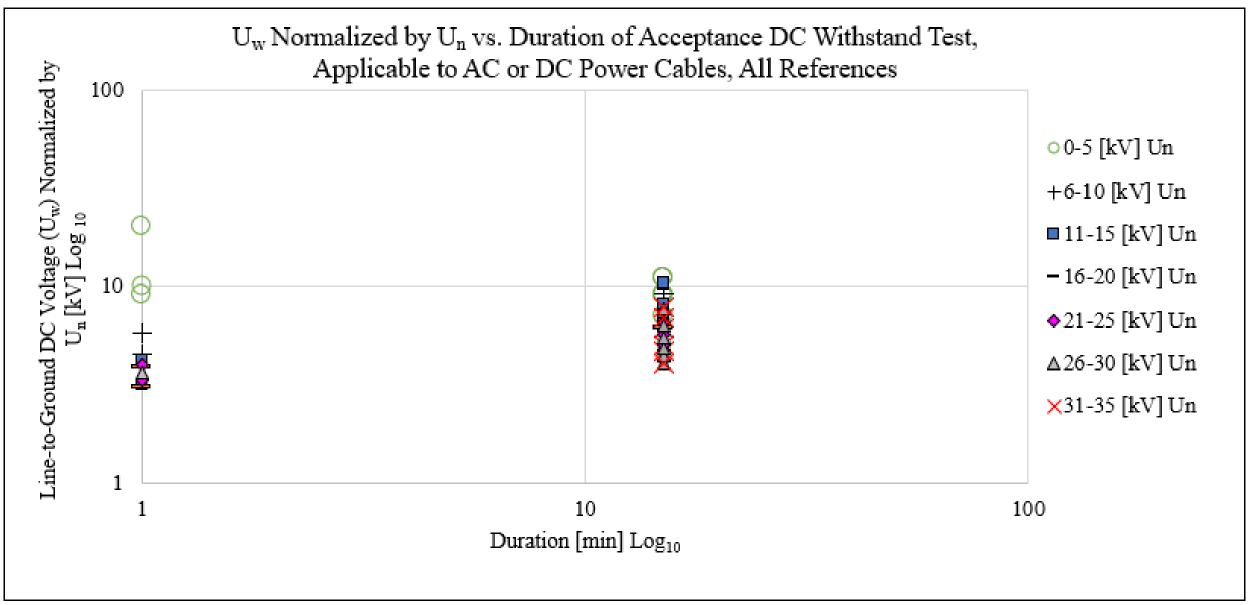


Figure 95: Comparison of DC Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

A comparison of shipboard applicable references is not created for DC Withstand Tests nor is a narrowed down duration, as IEEE Std. 1709 is the only reference within this category [2].

The trendlines fit to each reference's DC U_w vs. U_n in §5.2 were plotted as a function of U_n in Figure 96.

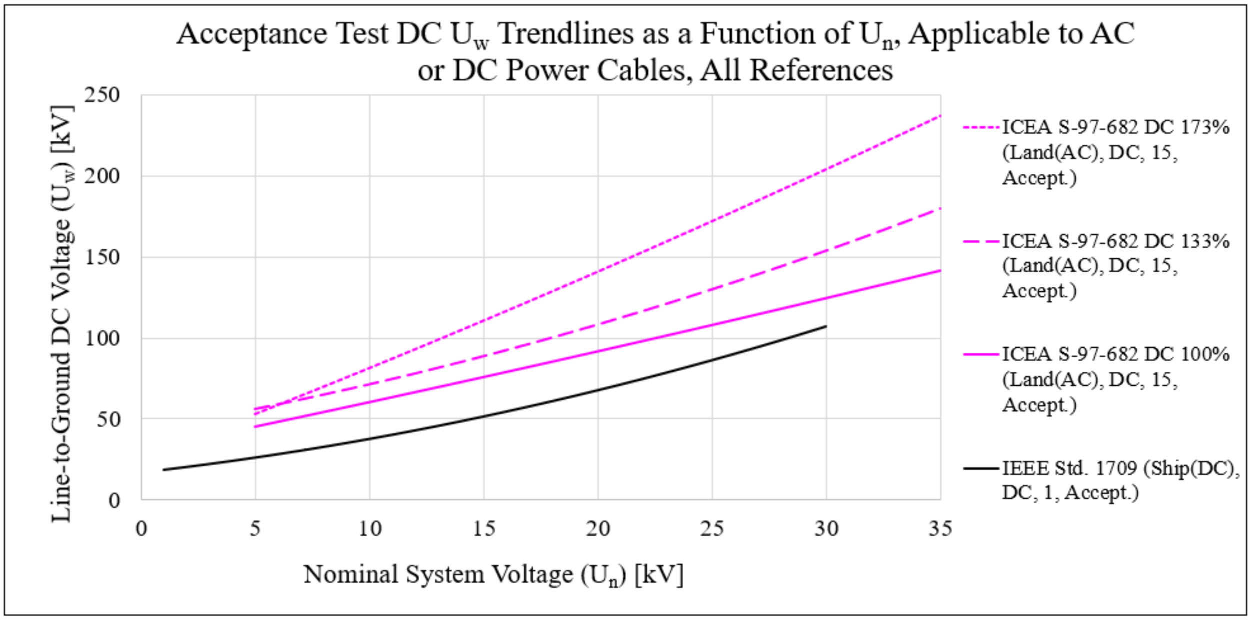


Figure 96: Trendline Comparison of DC Acceptance Withstand Test U_w vs. U_n for All References in §5.1

5.3.1.1 Comparison of AC and DC Acceptance Withstand Tests

The following figures compare the U_w relationship with test duration for all Acceptance AC and DC Withstand Tests, to illustrate the division of the test requirements due to voltage type.

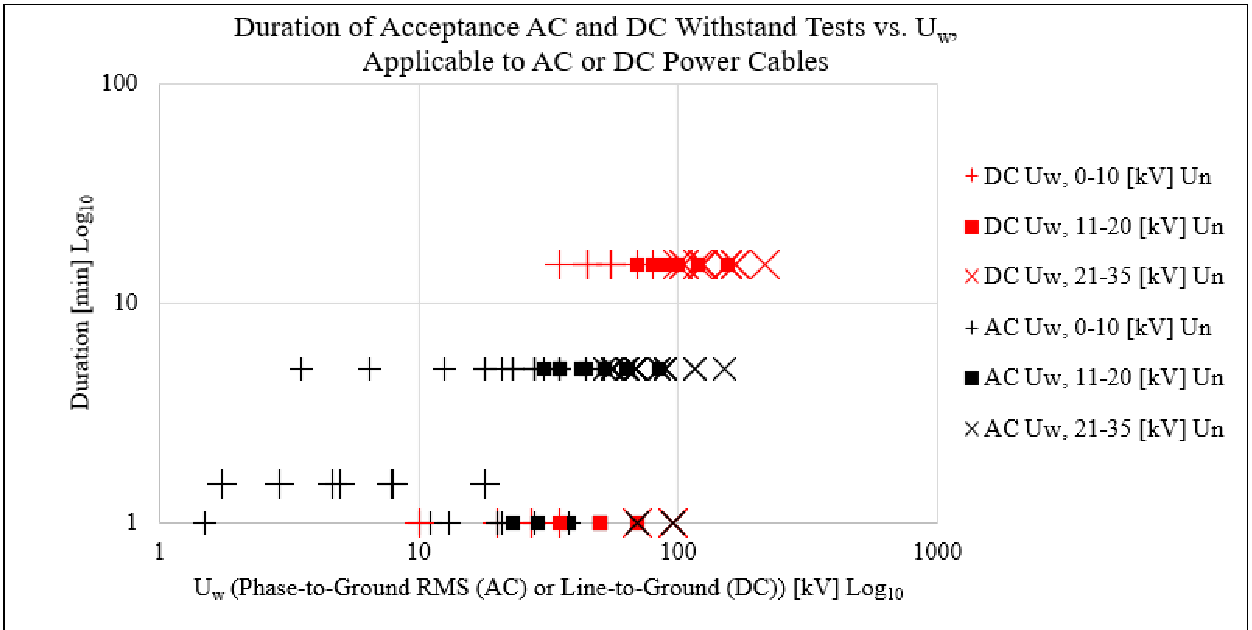


Figure 97: Comparison of Duration vs. Acceptance Withstand Test Voltages (U_w) for All References in §5.1, Log-Log

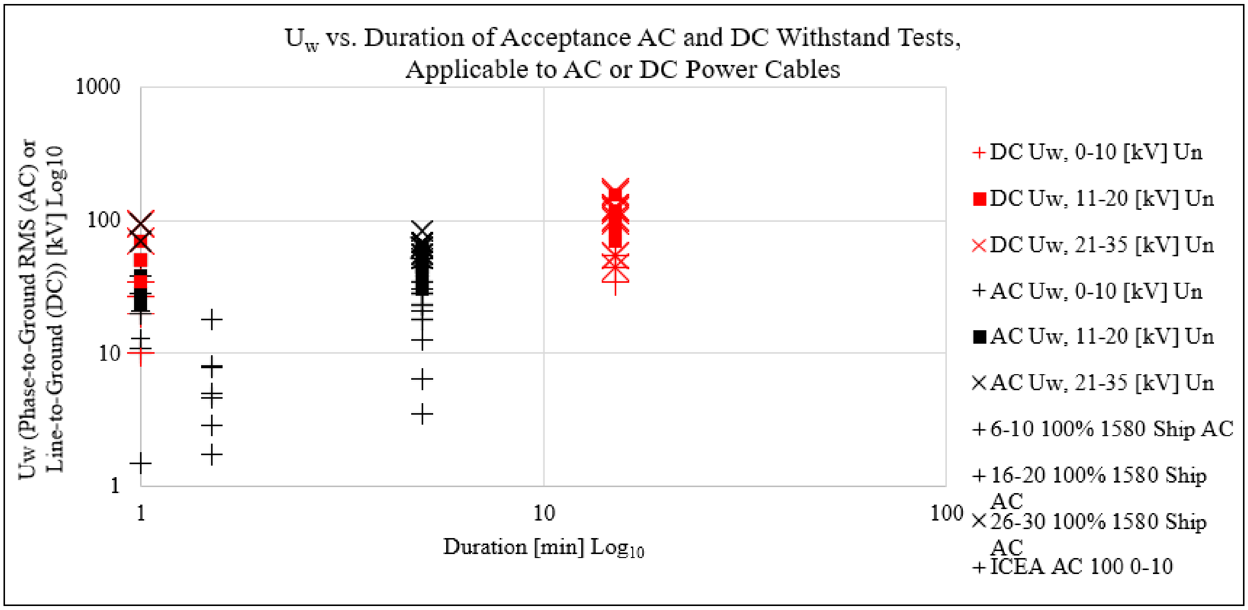


Figure 98: Comparison of Acceptance Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log

Figure 99 was created by taking Figure 98 and normalizing each U_w by U_n. Additionally, the average normalized AC or DC U_w for each duration bin are connected with dashed lines to show the difference of the averages between AC and DC U_w.

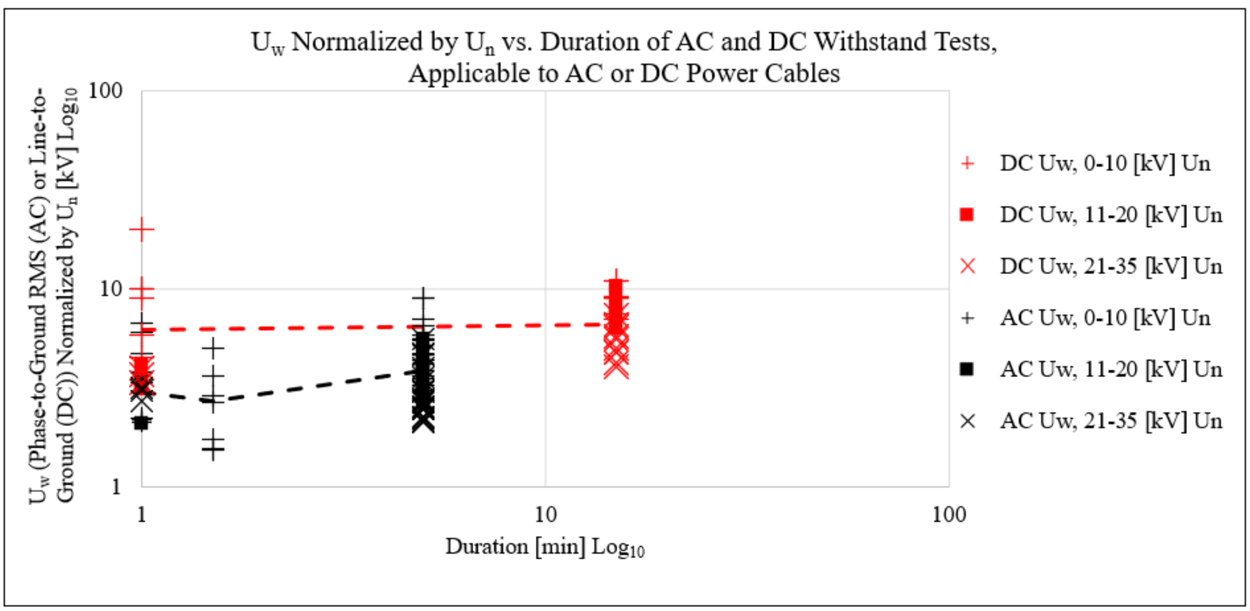


Figure 99: Comparison of Acceptance Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

For a different perspective on the data, Figure 99 is repeated below using the Nominal Peak Cable Voltage (U_p) to normalize the U_w. For AC cables U_p is $\sqrt{2}/\sqrt{3}$ of U_n, for DC cables U_p is ½ U_n. This allows for comparison of the Withstand Tests based on the normal highest voltages the AC and DC power cables experience during standard operation.

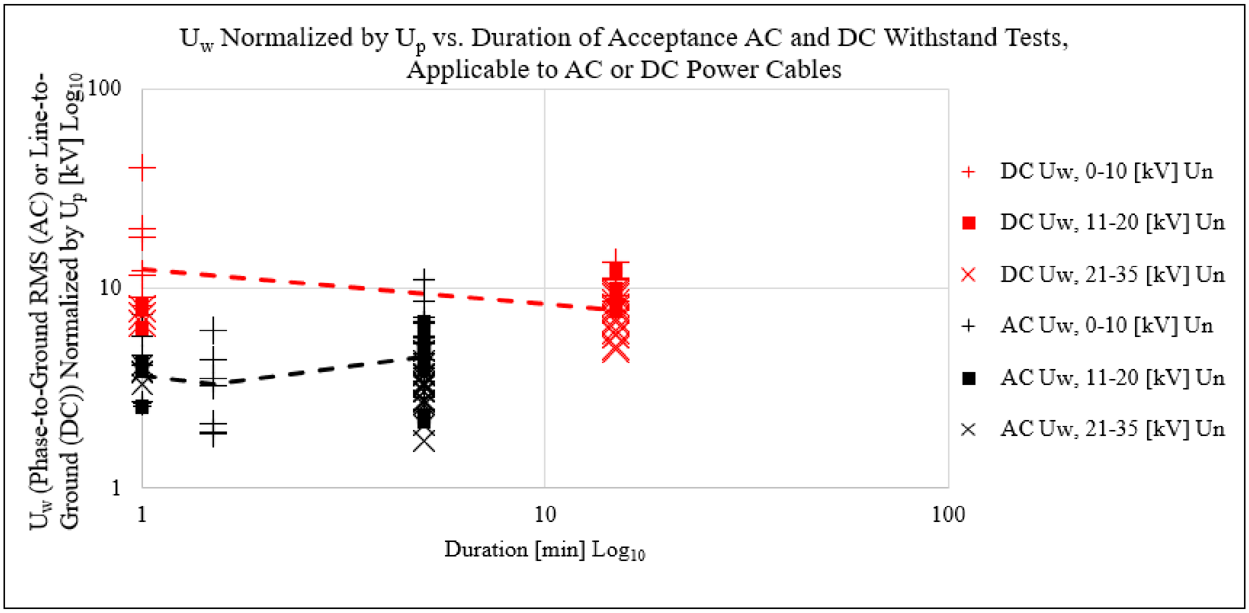


Figure 100: Comparison of Acceptance Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal Peak Cable Voltage (U_p)

Notice, based on the comparison of the normalized U_w in Figure 99 and Figure 100, the existing standards and recommendations require a higher Withstand Test voltage (U_w) for DC voltages compared to that for Withstand Tests with AC voltages of the same Nominal System Voltage (U_n) class rating.

5.3.2 Post-Installation Withstand Tests

The above process of §5.3.1 is repeated for post-installation Withstand Tests. Figure 101 shows all references that prescribe an AC U_w for a Post-Installation Withstand test. This figure applies to AC power cables.

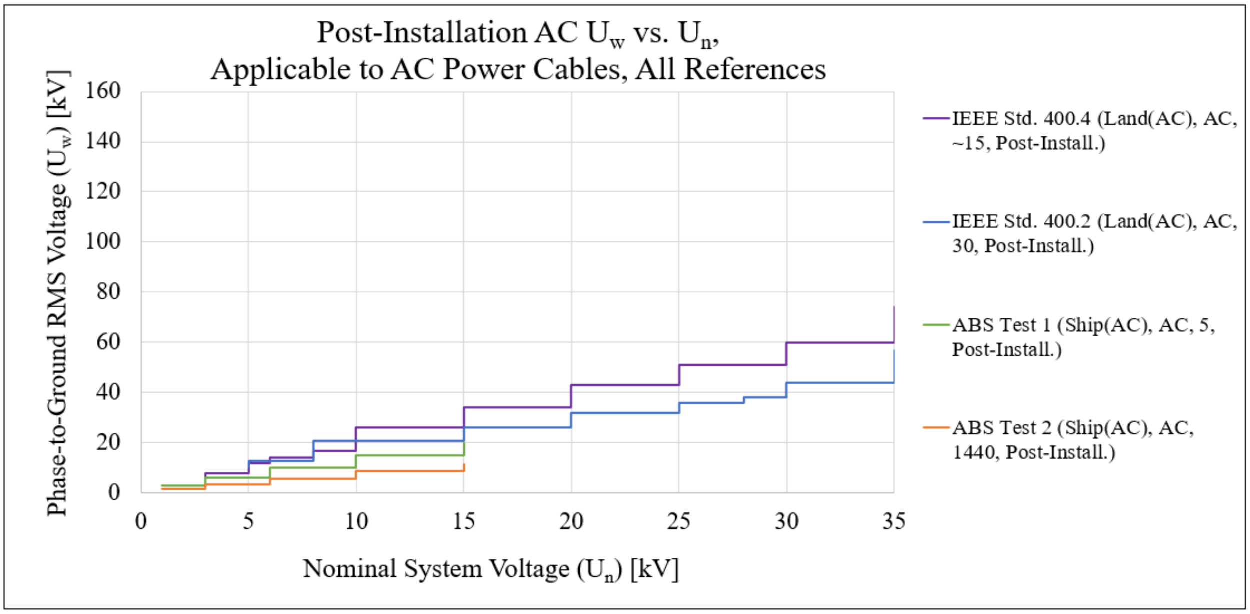


Figure 101: Comparison of Post-Installation Withstand Test AC Voltages (U_w) vs. U_n for All References in §5.1

Reference	Coordinates (U_n [kV], Post-Installation AC U_w [kV])								
IEEE Std. 400.4 [47]	3,6	3,8	5,8	5,12	6,12	6,14	8,14	8,17	10,17
	10,26	15,26	15,34	20,34	20,43	25,43	25,51	30,51	30,60
	35,60	35,74							
IEEE Std. 400.2 [43]	5,10	5,13	8,13	8,21	15,21	15,26	20,26	20,32	25,32
	25,36	28,36	28,38	30,38	30,44	35,44	35,57		
ABS Test 1 [36]	3,3	3,6	6,6	6,10	10,10	10,15	15,15	15,20	
ABS Test 2 [36]	3,1.73	3,3.46	6,3.46	6,5.77	10,5.77	10,8.66	15,8.66	15,11.55	

Table 10: Coordinates of Step-Functions in Figure 101

The trendlines generated for each reference's post-installation test AC U_w vs. U_n in §5.2 were plotted as a function of U_n in Figure 102.

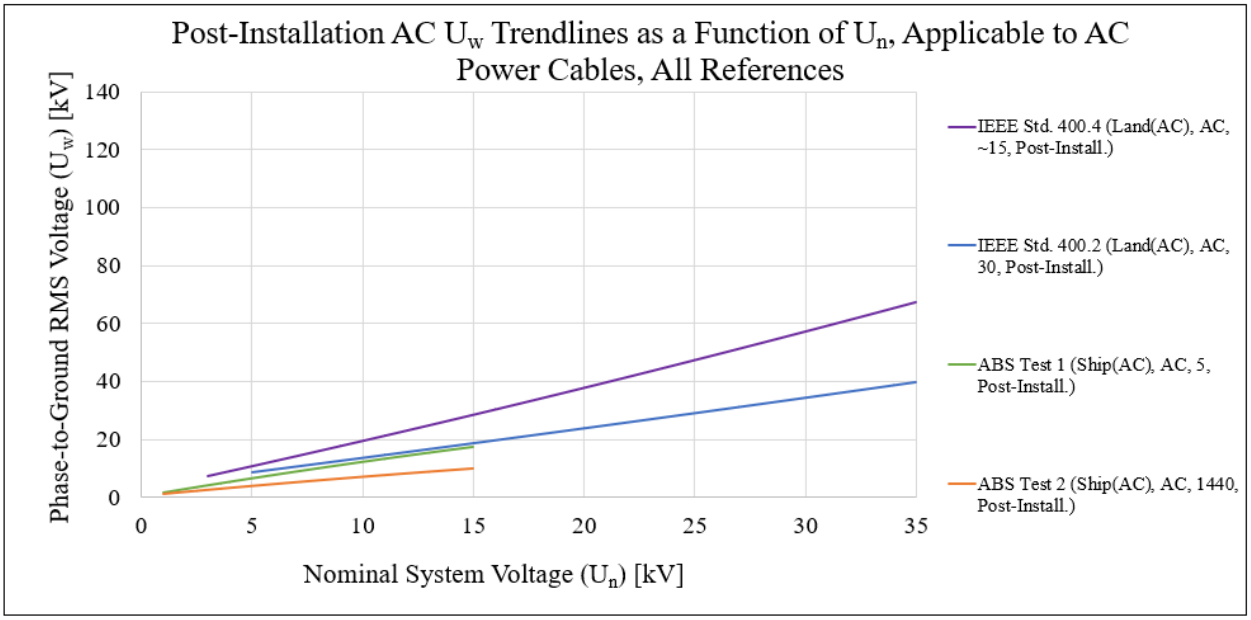


Figure 102: Trendline Comparison of Post-Installation Withstand Test AC Voltages (U_w) vs. U_n for All References in §5.1

To visualize the data another way, the phase-to-ground voltage values of Withstand Test Voltage (U_w) were organized into bins based on their applicable Nominal System Voltage (U_n). These bins were created with 5 [kV] intervals as seen in Figure 103. The U_w prescribed for the start of the bin (with 'start' meaning the lowest U_n value of that bin), as well as any increases to U_w within the bin were plotted below in Figure 103. For references specifying linear relationships of U_w with U_n, the U_w at the start and end of each bin is used to keep the information while reducing clutter. Figure 103 displays the log-linear scale of the relationship between duration and U_w, while Figure 104 and Figure 105 show the relationship on a log-log scale and then with inverted axis, respectively. The log-log scale relationship normalized by U_n is shown in Figure 106.

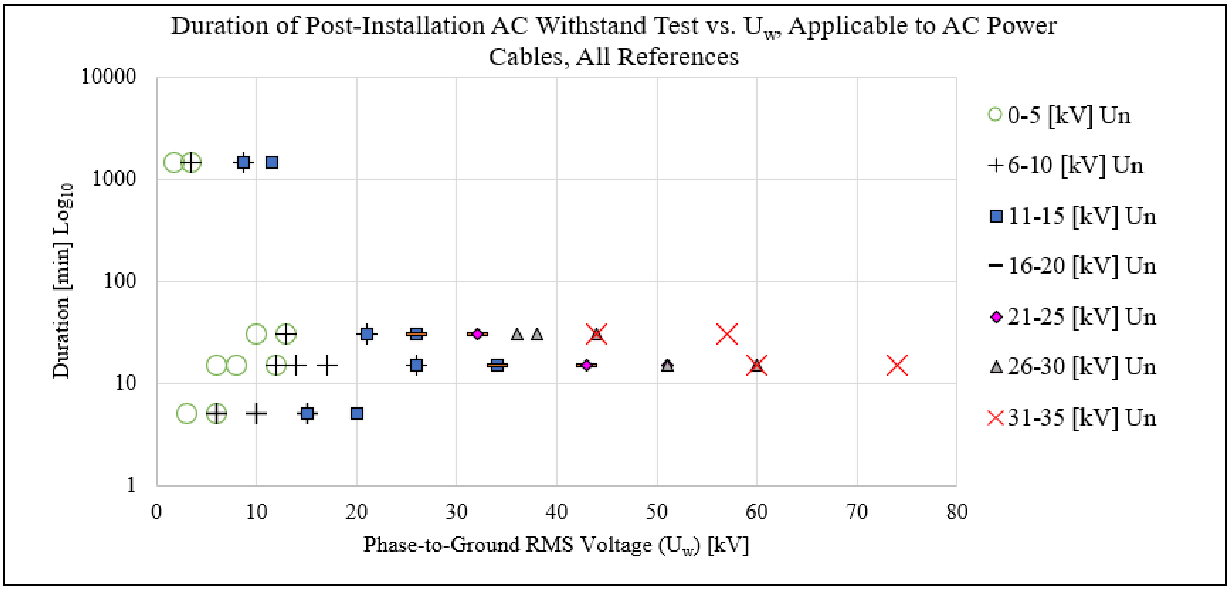


Figure 103: Comparison of Post-Installation Withstand Test AC Duration vs. Withstand Voltages (U_w) for All References in §5.1, Log-Linear

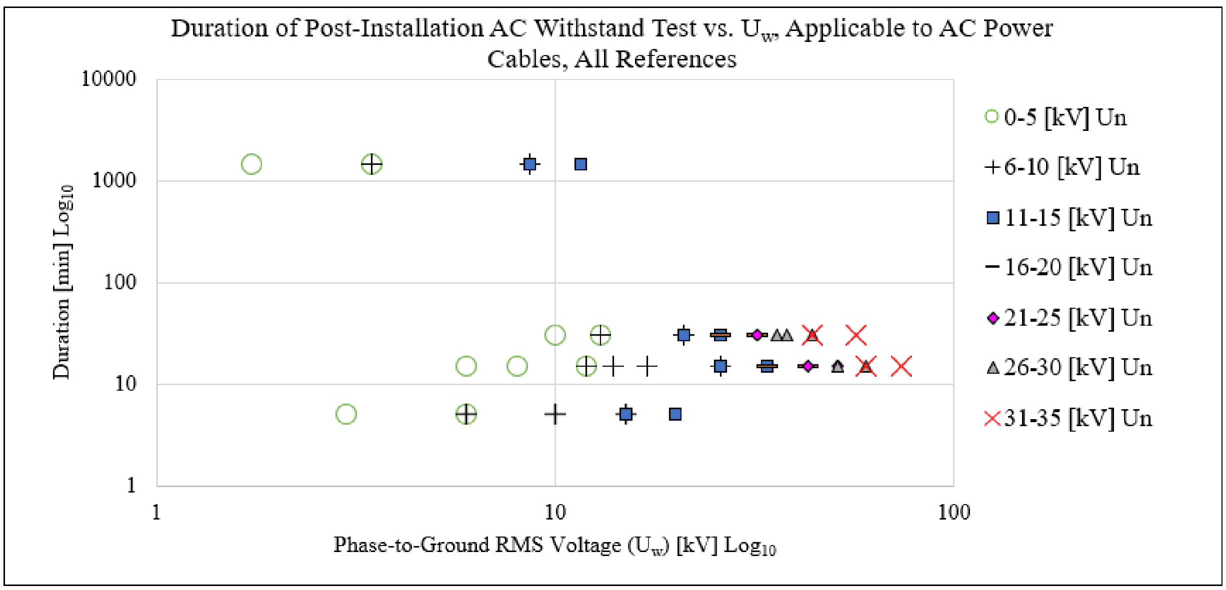


Figure 104: Comparison of Post-Installation Withstand Test AC Duration vs. Withstand Voltages (U_w) for All References in §5.1, Log-Log

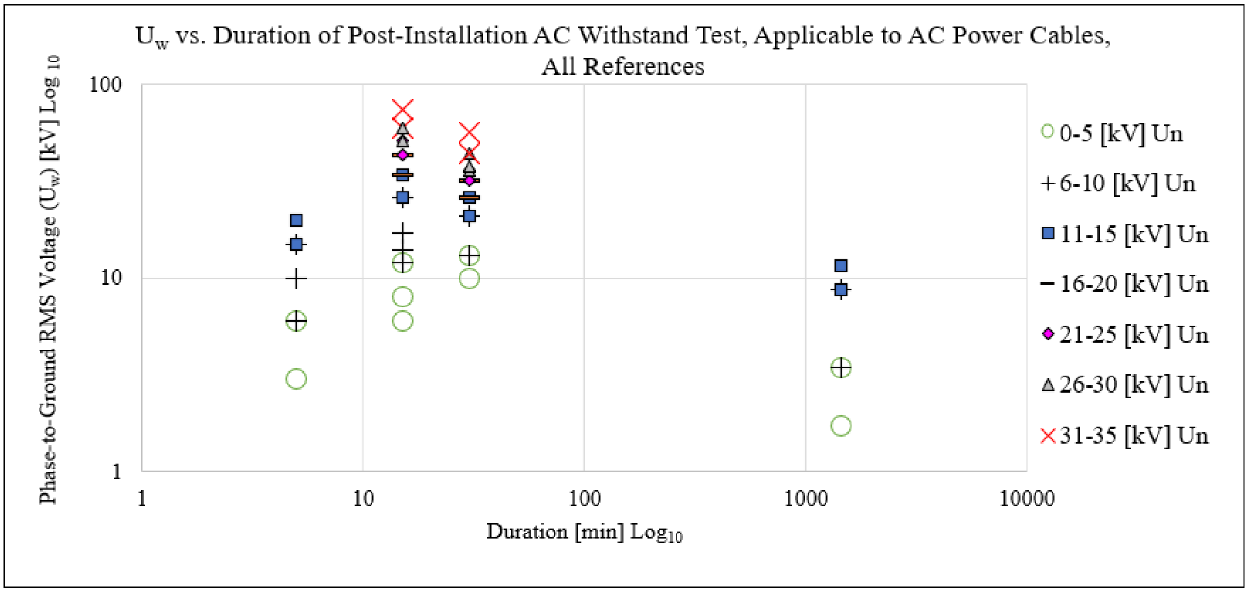


Figure 105: Comparison of Post-Installation Withstand Test AC Voltages (U_w) vs. Duration for All References in §5.1, Log-Log

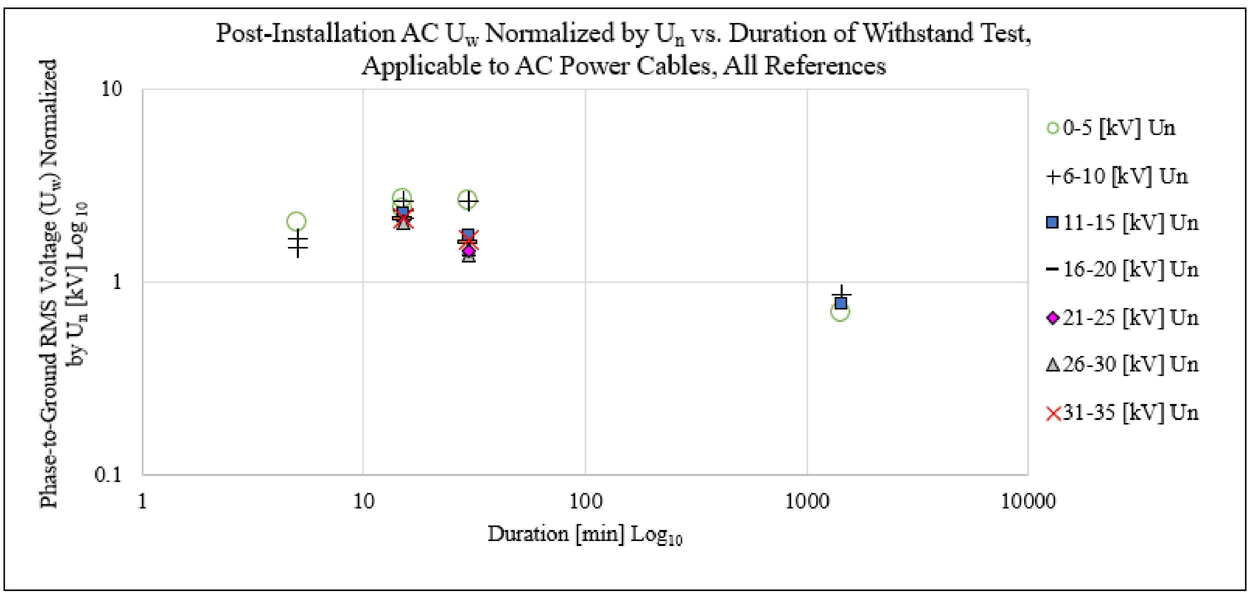


Figure 106: Comparison of Post-Installation Withstand Test AC Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

To emphasize the common parameters among the compared Withstand Voltage tests, Figure 107 through Figure 111 display only references that are applicable to shipboard power cables.

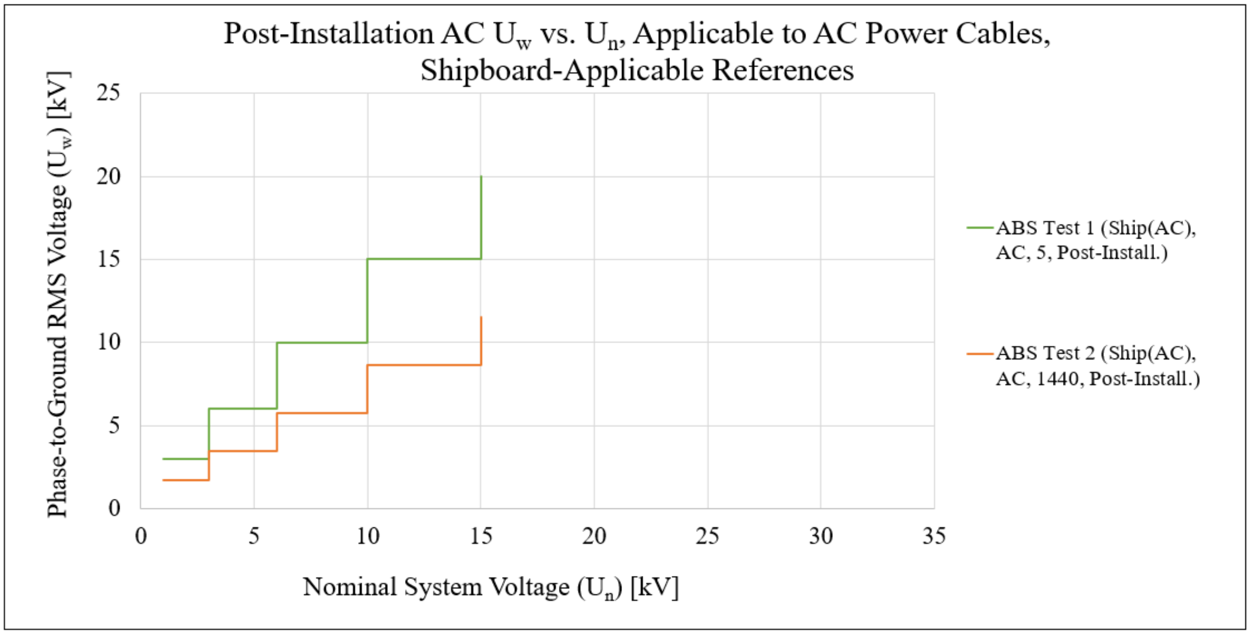


Figure 107: Comparison of Post-Installation Withstand Test AC Voltages (U_w) vs. U_n for Shipboard-Applicable References in §5.1

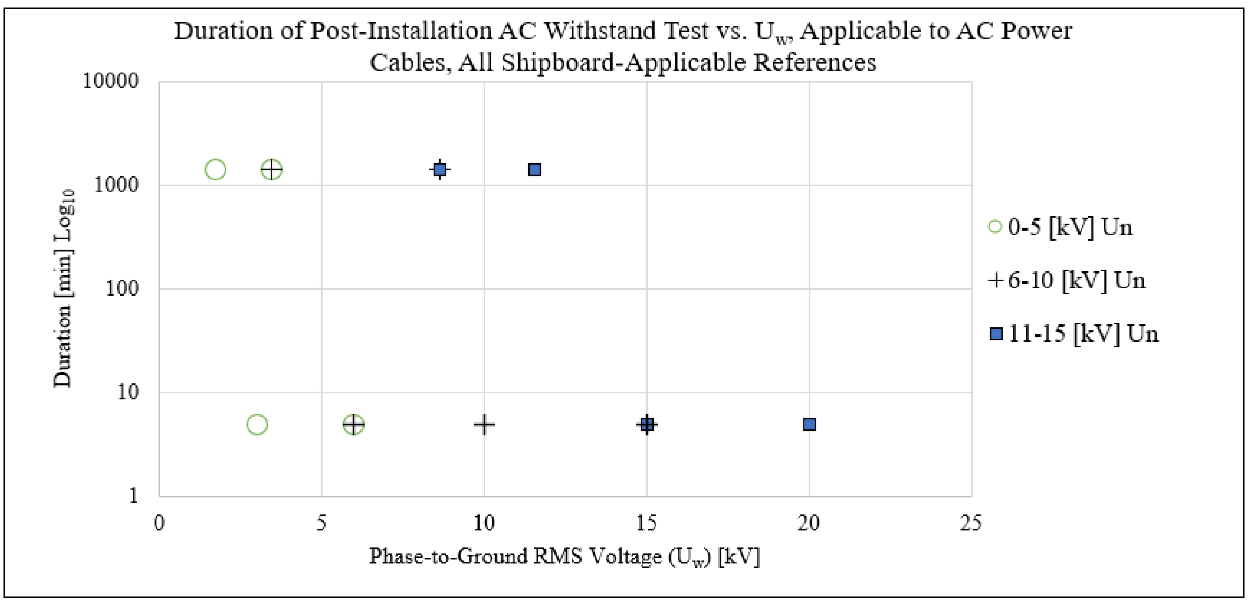


Figure 108: Comparison of Post-Installation Withstand Test Duration vs. AC Voltages (U_w) for Shipboard-Applicable References in §5.1, Log-Linear

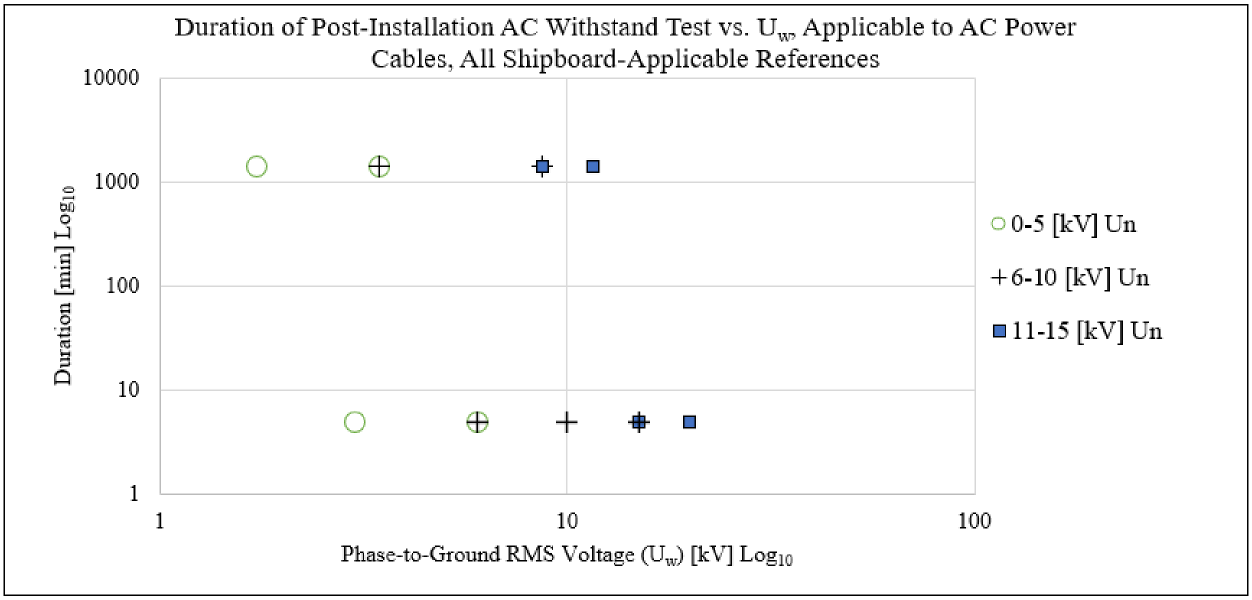


Figure 109: Comparison of Post-Installation Withstand Test Duration vs. AC Voltages (U_w) for Shipboard-Applicable References in §5.1, Log-Log

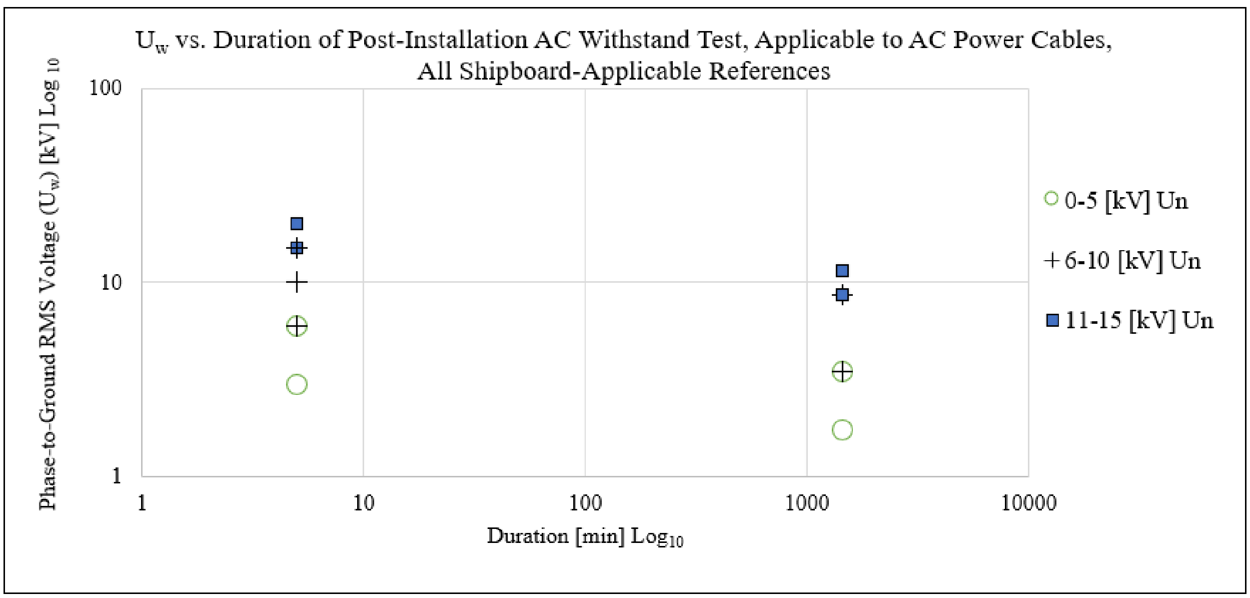


Figure 110: Comparison of Post-Installation Withstand Test AC Voltages (U_w) vs. Duration for Shipboard-Applicable References in §5.1, Log-Log

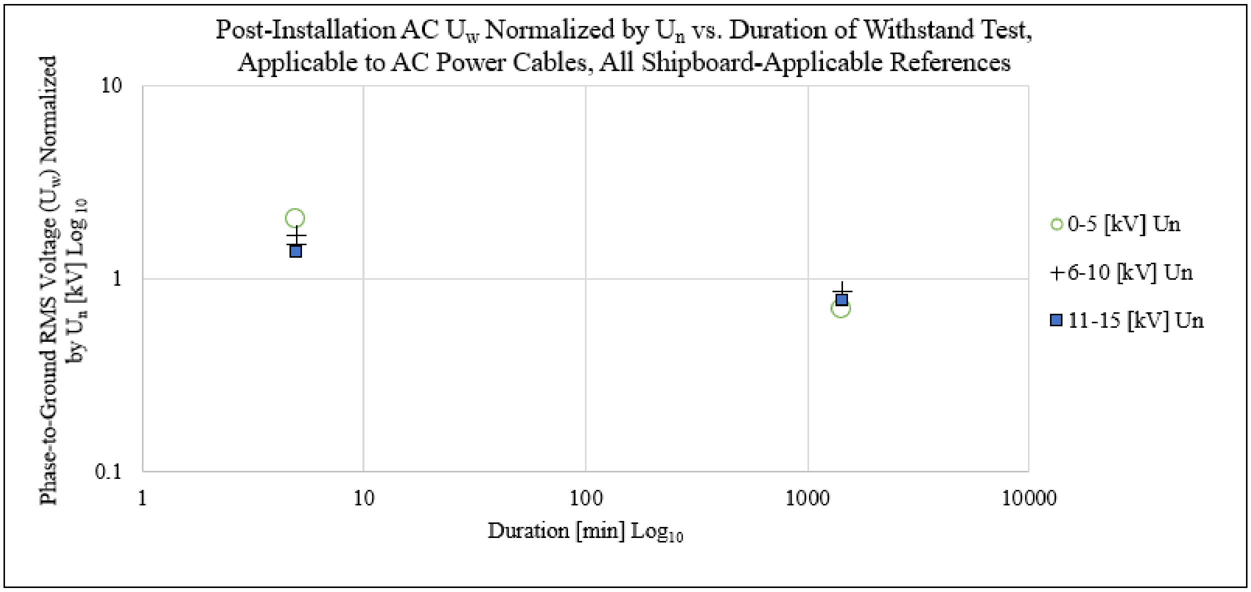


Figure 111: Comparison of Withstand Voltages (U_w) vs. AC Duration for Shipboard References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

The above process is repeated for DC U_w, with all references using an DC U_w being plotted vs. U_n in Figure 112.

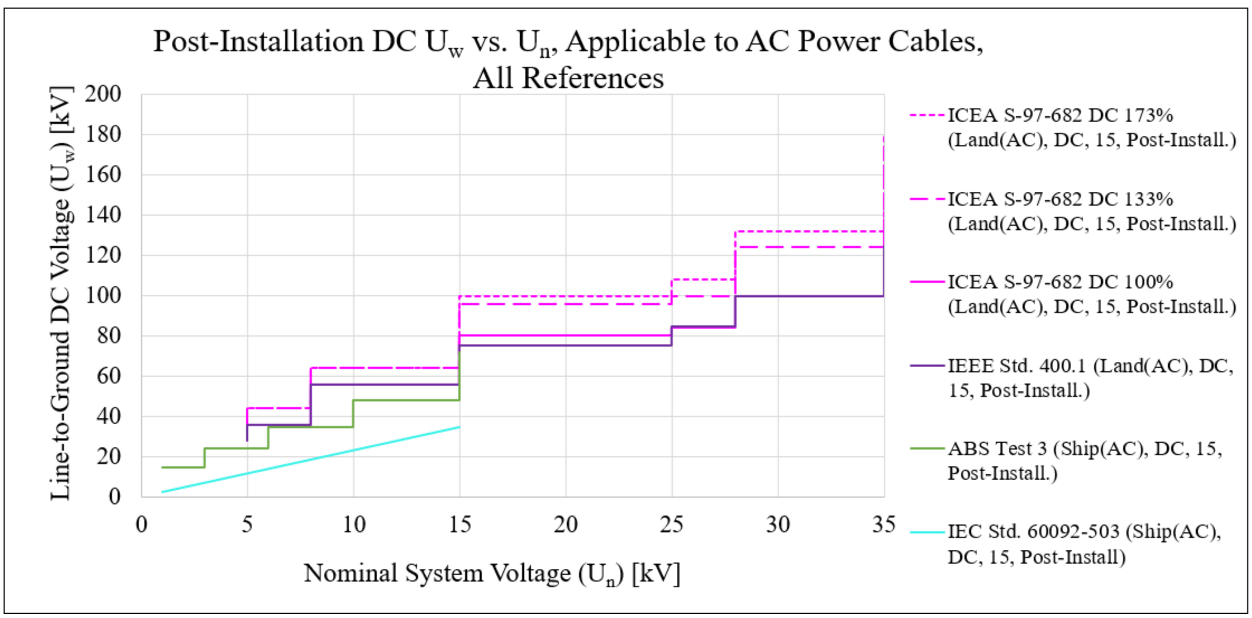


Figure 112: Comparison of Post-Installation Withstand Test DC Voltages (U_w) for All References in §5.1

Reference	Coordinates (U_n [kV], Post-Installation DC U_w [kV])								
ICEA S-97-682 173% [35]	5,36	5,44	8,44	8,64	15,64	15,100	25,100	25,108	28,108
	28,132	35,132	35,180						
ICEA S-97-682 133% [35]	5,36	5,44	8,44	8,64	15,64	15,96	25,96	25,100	28,100
	28,124	35,124	35,172						
ICEA S-97-682 100% [35]	5,28	5,36	8,36	8,56	15,56	15,80	25,80	25,84	28,84
	28,100	35,100	35,132						
IEEE Std. 400.1 [33]	5,28	5,35	8,36	8,56	15,56	15,75	28,75	25,85	28,85
	28,100	35,100	35,125						
ABS Test 3 [36]	3,14.4	3,24	6,24	6,34.8	10,34.8	10,48	15,48	15,72	
IEC Std. 60092-503 [39]	Post-Installation DC $U_w = 2.3094 * U_n \mid \{1 \leq U_n \leq 15$ [kV]$\}$								

Table 11: Coordinates of Step-Functions in Figure 112

To show arguably more comparable U_w, the common parameters between references were increased to only show references that are applicable to shipboard power cables, as shown in Figure 113.

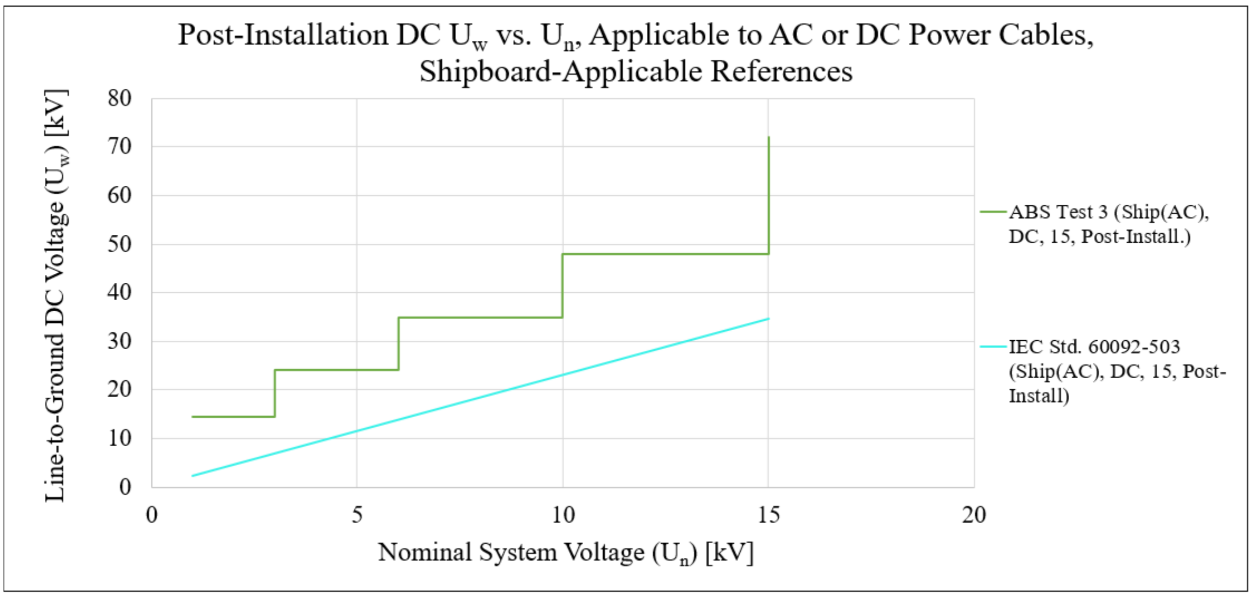


Figure 113: Comparison of Post-Installation Withstand Test DC Voltages (U_w) vs. U_n for Shipboard-Applicable References in §5.1

The trendlines fit to each reference's Post-Installation Withstand Voltage Test with a DC U_w vs. U_n in §5.2 were plotted as a function of U_n in Figure 114, and reduced to the shipboard-applicable tests in the region of interest for Figure 115.

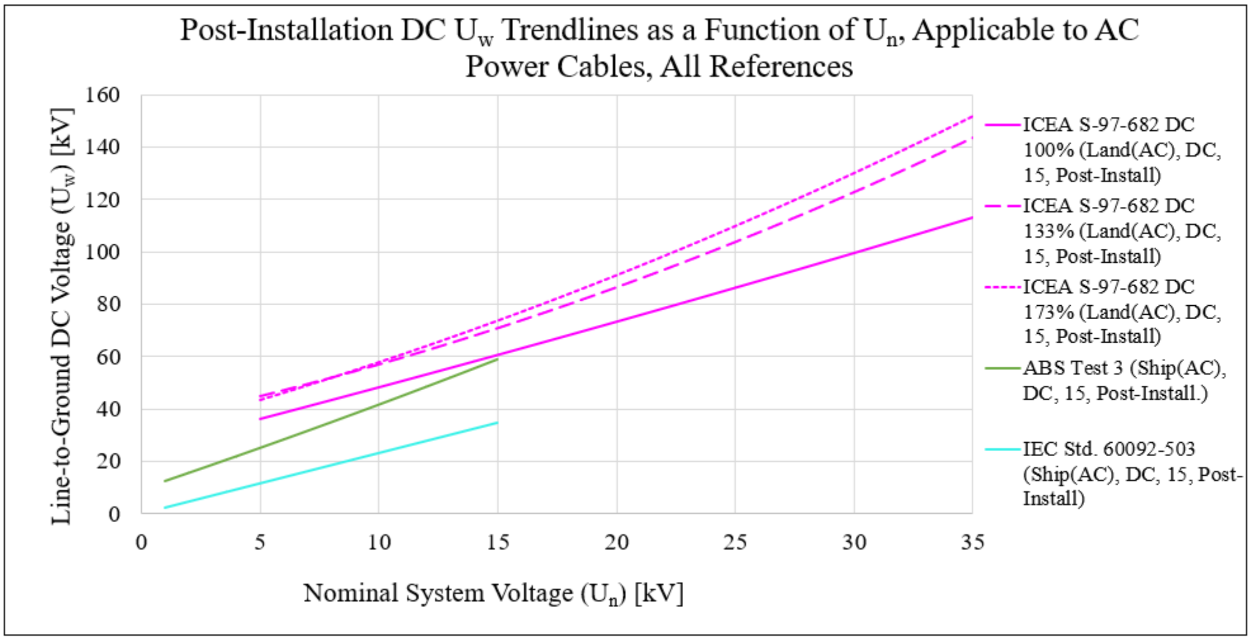


Figure 114: Trendline Comparison of Post-Installation Withstand Test DC U_w vs. U_n for All References in §5.1

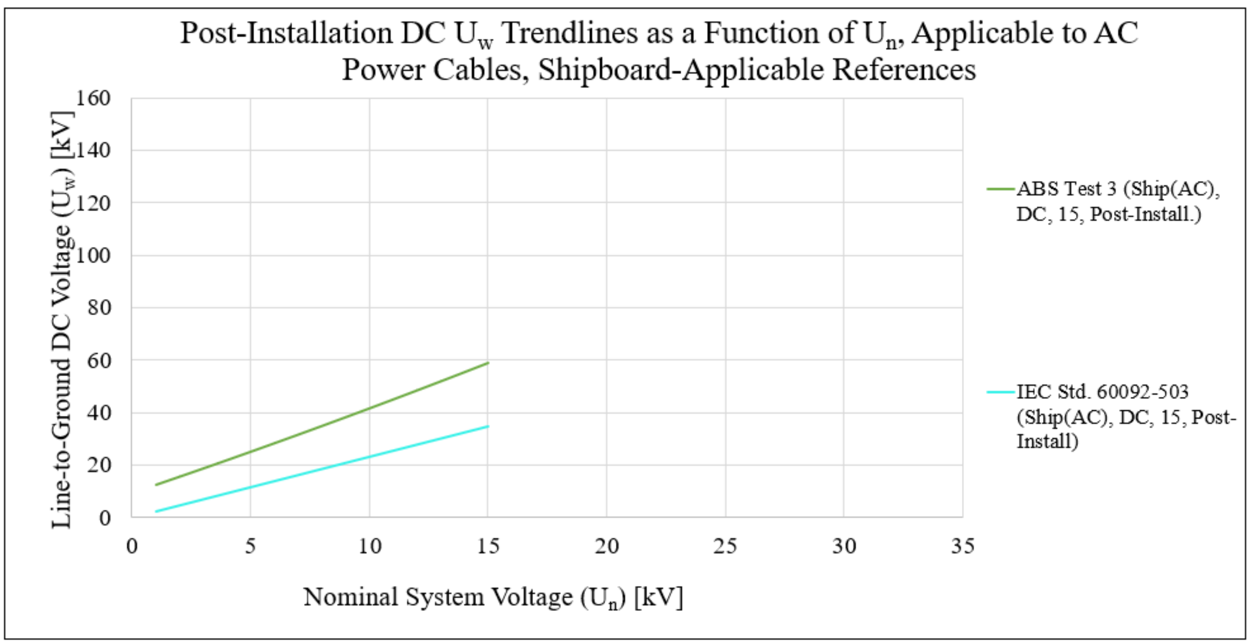


Figure 115: Trendline Comparison of Post-Installation Withstand Test DC U_w vs. U_n for Shipboard-Applicable References in §5.1

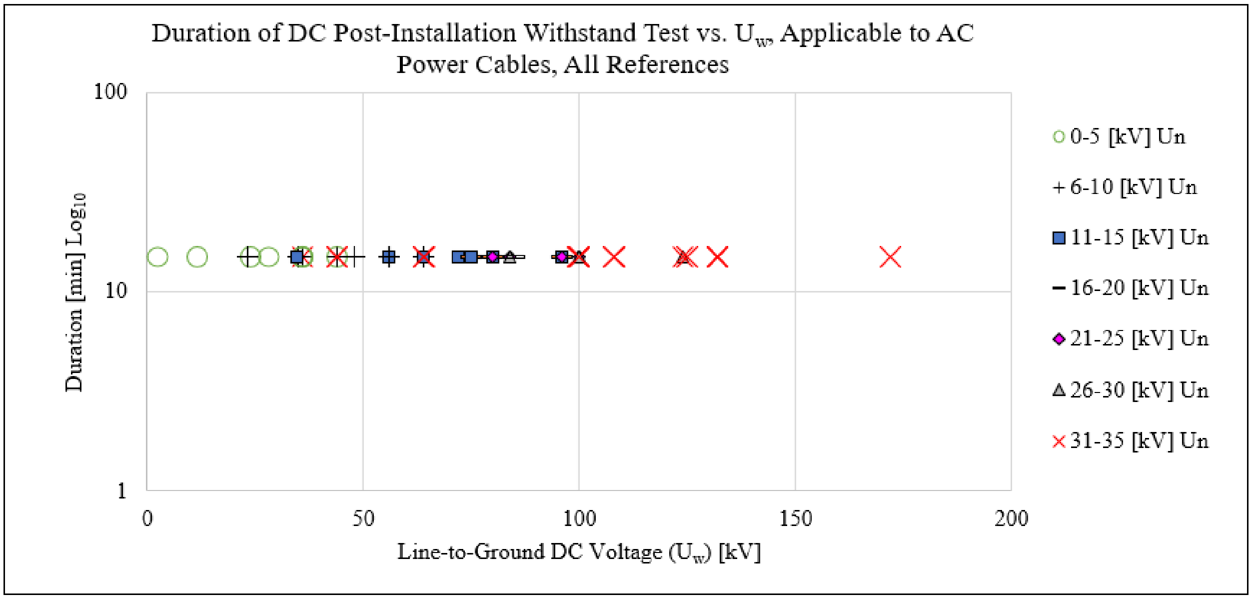


Figure 116: Comparison of Duration vs. Post-Installation DC Withstand Voltages (U_w) for All References in §5.1, Log-Linear

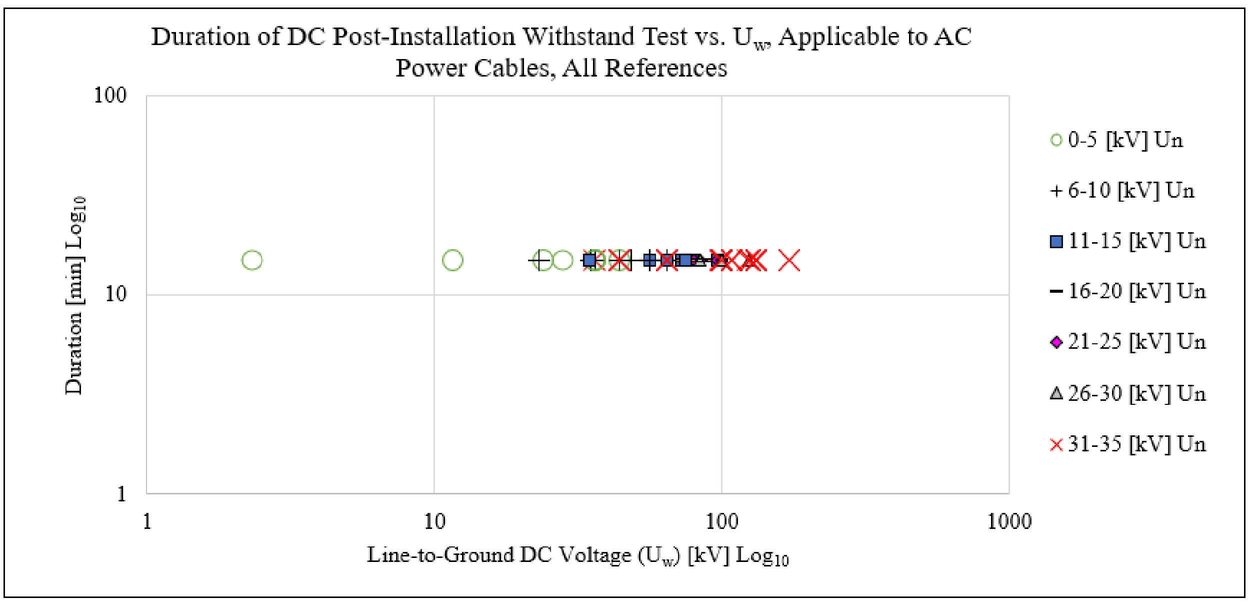


Figure 117: Comparison of Duration vs. Post-Installation DC Withstand Voltages (U_w) for All References in §5.1, Log-Log

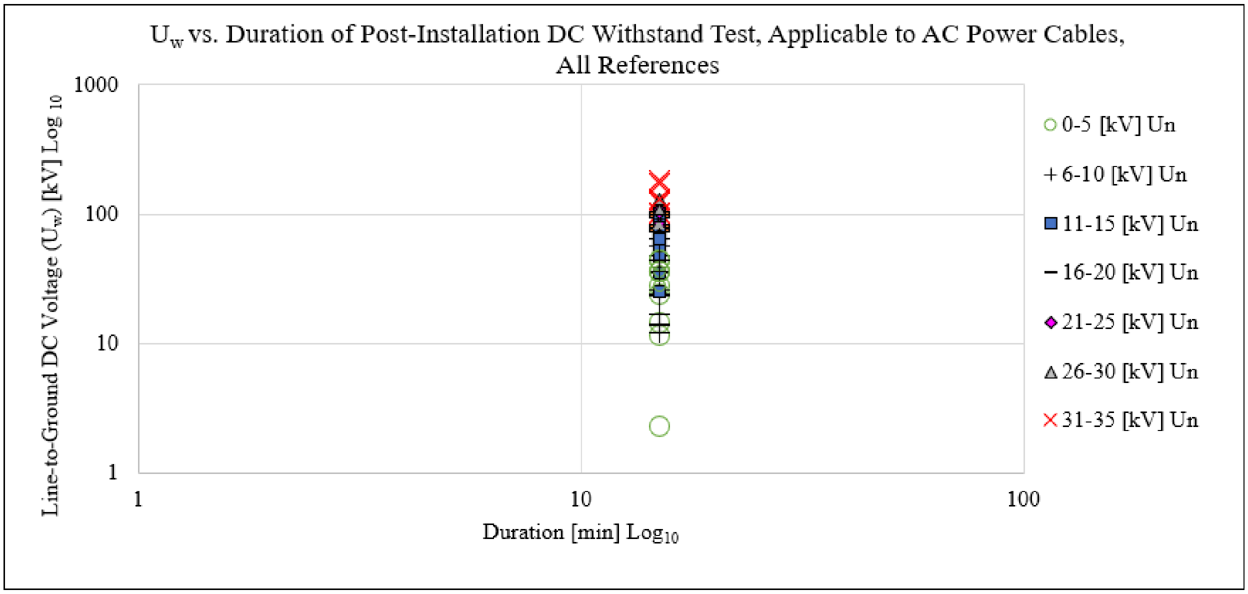


Figure 118: Comparison of Post-Installation DC Withstand Voltages (U_w) vs. Duration for All References in §5.1, Log-Log

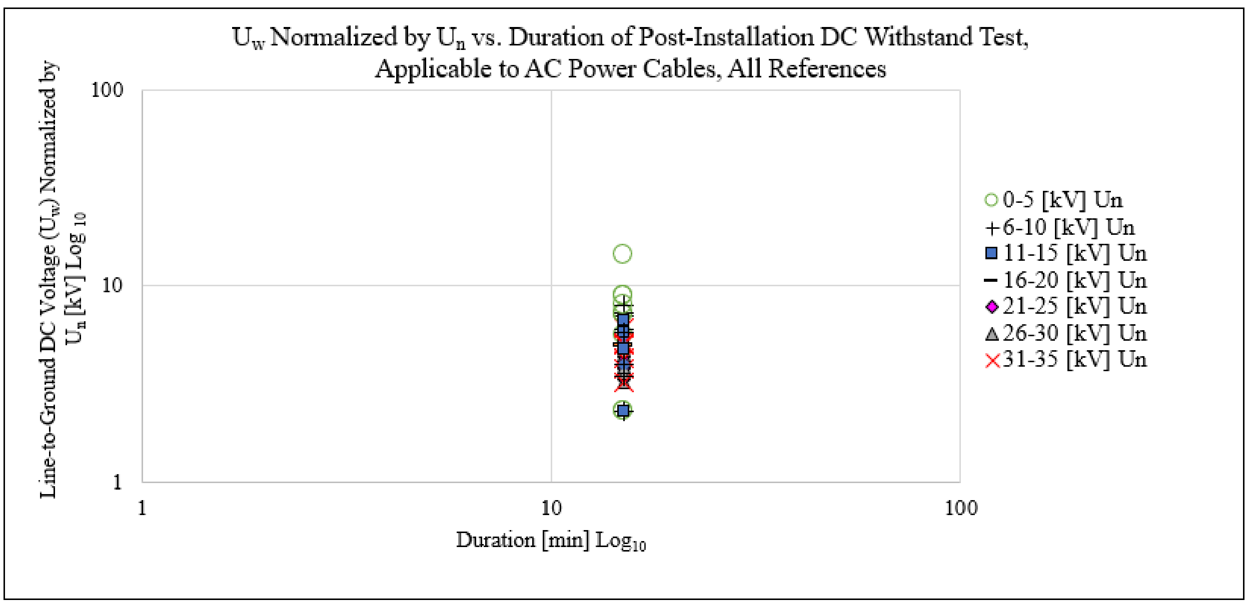


Figure 119: Comparison of Post-Installation DC Withstand Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

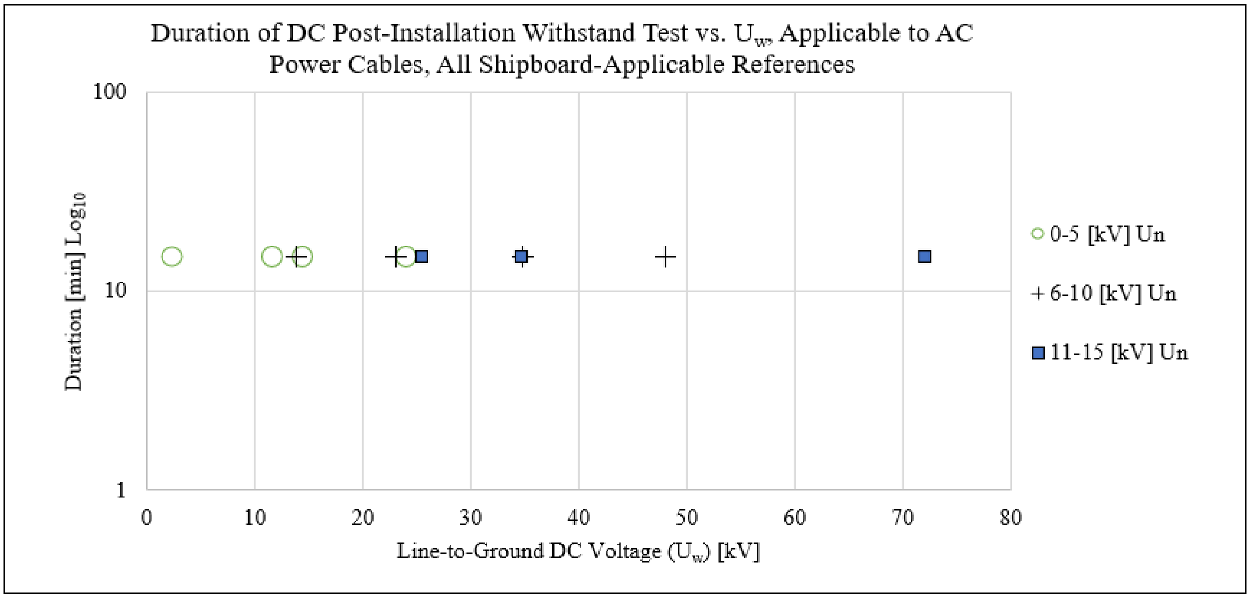


Figure 120: Comparison of Duration vs. Post-Installation Withstand Test DC Voltages (U_w) for Shipboard-Applicable References in §5.1, Log-Linear

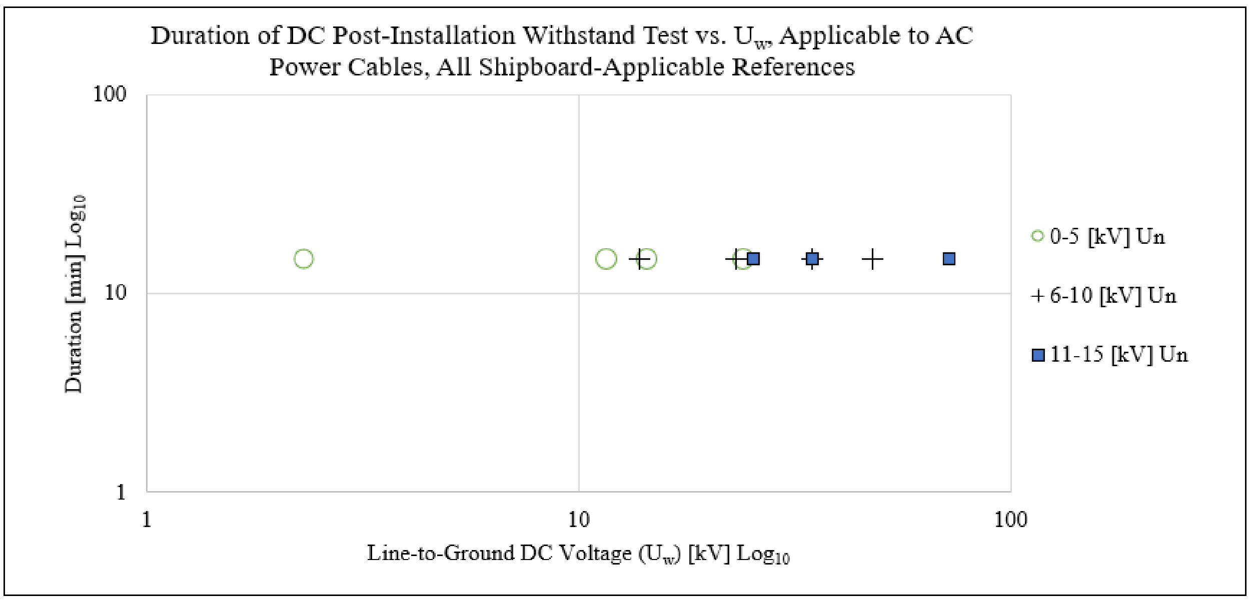


Figure 121: Comparison of Duration vs. Post-Installation Withstand Test DC Voltages (U_w) for Shipboard-Applicable References in §5.1, Log-Log

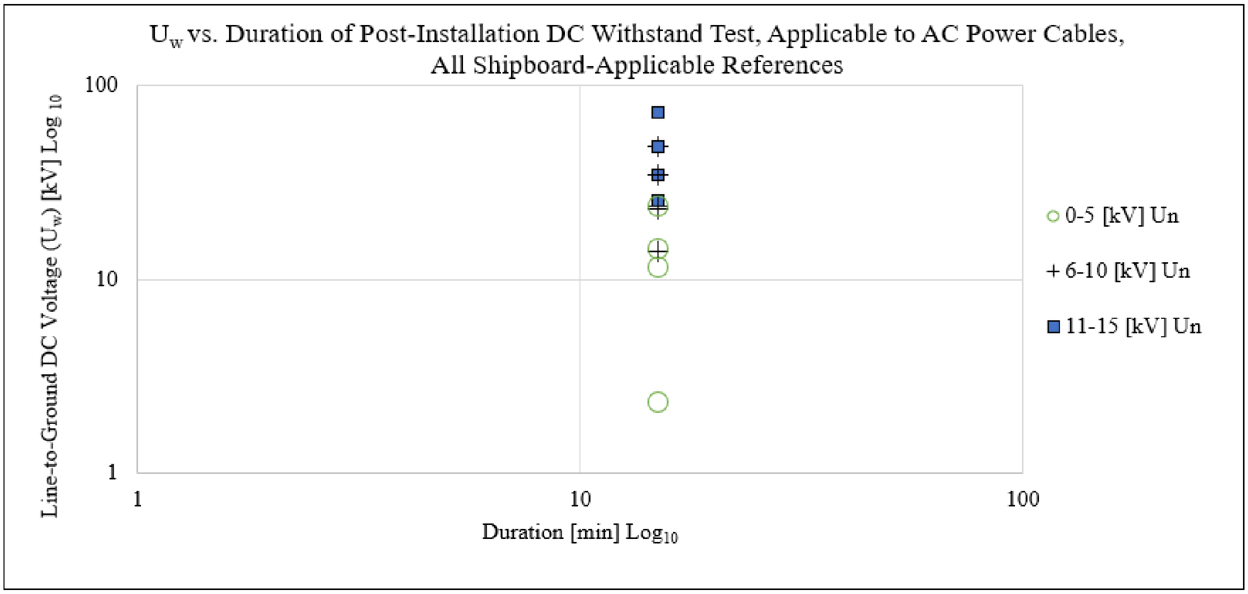


Figure 122: Comparison of Post-Installation Withstand Test DC Voltages (U_w) vs. Duration for Shipboard-Applicable References in §5.1, Log-Log

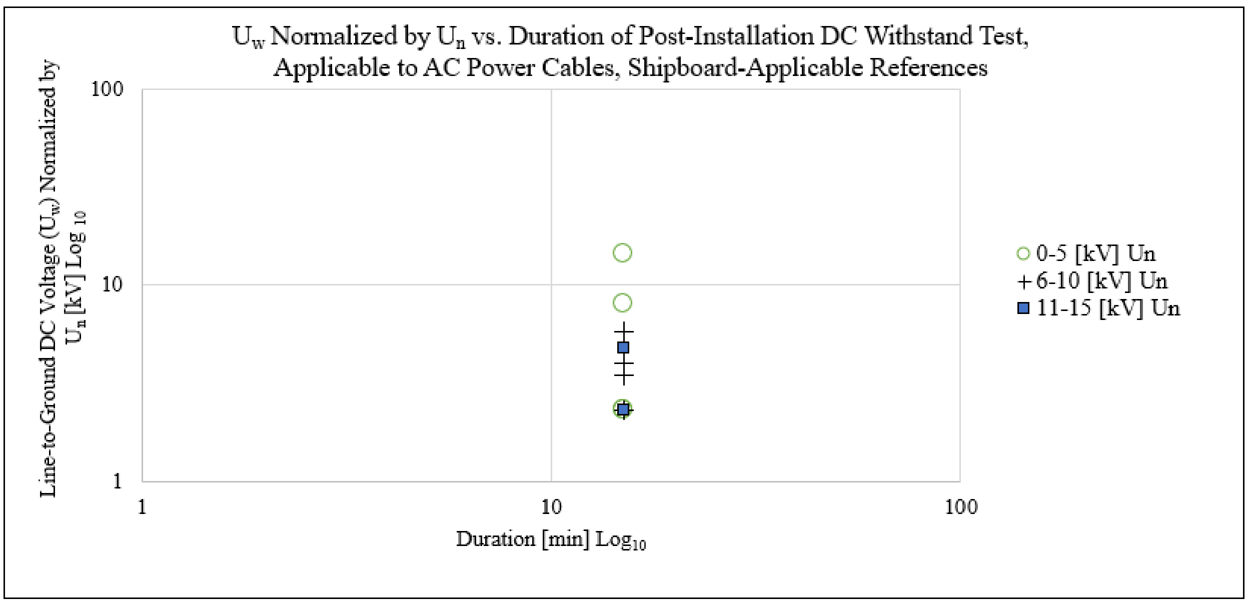


Figure 123: Comparison of Acceptance Test DC Withstand Voltages (U_w) vs. Duration for Shipboard-Applicable References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

5.3.2.1 Comparison of AC and DC Post-Installation Withstand Tests

The following figures compare the U_w relationship with test duration for all Post-Installation AC and DC Withstand Tests, to illustrate the division of the test requirements due to voltage type.

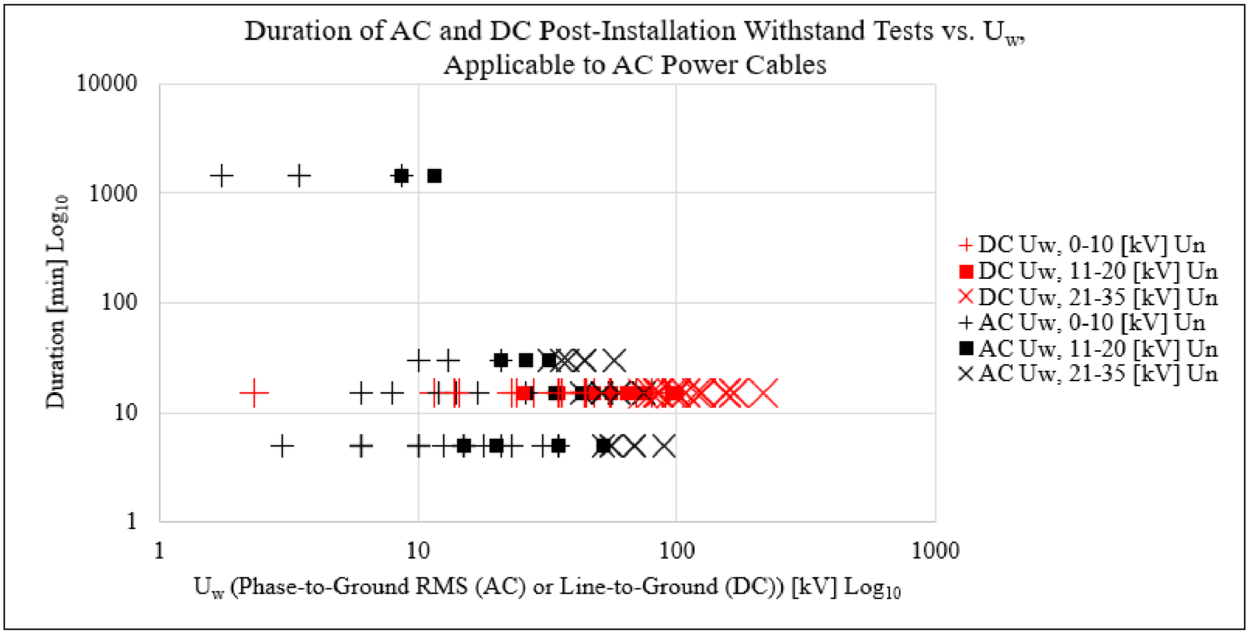


Figure 124: Comparison of Duration vs. Post-Installation Withstand Test Voltages (U_w) for All References in §5.1, Log-Log

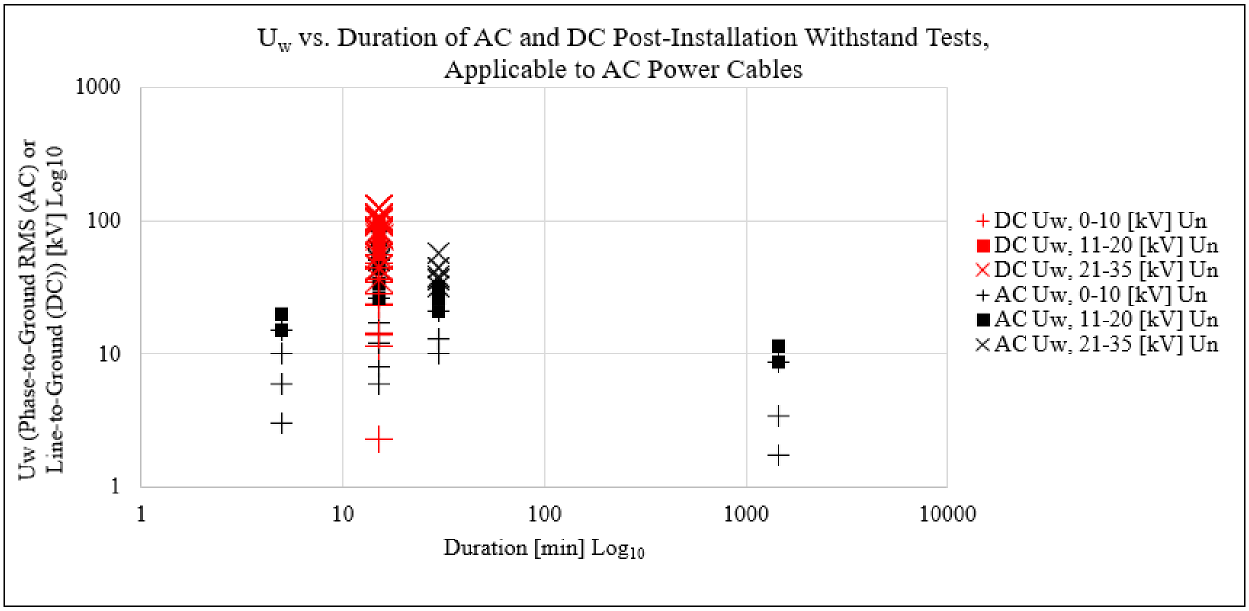


Figure 125: Comparison of Post-Installation Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log

Figure 126 was created by taking Figure 125 and normalizing each U_w by U_n.

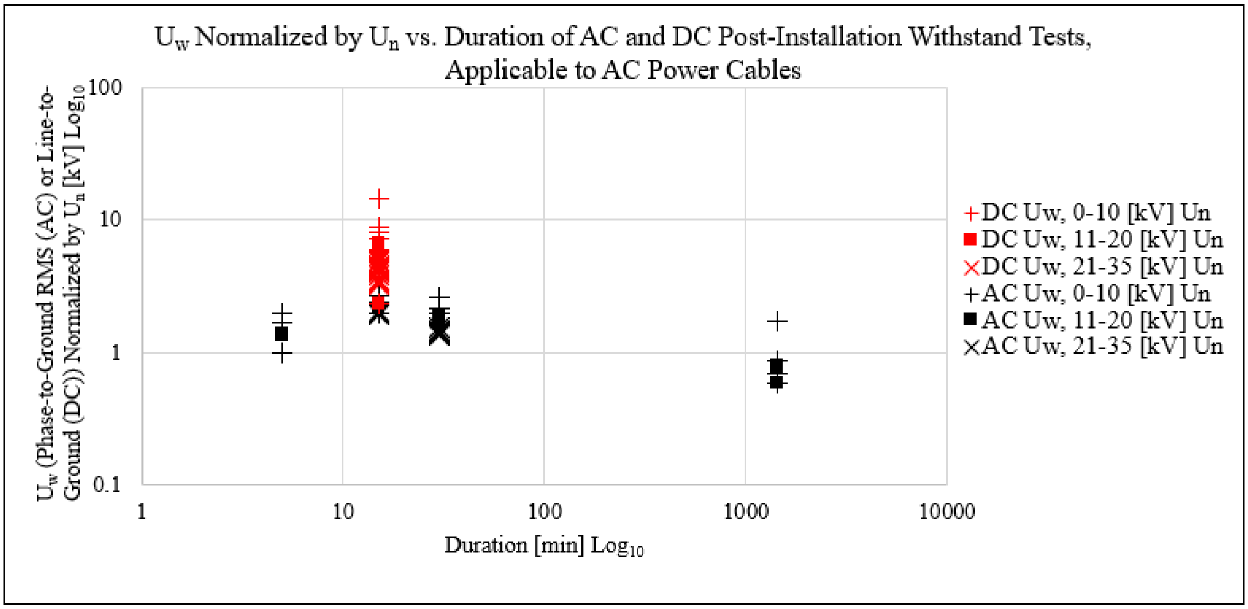


Figure 126: Comparison of Post-Installation Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal System Voltage (U_n)

For a different perspective on the data, Figure 127 is repeated below using the Nominal Peak Cable Voltage (U_p) to normalize the U_w. For AC cables U_p is $\sqrt{(2)}/\sqrt{(3)}$ of U_n.

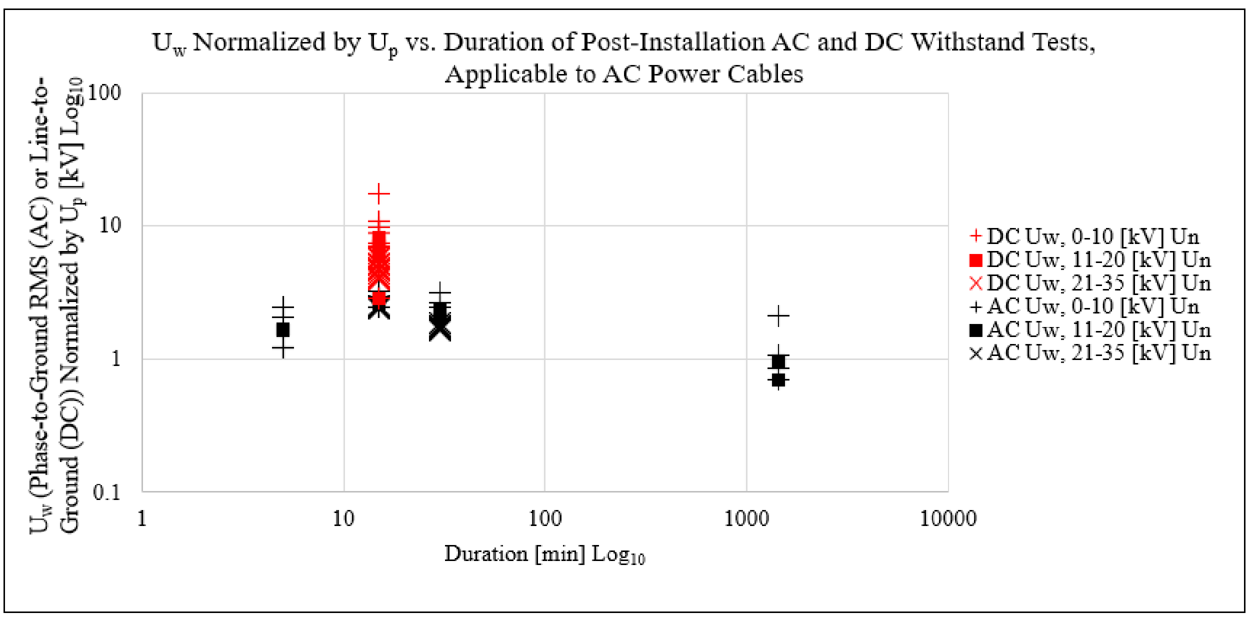


Figure 127: Comparison of Post-Installation Withstand Test Voltages (U_w) vs. Duration for All References in §5.1, Log-Log, Normalized by Nominal Peak Cable Voltage (U_p)

Notice, based on the comparison of the normalized U_w in Figure 126 and Figure 127, the existing standards and recommendations require a higher Withstand Test voltage (U_w) for DC voltages compared to that for Withstand Tests with AC voltages of the same Nominal System Voltage (U_n) class rating.

5.3.3 Comparison of Factory Acceptance and Post-Installation Withstand Tests

In general, there is a difference in magnitude between factory acceptance and post-installation withstand tests. Cable testing after manufacturing, a factory acceptance test, is generally conducted at a higher voltage than Withstand Tests occurring after the cable has been installed within a system. To show them in juxtaposition, the acceptance and post-installation Withstand Tests with AC test voltages shown in §5.3.1 and §5.3.2 are displayed in Figure 128. For another view of the data, the average of each type of test is taken, and compared in Figure 129. Figure 130 and Figure 131 repeat this process for the Withstand Tests in §5.3.1 and §5.3.2 with DC test voltages.

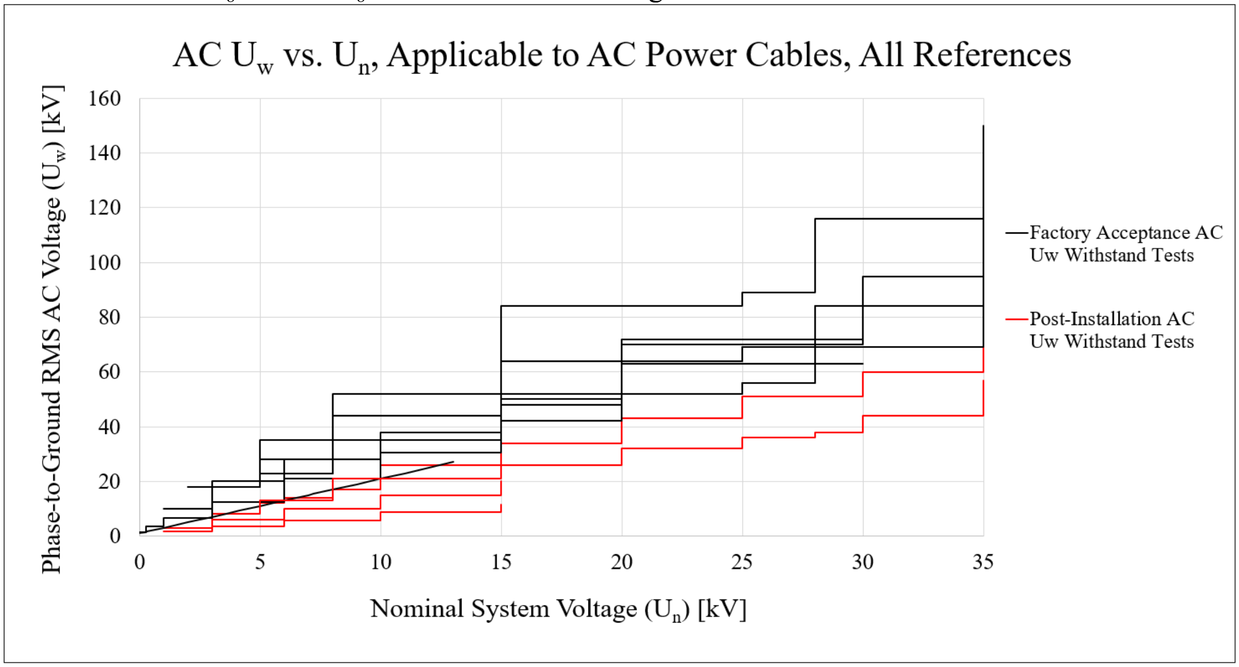


Figure 128: Comparison of Factory Acceptance and Post-Installation AC Withstand Tests

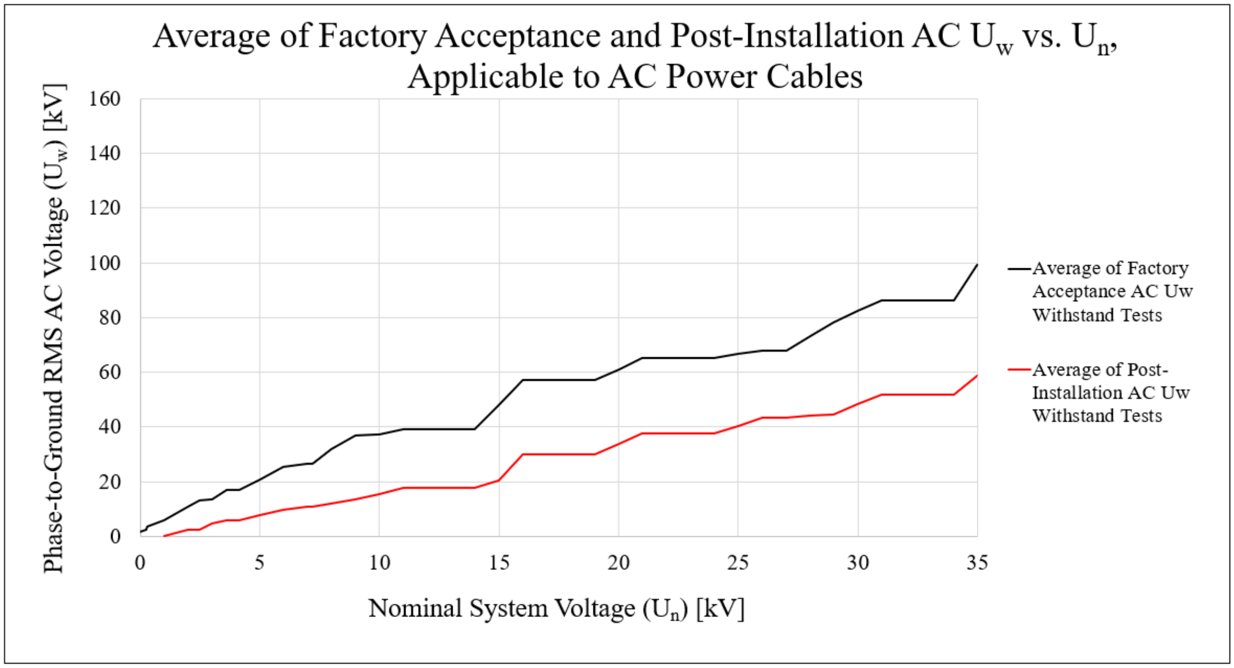


Figure 129: Comparison of Averages of Factory Acceptance and Post-Installation AC Withstand Tests

Note the average AC factory acceptance Withstand Test value at 12 [kV] Nominal System Voltage is about 2 times higher than the average post-installation Withstand Test.

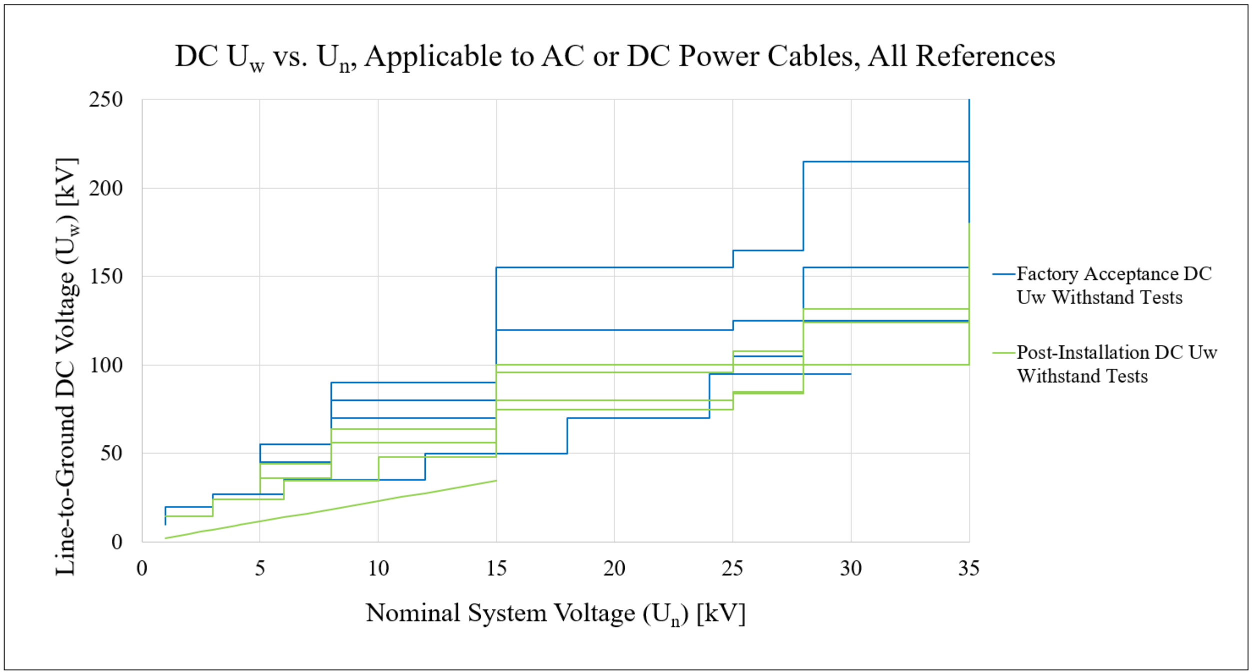


Figure 130: Comparison of Acceptance (Factory) and Post-Installation DC Withstand Tests

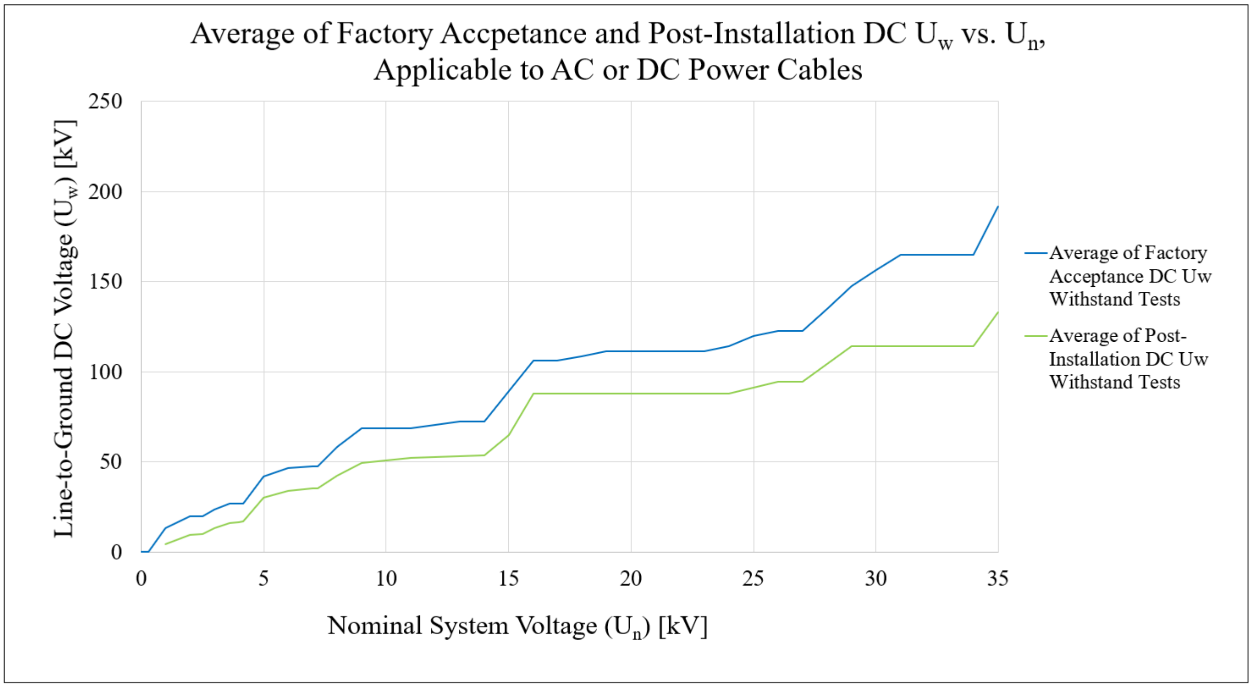


Figure 131: Comparison of Averages of Acceptance (Factory) and Post-Installation DC Withstand Tests

Note the average DC factory acceptance Withstand Test value at 12 [kV] Nominal System Voltage is only about 30% higher than the average DC post-installation Withstand Test. But the DC Withstand Test voltages are 60-100% larger at the 12 [kV] Nominal System Voltage level than the AC Withstand Tests. No reason is given within the references for these differences.

6.0 Test Voltage Levels Localized Around the Cable Voltages of Interest

This section expands on §4.3 and §5.3 with a localized view around the cable voltages of interest for this study, BIL and Acceptance Withstand Tests for systems near 12 [kV] U_n. For BIL, Figure 132 through Figure 135 the values directly from the references followed by the generated polynomial trendlines for all references and shipboard-applicable references. This allows for ease of examination of the range of test values deemed appropriate for MV cables by the various international committees, which will serve as a base for this study's prospective MVDC recommendations.

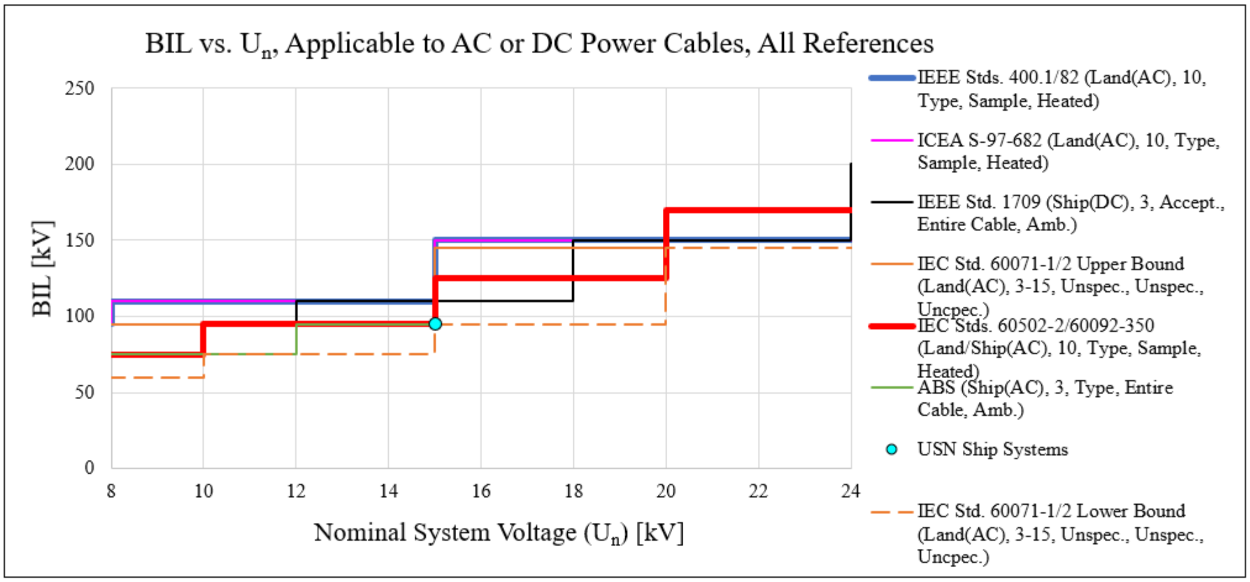


Figure 132: Comparison of BIL vs. U_n for All References in §4.3, Localized to 8-24 [kV] U_n

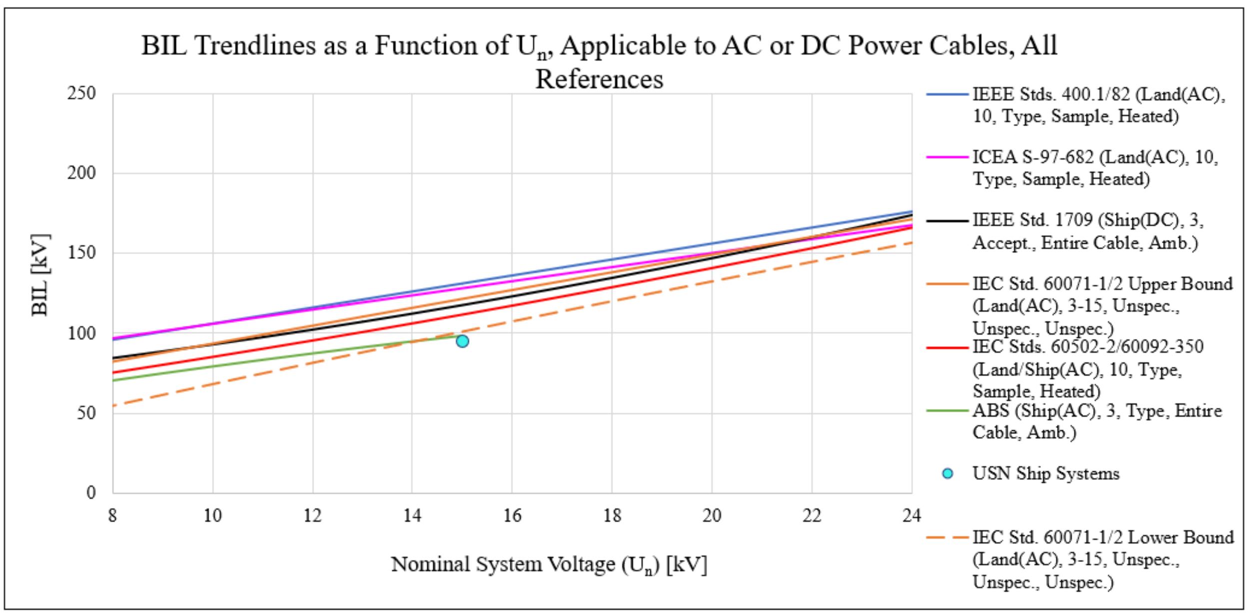


Figure 133: Comparison of BIL Trendlines vs. U_n for All References in §4.3, Localized to 8-24 [kV] U_n

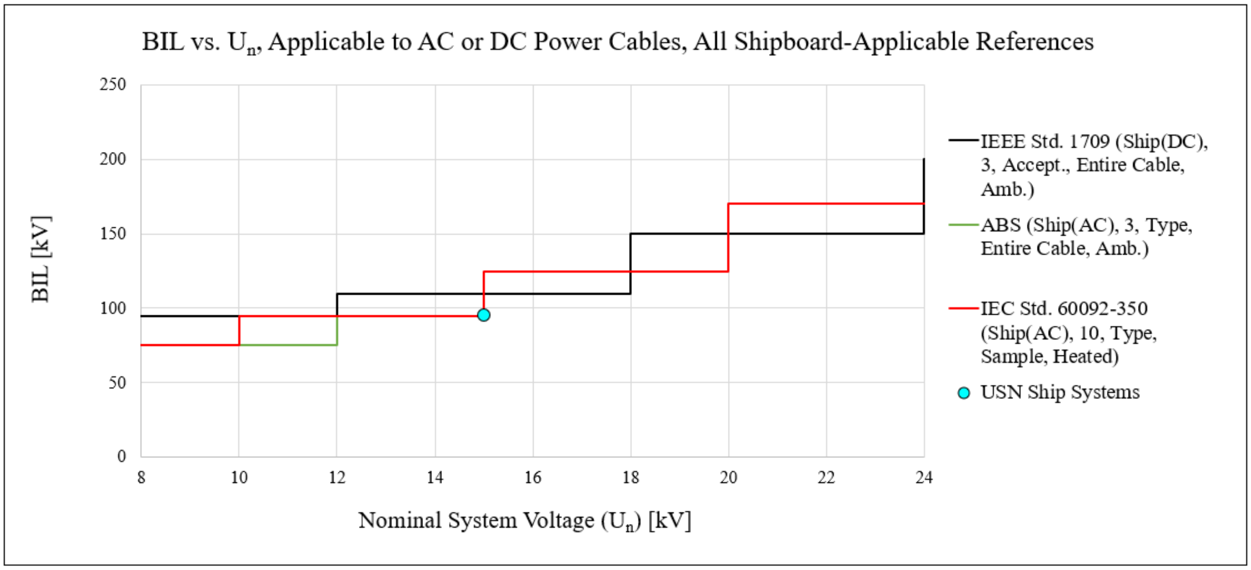


Figure 134: Comparison of BIL vs. U_n for Shipboard-Applicable References in §4.3, Localized to 8-24 [kV] U_n

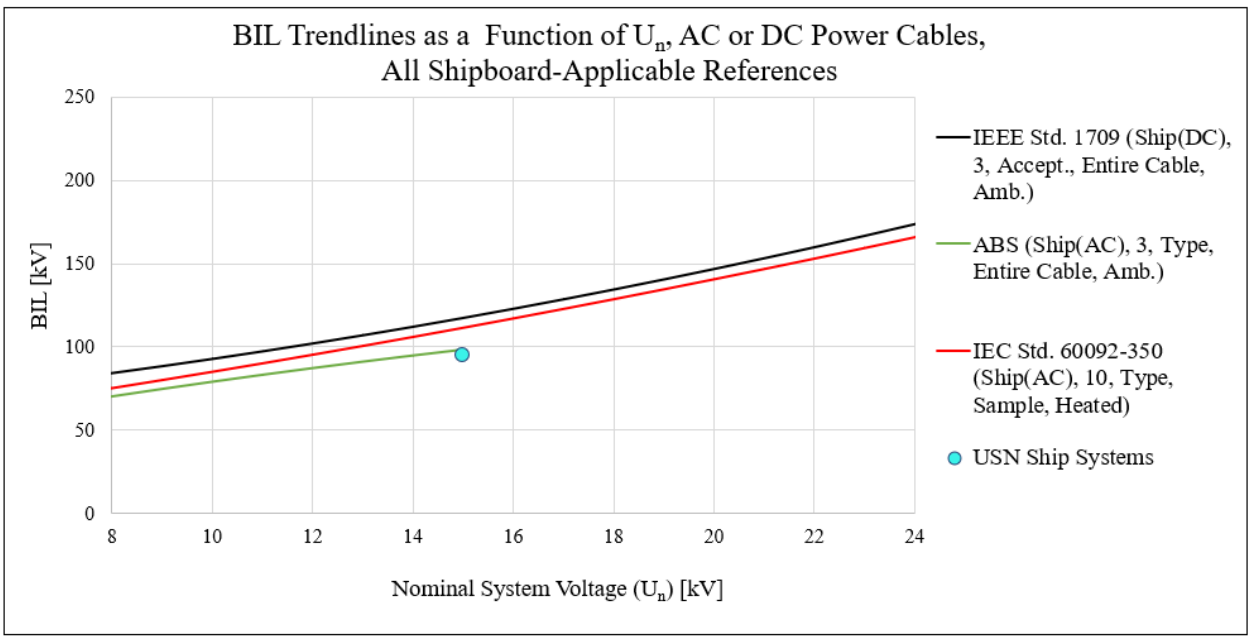


Figure 135: Comparison of BIL Trendlines vs. U_n for Shipboard-Applicable References in §4.3, Localized to 8-24 [kV] U_n

The resultant ranges of BIL for a 12 [kV] U_n system as seen in Figure 132 through Figure 135 are summarized in Table 12a. Additionally, the corresponding BIL ranges are collected for an 18 [kV] U_n system in Table 12b, as this could be the next higher system voltage after 12 [kV] U_n. Values in Table 12 collected from the trendline polynomials have been rounded to the nearest whole [kV] and are presented in italics. The direct values from shipboard-applicable references are highlighted in blue.

BIL Ranges for 12 [kV] U_n Systems			
References	**Direct Value or Generated Trendline**	**BIL Min [kV]**	**BIL Max [kV]**
All	Direct Value	75[a]	110[b]
All	*Generated Trendline*	*82*[c]	*116*[d]
Shipboard-Applicable	Direct Value	75[e]	110[f]
Shipboard-Applicable	*Generated Trendline*	*87*[g]	*102*[h]

[a] Value from IEC Std. 60071-1 and ABS Steel Vessels, note that ABS Steel Vessels is at a transition point [4] [36]
[b] Value from IEEE Std. 400.1, ICEA S-97-682, and IEEE Std. 1709, note that this is at the transition for IEEE Std. 1709 [33] [35] [2]
[c] Value from generated trendline based on IEC Std. 60071-1
[d] Value from generated trendline based on IEEE Std. 400.1
[e] Value from ABS Steel Vessels, note that this is at the transition for ABS Steel Vessels [36]
[f] Value from IEEE Std. 1709 note that this is at the transition for IEEE Std. 1709 [2]
[g] Value from generated trendline based on ABS Steel Vessels
[h] Value from generated trendline based on IEEE Std. 1709

Table 6a: BIL Ranges for 12[kV] U_n Systems

BIL Ranges for 18 [kV] U_n Systems			
References	**Direct Value or Generated Trendline**	**BIL Min [kV]**	**BIL Max [kV]**
All	Direct Value	95[a]	150[b]
All	*Generated Trendline*	*120*[c]	*146*[d]
Shipboard-Applicable	Direct Value	110[e]	150[e]
Shipboard-Applicable	*Generated Trendline*	*129*[f]	*135*[g]

[a] Value from IEC Std. 60071-1 [4]
[b] Value from IEEE Std. 400.1, ICEA S-97-682, and IEEE Std. 1709, note that this is at the transition for IEEE Std. 1709 [33] [35] [2]
[c] Value from generated trendline based on IEC Std. 60071-1
[d] Value from generated trendline based on IEEE Std. 400.1
[e] Value from IEEE Std. 1709, note that this is at the transition for IEEE Std. 1709 [2]
[f] Value from generated trendline based on IEC Std. 60092-350
[g] Value from generated trendline based on IEEE Std. 1709

Table 6b: BIL Ranges for 18[kV] U_n Systems

Table 12: Collected BIL Ranges for 12 and 18 [kV] U_n Systems

The above process is repeated for Acceptance Withstand Test Voltages, for AC U_w followed by DC U_w in Figure 136 through Figure 143. Table 13 contains the collected ranges for both AC and DC Acceptance Withstand Voltage U_w for 12 [kV] and 18 [kV] U_n systems.

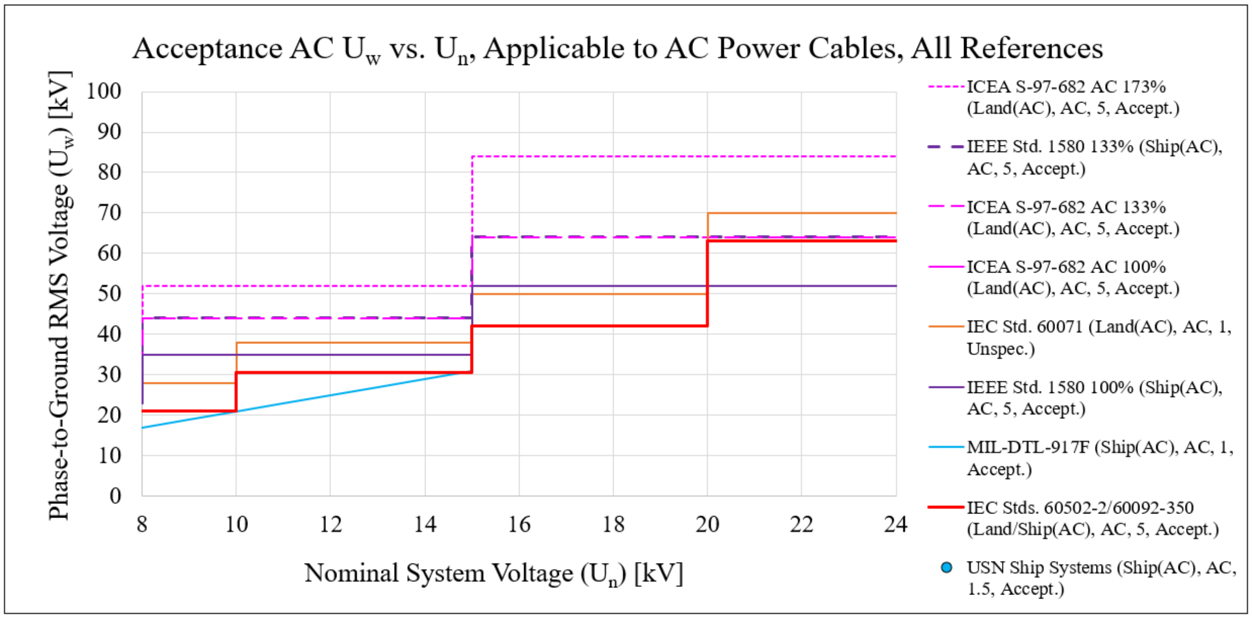


Figure 136: Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. U_n for All References in §5.3, Localized to 8-24 [kV] U_n

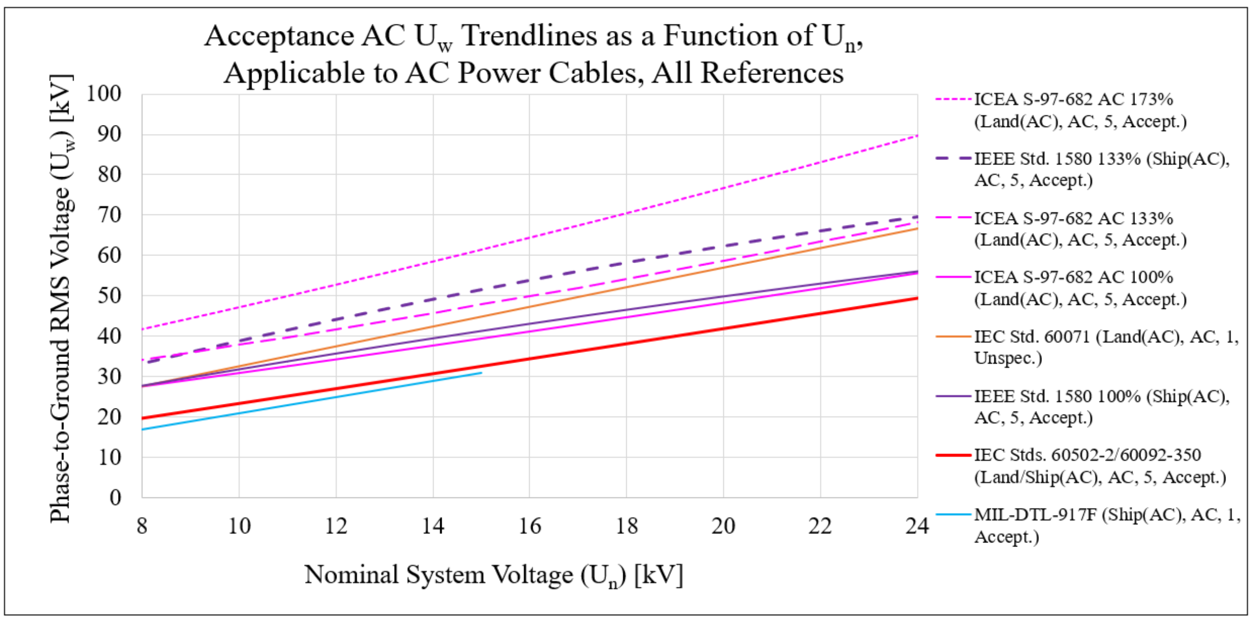


Figure 137: Comparison of Acceptance Withstand Test AC Voltage Trendlines vs. U_n for All References in §5.3, Localized to 8-24 [kV] U_n

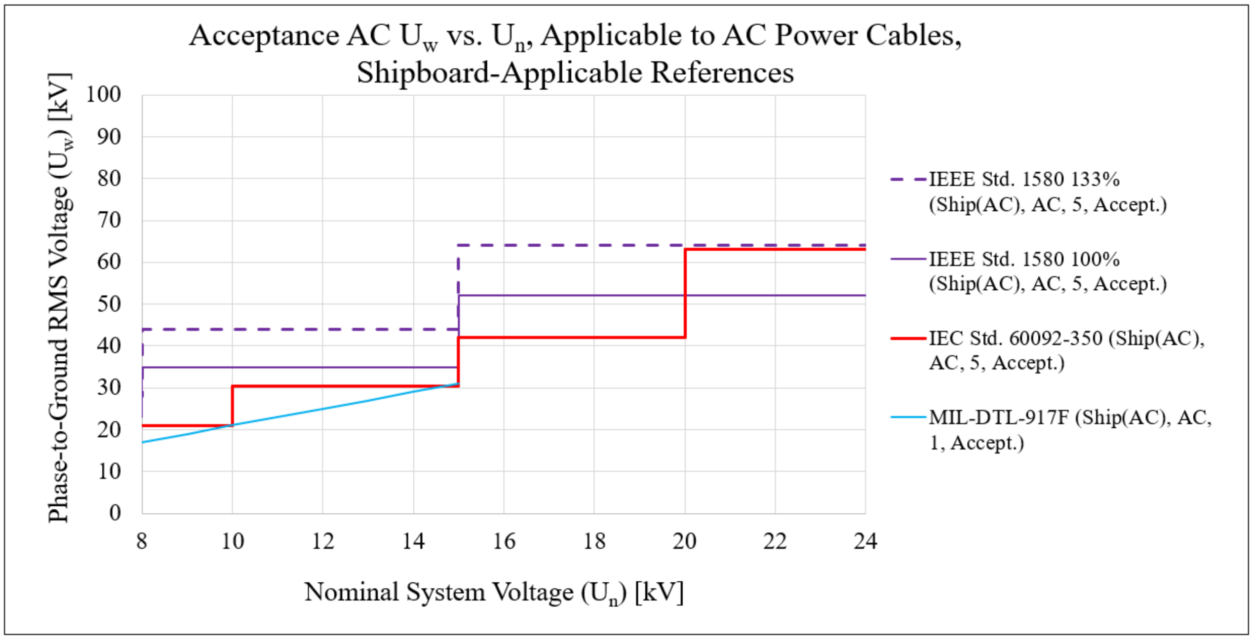


Figure 138: Comparison of Acceptance Withstand Test AC Voltages (U_w) vs. U_n for Shipboard-Applicable References in §5.3, Localized to 8-24 [kV] U_n

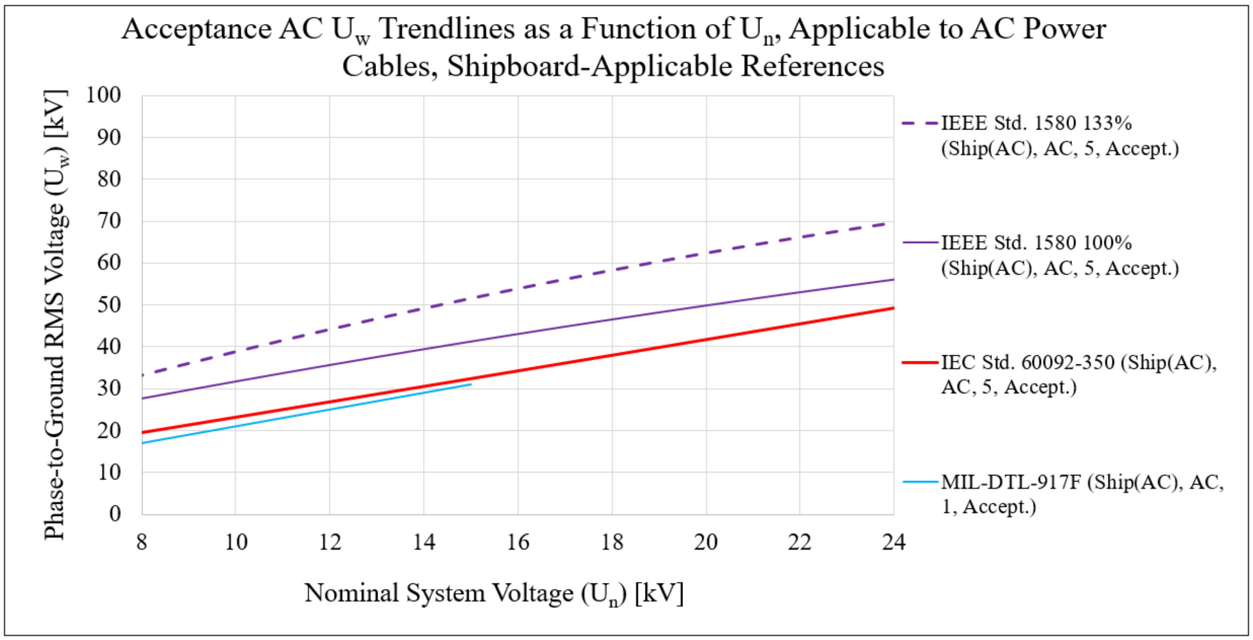


Figure 139: Comparison of Acceptance Withstand Test AC Voltage Trendlines (U_w) vs. U_n for Shipboard-Applicable References in §5.3, Localized to 8-24 [kV] U_n

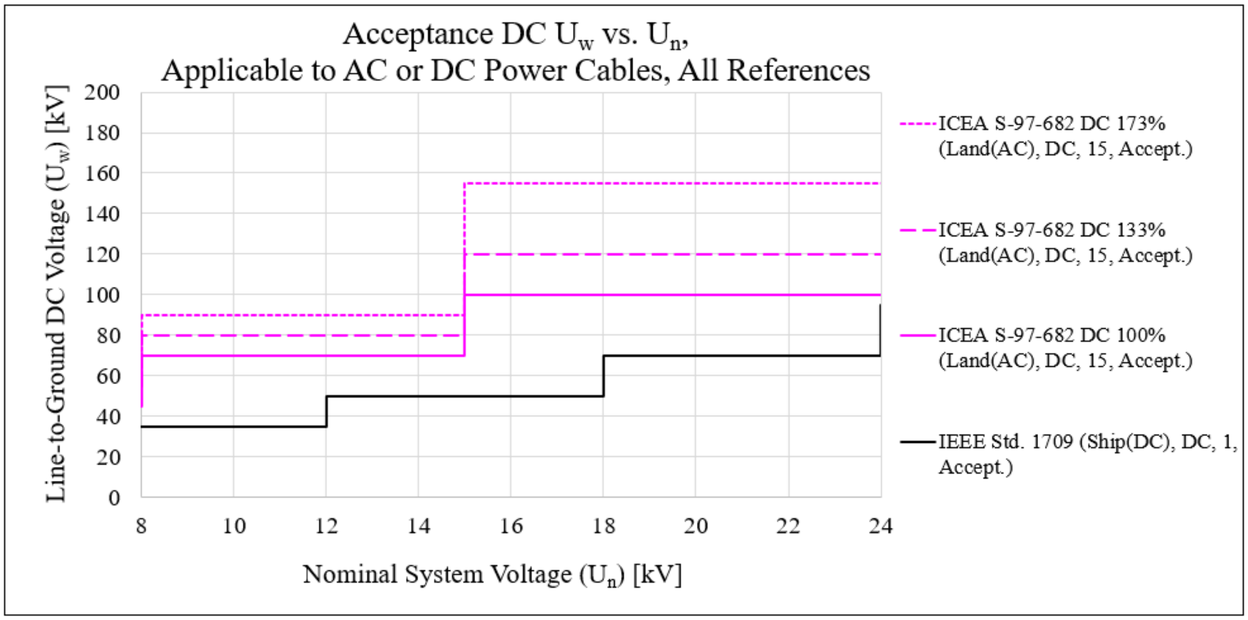


Figure 140: Comparison of Acceptance Withstand Test DC Voltages (U_w) vs. U_n for All References in §5.3, Localized to 8-24 [kV] U_n

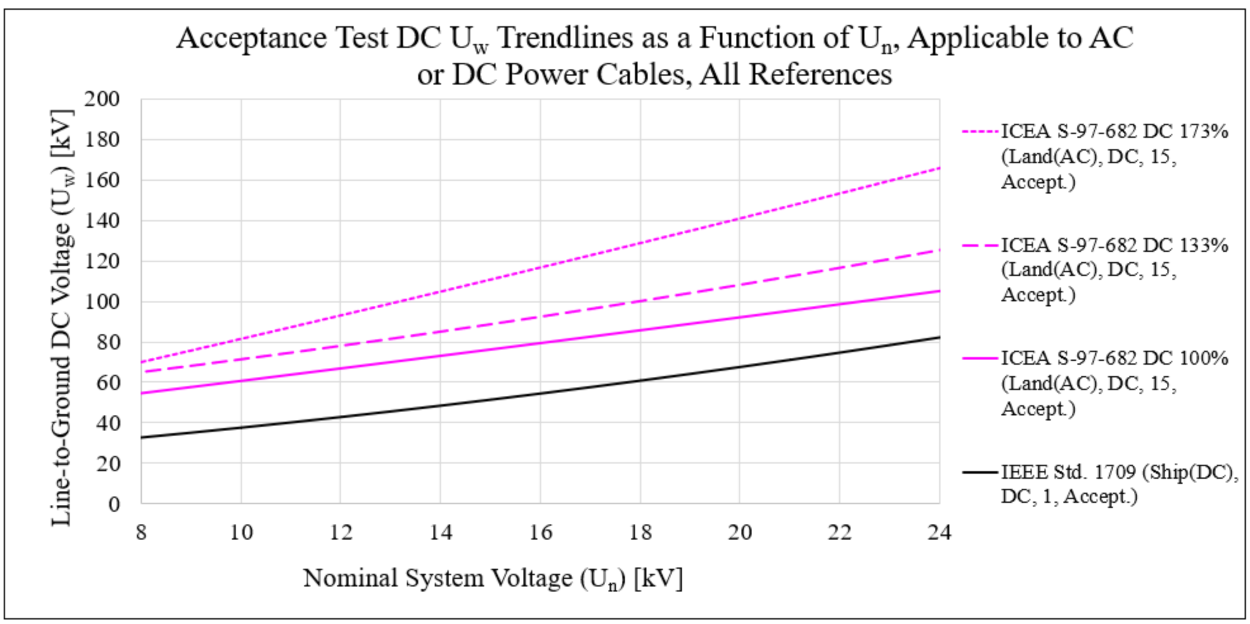


Figure 141: Comparison of Acceptance Withstand Test DC Voltage Trendlines (U_w) vs. U_n for All References in §5.3, Localized to 8-24 [kV] U_n

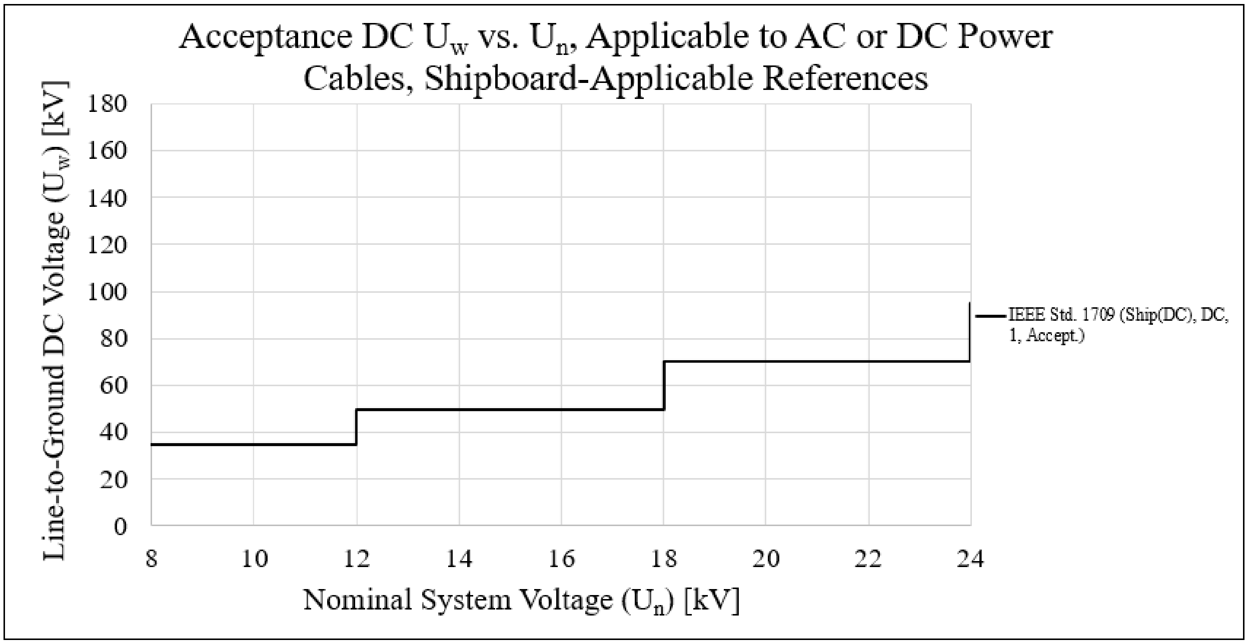


Figure 142: Comparison of Acceptance Withstand Test DC Voltages (U_w) vs. U_n for Shipboard-Applicable References in §5.3, Localized to 8-24 [kV] U_n

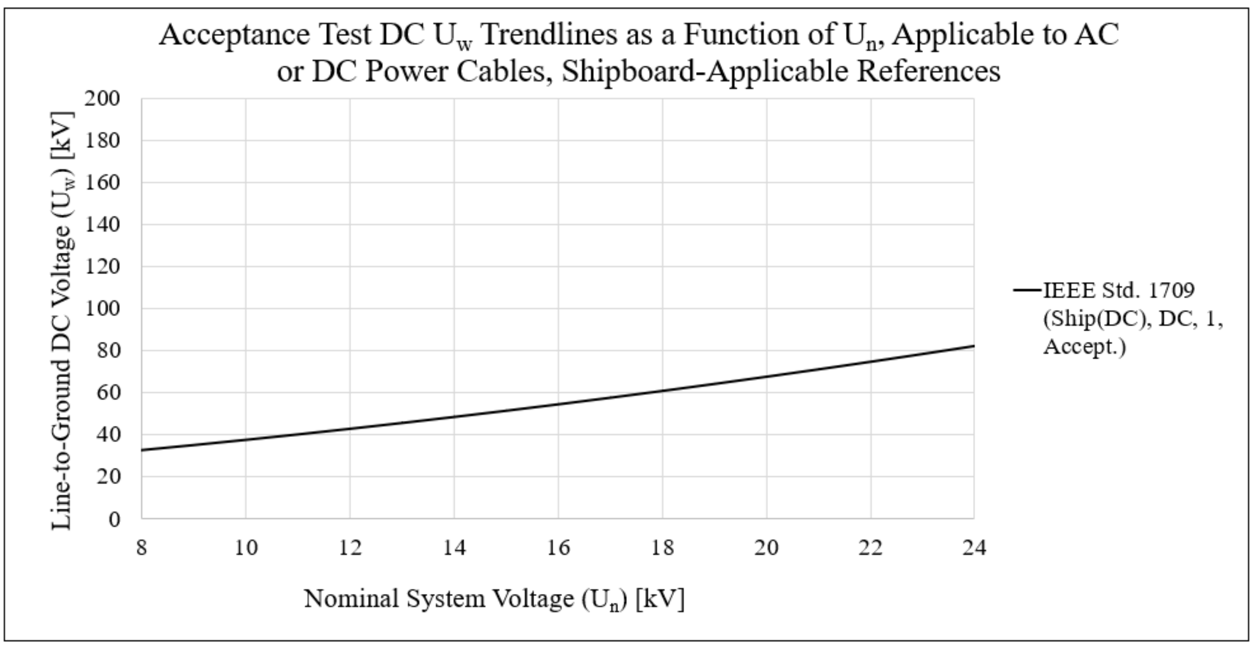


Figure 143: Comparison of Acceptance Withstand Test DC Voltage Trendlines (U_w) vs. U_n for Shipboard-Applicable References in §5.3, Localized to 8-24 [kV] U_n

The below tables display the range of AC and DC U_w for a 12 [kV] U_n system as seen in Figure 136 through Figure 143. Table 13a and Table 13b display U_w values for Acceptance Tests and Post-Installation Tests, respectively. The rows in these tables highlighted in green represent the range of U_w from shipboard-applicable references.

Acceptance Test AC and DC U_w Ranges for 12 [kV] U_n Systems				
References	**U_w Voltage Type**	**Direct Value or Generated Trendline**	**U_w Min (Duration)**	**U_w Max (Duration)**
All	AC	Direct Value	25 [kV] (1 [min])[a]	52 [kV] (5 [min])[b]
All	*AC*	*Generated Trendline*	*25 [kV] (5 [min])*[c]	*53 [kV] (5 [min])*[d]
Shipboard-Applicable	AC	Direct Value	25 [kV] (5 [min])[a]	44 [kV] (5 [min])[e]
Shipboard-Applicable	*AC*	*Generated Trendline*	*25 [kV] (5 [min])*[c]	*44 [kV] (5 [min])*[f]
All	DC	Direct Value	35 [kV] (1 [min])[g]	80 [kV] (5 [min])[b]
All	*DC*	*Generated Trendline*	*43 [kV] (1 [min])*[h]	*93 [kV] (5 [min])*[d]
Shipboard-Applicable	DC	Direct Value	35 [kV] (1 [min])[g]	35 [kV] (1 [min])[g]
Shipboard-Applicable	*DC*	*Generated Trendline*	*43 [kV] (1 [min])*[h]	*43 [kV] (1 [min])*[h]

[a] Value from MIL-DTL-917F [44]
[b] Value from ICEA S-97-682 173% insulation level [35]
[c] Value from generated trendline based on MIL-DTL-917F
[d] Value from generated trendline based on ICEA S-97-682 173% insulation level
[e] Value from IEEE Std. 1580 133% insulation level [28]
[f] Value from generated trendline based on IEEE Std. 1580 133% insulation level
[g] Value from IEEE Std. 1709, note that this is at the transition for IEEE Std. 1709 [2]
[h] Value from generated trendline based on IEEE Std. 1709

Table 7a: Acceptance Test AC and DC U_w Ranges for 12[kV] U_n Systems

Acceptance Test AC and DC U_w Ranges for 18 [kV] U_n Systems				
References	**U_w Voltage Type**	**Direct Value or Generated Trendline**	**U_w Min (Duration)**	**U_w Max (Duration)**
All	AC	Direct Value	42 [kV] (5 [min])[a]	84 [kV] (5 [min])[b]
All	*AC*	*Generated Trendline*	*38 [kV] (5 [min])*[c]	*71 [kV] (5 [min])*[d]
Shipboard-Applicable	AC	Direct Value	45 [kV] (5 [min])[a]	64 [kV] (5 [min])[e]
Shipboard-Applicable	*AC*	*Generated Trendline*	*38 [kV] (5 [min])*[f]	*58 [kV] (5 [min])*[g]
All	DC	Direct Value	50 [kV] (1 [min])[h]	155 [kV] (5 [min])[b]
All	*DC*	*Generated Trendline*	*61 [kV] (1 [min])*[i]	*128 [kV] (5 [min])*[d]
Shipboard-Applicable	DC	Direct Value	50 [kV] (1 [min])[h]	70 [kV] (1 [min])[h]
Shipboard-Applicable	*DC*	*Generated Trendline*	*61 [kV] (1 [min])*[i]	*61 [kV] (1 [min])*[i]

[a] Value from IEC Stds. 60092-350/60502-2 [31] [30]
[b] Value from ICEA S-97-682 173% insulation level [35]
[c] Value from generated trendline based on IEC Stds. 60092-350/60502
[d] Value from generated trendline based on ICEA S-97-682 173% insulation level
[e] Value from IEEE Std. 1580 133% insulation level [28]
[f] Value from generated trendline based on IEC Std. 60092-350
[g] Value from generated trendline based on IEEE Std. 1580 133% insulation level
[h] Value from IEEE Std. 1709, note that this is at the transition for IEEE Std. 1709 [2]
[i] Value from generated trendline based on IEEE Std. 1709

Table 7b: Acceptance Test AC and DC U_w Ranges for 18[kV] U_n Systems

Table 13: Collected Acceptance Test AC and DC U_w Ranges for 12 and 18 [kV] U_n Systems

7.0 Cable System Sizing

The size of a cable system depends on the size of the individual cables, the maximum power required, and the Nominal System Voltage of the system. The individual cable size for a cable in an MV power system is governed by two main parameters: the conductor sizing and the insulation thickness. These parameters directly impact the cable dimensions and thus the spatial allocation requirements for a given system. This section evaluates these parameters to allow for the calculation of example MVDC systems further on within the study.

Conductor sizing is one of the few variables that can be manipulated to change the resultant cable system sizing, therefore a range of conductor sizes were evaluated in this study. This range is discussed in §7.1. The cable insulation thickness for MV systems is largely dictated by the Nominal System Voltage level and conventions identified in the standards and guidance documents, addressed in §7.2. The conductor size also directly affects the rated current of the cable, and while this does not affect the individual cable size it does affect the overall cable system sizing by determining the number of cables required for a given system power level and Nominal System Voltage. The ampacity ratings of individual cables and their effects are addressed in §7.3.

7.1 Conductor Size Limitations

For this study, conductor sizes are bound between AWG size 1/0 and 1000 [kcmil] (53.5 – 506.7 [mm^2]). These bounds are based on the ranges of allowable conductor sizes for given MV system voltages within the evaluated references, shown in Figure 151 through Figure 154.

The smallest conductor allowable for the highest MV Nominal System Voltage (35 [kV] U_n) is AWG 1/0 (53.5 [mm^2] in accordance with the IEEE, NEC, and ICEA [28] [59] [29] [35]. The IEC standards governing insulation thickness covers up to 30 [kV] U_n, and the smallest conductor allowable is 50 [mm^2] [40] [30]. AWG 1/0 (53.5 [mm^2]) meets the minimum requirement for all MV conductors in accordance with the IEC, IEEE, and ICEA standards. While smaller conductor sizes can be used for lower system voltages within the MV range, AWG1/0 is the smallest conductor size that can be used for any MV power system and is selected as the lower bound of conductor size for this study.

The largest conductor size for which insulation thickness is given with the IEEE standard is 1000 [kcmil] (506.7 [mm^2]) [28] [29]. For the IEC standards, the shipboard standard (IEC Std. 60092-354) insulation thicknesses are also only given for conductors up to 1000 [kcmil] [40]. The ICEA insulation thickness guidance has a transition point at 1000 [kcmil] at which larger conductors require thicker insulation [35]. Due to these factors, 1000 [kcmil] (506.7 [mm^2]) is the upper bound of conductor sizes for this evaluation.

7.2 Insulation Thickness

By convention and as reflected in all evaluated standards, international and local, the power cable insulation thickness for MV systems is fixed at specific values defined within the standards. These cable insulation thickness values are fixed according to three users selected quantities: the conductor diameter, the Nominal System Voltage (U_n), and the expected ground fault clearing time, which is often expressed as a percent increase insulation level. This third quantity by convention has 3 levels if expressed as a percentage: 100% insulation level to be used in systems where ground faults will be cleared within 1 [min], 133% insulation level to be used in systems where ground fault clearing times exceed 1 [min] but are less than 60 [min], and 173% insulation level to be used in systems where ground fault clearing times exceed 60 [min] [27]. If not expressed as a percentage, the clearance time is given as a time or not at all. Within all evaluated references insulation thickness for a given Nominal System Voltage and percent insulation level was constant for conductor diameters within the range of 8.25-25.4 mm (AWG 1/0-1000 kcmil).

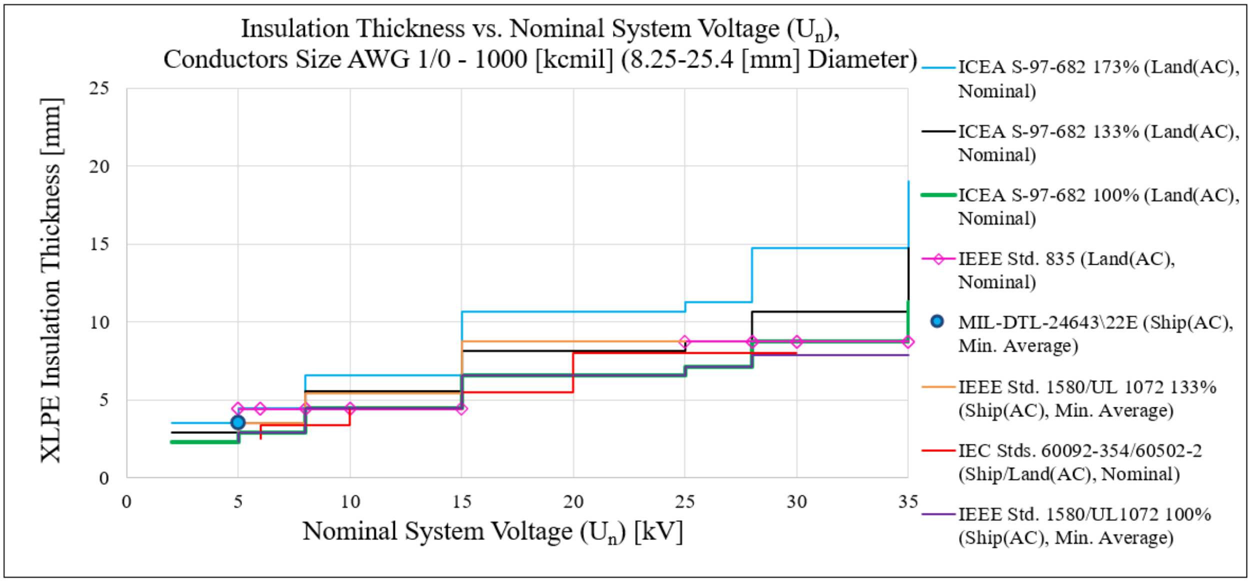
IEEE Std. 1580, IEC Std. 835, IEC Std. 60092-354, IEC Std. 60502-2, ICEA-S-97-682, and MIL-DTL-24643/22E contain guidance for insulation thickness of MVAC cables based on a given Nominal System Voltage (U_n). These references have been evaluated and explained within this report in previous sections except for IEEE Std. 835, which is the IEEE's "Standard Power Cable Ampacity Tables" [60]. The insulation thicknesses from these references apply to cables in 3-phase AC systems with single conductor shielded cables with XLPE insulation [28] [60] [40] [30] [35] [57]. As the prescribed insulation thicknesses are based on incremental system voltages, it is the expected practice that if the desired system voltage is in-between given voltage classes, then the thicknesses are to be that of the next higher voltage class. Within the references evaluated, insulation thickness is dependent on conductor size. Specifically at the lowest voltage class covered, thicker insulation is required for larger conductors within IEC Std. 60092-354 and IEC Std. 60502-2 [40] [30]. This increase in insulation thickness occurs at a step-increase shown in Figure 145, and therefore is not visible in the figure.

Of note, XLPE is commonly used and is successful with MVAC power cables. However, with a MVDC power cable XLPE is susceptible to charge accumulation leading to a DC breakdown (i.e. insulation failure). This issue can be overcome by modifying the material with additives, referred to as "filled XLPE" [61]. For this study the insulation will be referred to as XLPE, but a suitably modified XLPE insulation must be considered when designing an MVDC cable.

The legend in Figure 145 through Figure 148 contain each insulation thickness references' relevant parameters. The reference name, applicability (shipboard or land-based), system voltage (AC or DC), and thickness description are shown in the legend of Figure 145 through Figure 148 in the format shown below in Figure 144. Figure 146 displays the thicknesses defined by the standards localized to the area of interest, the 8-24 [kV] U_n range. Figure 147 and Figure 148 display the trendlines generated from the step-function nature of the standards for the 0-35 [kV] range and localized to 8-24 [kV] respectively, following the method shown in §4.2 and §5.2. The average insulation thickness of all the evaluated references for the 100%, 133%, and 173% insulation levels are shown in Figure 149, followed by the averages of the shipboard and land-based references, respectively. Of note, IEC Std. 60502-2 defines insulation thicknesses such that they meet the criteria of both the IEEE defined 100% and 133% insulation levels, so it is accounted for within both averages [27] [30]. IEEE Std. 835 and IEC Std. 60092-354 do not mention fault clearing time or insulation thicknesses as a percentage, so for this study they are assumed to be at the 100% level [60] [40]. The supporting data from each reference are discussed and shown following these figures. The color scheme of the graphed references is different than the proceeding sections for increased legibility.

Format:	Reference	(Applicability	(System Voltage Type),	Thickness Description)
Options:	All Refs.	Land or Ship	AC or DC	Nominal or Min. Average
Example:	ICEA S-97-682 100% (Land(AC), Nominal)			

Figure 144: Key for Legends in §7.2

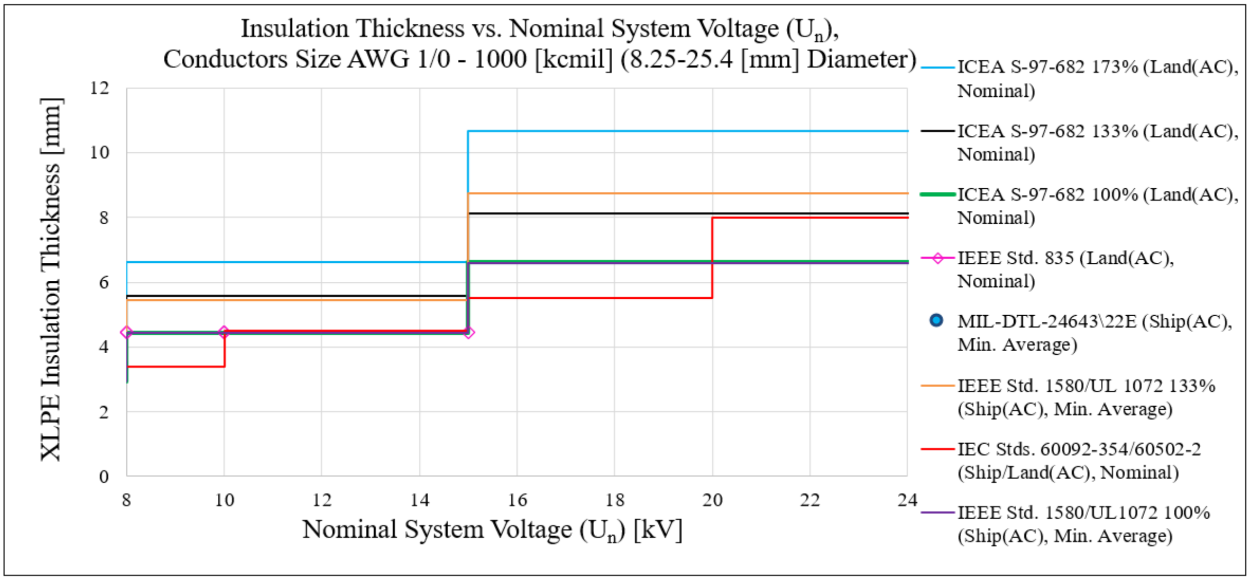


Note: MIL-DTL-24643\22E specifies conductors from AWG 1/0 through 413.6 [kcmil] (210 [mm^2]), and IEC 60092-354 specifies conductor from AWG 1/0 through 630 [kcmil] (319 [mm^2])

Figure 145: Insulation Thicknesses vs. U_n

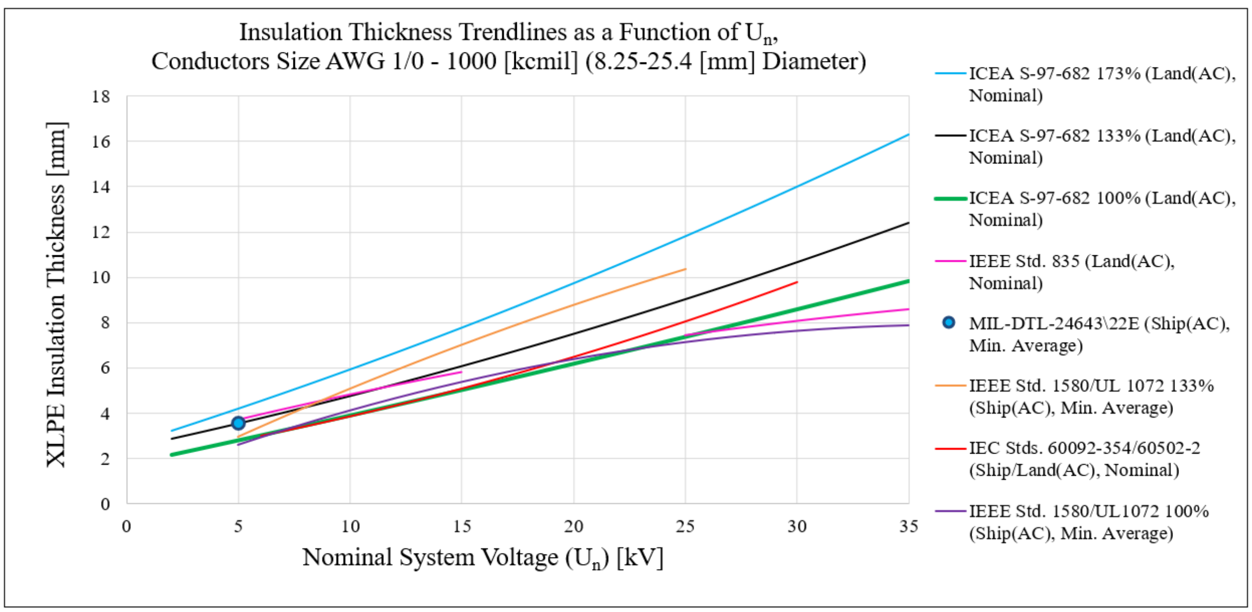
Reference	Coordinates (U_n [kV], Acceptance AC U_w [kV])							
ICEA S-97-682 173% [35]	2,3.56	5,3.56	5,4.45	8,4.45	8,6.6	15,6.6	15,10.67	25,10.67
	25,11.3	28,11.3	28,14.73	35,14.73	35,19.05			
ICEA S-97-682 133% [35]	2,2.92	5,2.92	5,3.56	8,3.56	8,5.59	15,5.59	15,8.13	25,8.13
	25,8.76	28,8.76	28,10.67	35,10.67	35,14.73			
ICEA S-97-682 100% [35]	2,2.29	5,2.29	5,2.92	8,2.92	8,4.45	15,4.45	15,6.6	25,6.6
	25,7.11	28,7.11	28,8.76	35,8.76	35,11.3			
IEEE Std. 835 [60]	5,4.45	15,4.45	25,8.76	35,8.76				
MIL-DTL-24643/22E [57]	5,3.56							
IEEE Std. 1580 133% [28]	5,2.29	5,3.56	8,3.56	8,5.46	15,5.46	15,8.76		
IEC Stds. 60502-2/ 60092-354 [30] [40]	6,2.5	6,3.4	10,3.4	10,4.5	15,4.5	15,5.5	20,5.5	20,8.0
	30,8.0							
IEEE Std. 1580 100% [28]	5,2.29	5,2.92	8,2.92	8,4.45	15,4.45	15,6.6	25,6.6	25,7.11
	28,7.11	28,8.76	35,8.76					

Table 14: Coordinates of Step-Functions in Figure 145



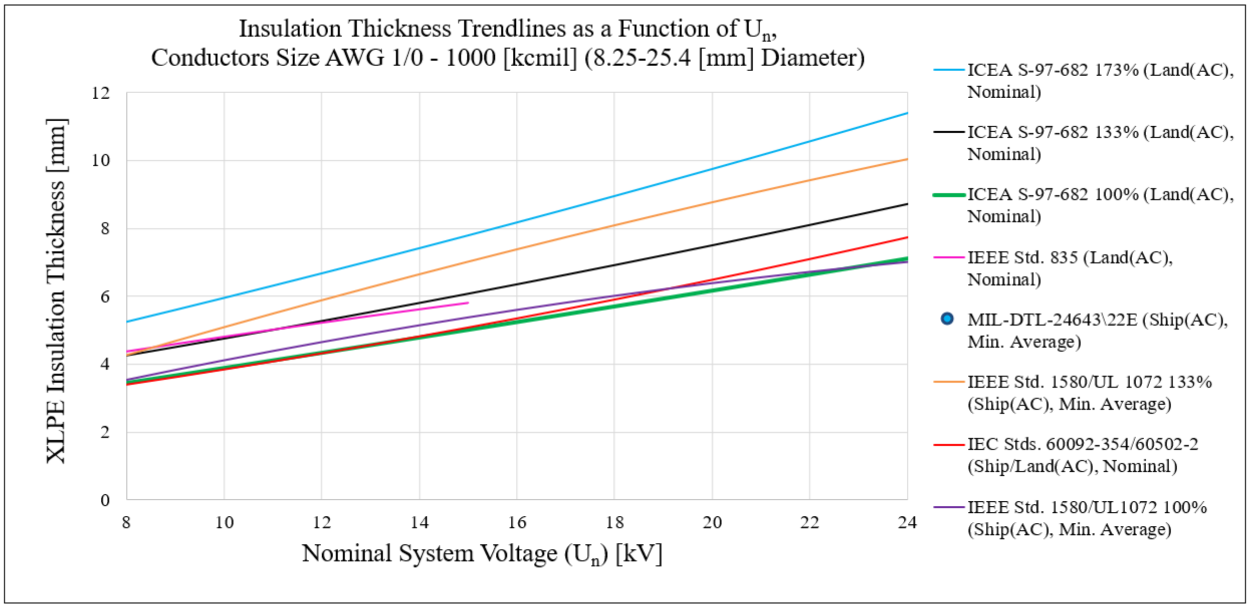
Note: MIL-DTL-24643\22E specifies conductors from AWG 1/0 through 413.6 [kcmil] (209.6 [mm^2]), and IEC 60092-354 specifies conductor from AWG 1/0 through 630 [kcmil] (319 [mm^2])

Figure 146: Insulation Thicknesses vs. U_n, Localized to 8-24 [kV] U_n



Note: MIL-DTL-24643\22E specifies conductors from AWG 1/0 through 413.6 [kcmil] (209.6 [mm^2]), and IEC 60092-354 specifies conductor from AWG 1/0 through 630 [kcmil] (319 [mm^2])

Figure 147: Trendline Comparison of Insulation Thicknesses vs. U_n



Note: MIL-DTL-24643\22E specifies conductors from AWG 1/0 through 413.6 [kcmil] (209.6 [mm^2]), and IEC 60092-354 specifies conductor from AWG 1/0 through 630 [kcmil] (319 [mm^2])

Figure 148: Trendline Comparison of Insulation Thicknesses vs. U_n, Localized to 8-24 [kV] U_n

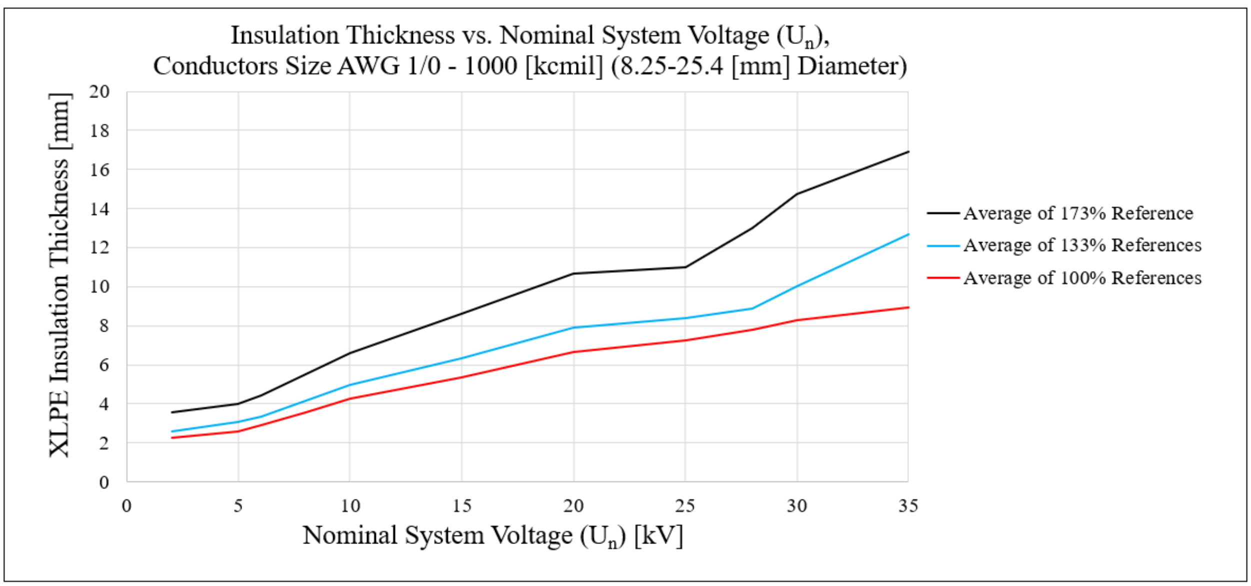


Figure 149: Average Insulation Thickness of All Evaluated References vs. U_n

The averages shown above in Figure 149 include all evaluated references that provided an insulation percentage or ground-fault clearing time, for both shipboard and land-based references. As this study seeks to evaluate shipboard systems, the separated averages for insulation thicknesses for shipboard and land-based references are provided in juxtaposition below in Figure 150.

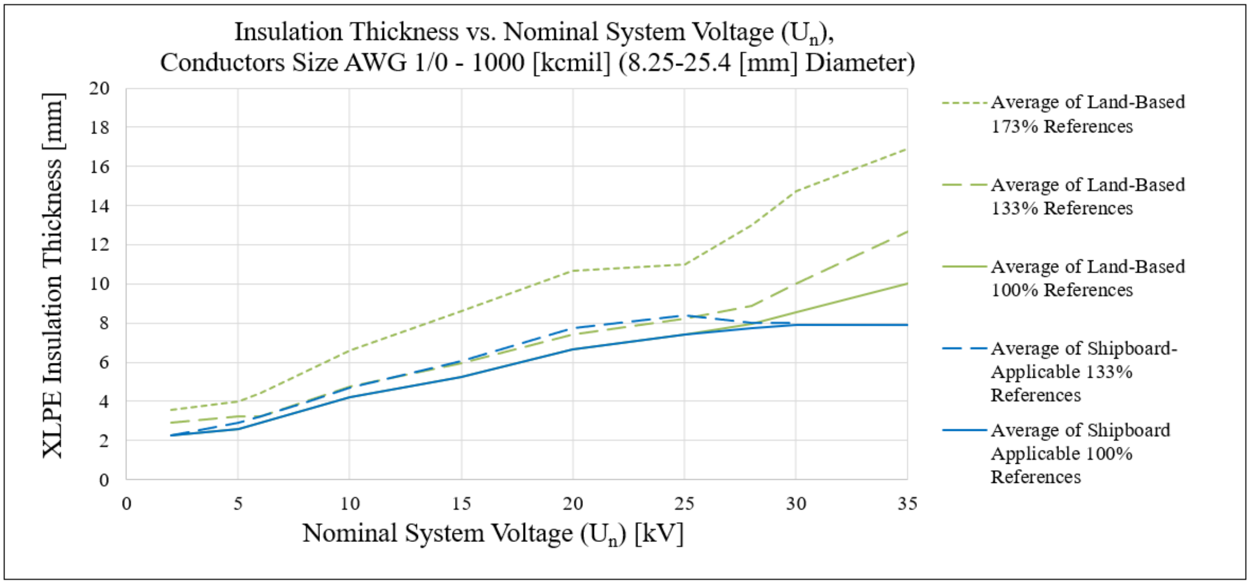


Figure 150: Comparison of Shipboard-Applicable and Land-Based Evaluated Reference's Average Insulation Thicknesses vs. U_n

The remainder of §7.2 discusses the sources of information presented in Figure 145 through Figure 150.

IEEE Std. 1580, the recommended practices for shipboard cable, directs that insulation thicknesses for 2-35 [kV] AC systems be in accordance with UL 1072, a land-based standard for medium voltage power cables. [28]. UL 1072 contains table 13.1 which outlines 100% and 133% insulation thickness for systems with 5-35 [kV] U_n, shown in Figure 151 [29]. This standard outlines an acceptable range of cable size for each U_n, however, the insulation thickness is independent of the conductor size within this range.

Voltage rating of cable (phase-to-phase circuit voltage)	Size of conductor	100 percent insulation level (grounded neutral)[a]				133 percent insulation level (ungrounded neutral)[a]			
		mils		mm		mils		mm	
		Minimum acceptable average thickness	Minimum acceptable thickness at any point	Minimum acceptable average thickness	Minimum acceptable thickness at any point	Minimum acceptable average thickness	Minimum acceptable thickness at any point	Minimum acceptable average thickness	Minimum acceptable thickness at any point
5000	8 AWG – 1000 kcmil	90	81	2.29	2.06	90	81	2.29	2.06
8000	6 – 1000	115	104	2.92	2.64	140	126	3.56	3.20
15000	2 – 1000	175	158	4.45	4.01	215	194	5.46	4.93
25000	1 – 1000	260	234	6.60	5.94	345	311	8.76	7.90
28000	1 – 1000	280	252	7.11	6.40	–	–	–	–
35000	1/0 – 1000	345	311	8.76	7.90	–	–	–	–

[a] The selection of the cable insulation level to be used in a particular installation is made on the basis of the applicable phase-to-phase voltage of the circuit and of the general system category (expressed as a percent insulation level) as outlined below:

100 PERCENT LEVEL – Cables in this category are intended for use where the system is provided with relay protection such that ground faults clear as rapidly as possible but, in any case, within 1 min. While these cables are applicable to the great majority of cable installations that are on grounded systems, these cables also are installed for use on other systems for which the application of cables is acceptable (see next paragraph), provided that the above clearing requirements are met in completely de-energizing the faulted section.

In common with other electrical equipment, the use of cables is not recommended on systems where the ratio of the zero to positive phase reactance of the system at the point of cable application lies between −1 and −40 because excessively high voltages may be encountered in the case of ground faults.

133 PERCENT LEVEL – This insulation level corresponds to that formerly designated for underground systems. Cables in this category are intended for use in situations in which the clearing-time requirements of the 100 percent level category cannot be met, and yet there is reason to expect that the faulted section is de-energized in a time not exceeding 1 h. Also, they may be used when additional insulation strength over the 100 percent level category is desirable.

Figure 151: UL 1072 Table 13.1, 100% and 133% Insulation Thicknesses [29]

IEEE Std. 835, Standard Power Cable Ampacity Tables, contains Table 3 giving the recommended insulation thicknesses based on the cable type and Nominal System Voltage (U_n) [60]. Within this standard, cable type 3 applies to cables within 5-46 [kV] U_n systems with a single conductor, shielding, and extruded insulation. The insulation thicknesses given in [mils] from this standard are shown below in Figure 152, where it illustrates that for MV cables within the range of this study, insulation thickness is only dependent on U_n.

Cable type	Voltage	Conductor sizes	Insulation thickness (mils)
1	600 to 5 kV	#12AWG–#10AWG	45
1	600 to 5 kV	#8AWG–#2AWG	60
1	600 to 5 kV	#1AWG–#4/0 AWG	80
1	600 to 5 kV	250–500 kcmil	95
1	600 to 5 kV	600–1000 kcmil	110
2	5 kV	#4–4/0 AWG	90
2	15 kV	#4–4/0 AWG	175
3	5–15 kV	#2AWG–1000 kcmil	175
3	5–15 kV	1000–2000 kcmil	220
3	25–46 kV	#1AWG–2000 kcmil	345

Figure 152: IEEE Std. 835 Table 3, Cable Conductor Sizes and Insulation Thicknesses [60]

IEC Std. 60092-354, electrical installations in ships, contains a table of minimum average insulation thicknesses based on conductor size and voltage class, shown in Table 15. The voltage indicated by ‘U’ in this figure is equivalent to this study’s U_n. Within this standard the insulation thickness is dependent on the U_n as well as the conductor size for only the lowest U_n covered, 6 [kV] U_n [40]. Additionally, IEC Std. 60502-2 contains Table 6 shown in Figure 153 below. Note that these shipboard and land-based standards (respectively) contain identical guidance for insulation thickness within the range of conductor sizes evaluated within this study. Ground fault clearing guidance for IEC Std. 60502-2 matches both the 100% and 133% insulation levels defined by the IEEE, and guidance is not given within IEC Std. 60092-354 [30] [40].

Nominal cross sectional area of conductor mm^2	**Nominal thickness of insulation at rated voltage U_o/U (U_m)** 3,6/6 (7,2) kV mm	6/10 (12) kV mm	8,7/15 (17,5) kV mm	12/20 (24) kV mm	18/30 (36) kV mm
10	2,5	-	-	-	-
16	2,5	3,4	-	-	-
25	2,5	3,4	4,5	-	-
35	2,5	3,4	4,5	5,5	-
50 to 185	2,5	3,4	4,5	5,5	8,0
240	2,6	3,4	4,5	5,5	8,0
300	2,8	3,4	4,5	5,5	8,0
400	3,0	3,4	4,5	5,5	8,0
500 to 630	3,2	3,4	4,5	5,5	8,0

Table 15: IEC Std. 60092-354 Nominal Thickness of Insulation [40]

Nominal cross-sectional area of conductor mm^2	Nominal thickness of insulation at rated voltage U_0/U (U_m)				
	3,6/6 (7,2) kV mm	6/10 (12) kV mm	8,7/15 (17,5) kV mm	12/20 (24) kV mm	18/30 (36) kV mm
10	2,5	–	–	–	–
16	2,5	3,4	–	–	–
25	2,5	3,4	4,5	–	–
35	2,5	3,4	4,5	5,5	–
50 to 185	2,5	3,4	4,5	5,5	8,0
240	2,6	3,4	4,5	5,5	8,0
300	2,8	3,4	4,5	5,5	8,0
400	3,0	3,4	4,5	5,5	8,0
500 to 1 600	3,2	3,4	4,5	5,5	8,0

Figure 153: IEC Std. 60502-2 Nominal Thickness of Insulation [30]

ICEA S-97-682, standard for utility shielded power cables rated 5 through 46 [kV], contains nominal insulation thicknesses based on U_n for the 100%, 133%, and 173% insulation levels in Table 8-1. These values are shown in Figure 154 below. The insulation thicknesses given by this reference are dependent on the U_n as well as the conductor size [35]. However, within the area of interest for this study (AWG size 1/0 and 1000 [kcmil] (53.5 – 506.7 [mm^2])), the insulation thickness is independent of conductor size for this reference.

Rated Phase-to-Phase Circuit Voltage	Conductor Size, AWG or kcmil (mm^2)	Nominal Insulation Thickness (mils)		
		100 Percent Level	133 Percent Level	173 Percent Level
2001-5000	8-1000 (8.37-507)	90	115	140
	1001-3000 (507-1520)	140	140	140
5001-8000	6-1000 (13.3-507)	115	140	175
	1001-3000 (507-1520)	175	175	220
8001-15000	2-1000 (33.6-507)	175	220	260
	1001-3000 (507-1520)	220	220	260
15001-25000	1-3000 (42.4-1520)	260	320	420
25001-28000	1-3000 (42.4-1520)	280	345	445
28001-35000	1/0-3000 (53.5-1520)	345	420	580
35001-46000	4/0-3000 (107-1520)	445	580	750

Figure 154: ICEA S-97-682 Nominal Insulation Thicknesses [35]

MIL-DTL-24643\22E is a detail specification sheet for shipboard cables to be used in 5 [kV] systems [57]. This document states that cables shall have a minimum average insulation wall thickness of 0.14 [in], or 3.556 [mm], for conductor sizes AWG 1/0 through 400 [kcmil] (202.7 [mm^2]) [57].

7.3 Ampacity Ratings

Ampacity is "the maximum current, in amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating" [59].

Ampacity ratings vary substantially depending on several characteristics of the cable in question and its environment. The standards evaluated in this section give an initial base ampacity value that is adjusted with multiplicative factors based on the following cable characteristics:

- Size of conductors
- Number of conductors
- Conductor material
- Maximum allowable conductor temperature
- Ambient temperature
- Nominal System voltage
- Insulation material
- Spacing between cables
- Cable grouping geometry

All references used give base ampacity values for single XLPE insulated copper conductors, in a triplex grouping of 3 cables in free air. These characteristics (number of conductors, conductor material, insulation material, spacing between cables, and cable grouping geometry) are omitted from the rest of this section.

Within §7.3 the base ampacities for MV cables with a range of conductor sizes are shown, followed by each reference's correction factors for the cable characteristics. This allows the references to be directly compared. The characteristics of the base ampacities were adjusted to are shown below in Table 16.

Characteristic	Value
Diameter of Conductors	8.25-25.4 [mm^2]
Maximum Allowable Conductor Temperature	90 [°C]
Ambient Temperature	45 [°C]
Nominal System Voltage	1-35 [kV]

Table 16: Cable Characteristics for Ampacity Ratings

From Table 16, only the Maximum Allowable Conductor Temperature and Ambient Temperature require adjustment factors to the ampacities given within the references' tables. For example, IEC 60502-2's given ampacities are for an ambient temperature of 30 [°C] and therefore must be adjusted for proper comparison [30]. The standard gives an adjustment factor of 0.87 to adjust the ampacities to 45 [°C] ambient temperature [30]. Figure 155 shows the base ampacities from IEC 60502-2, along with the adjusted ampacities with the applied adjustment factor versus conductor diameter.

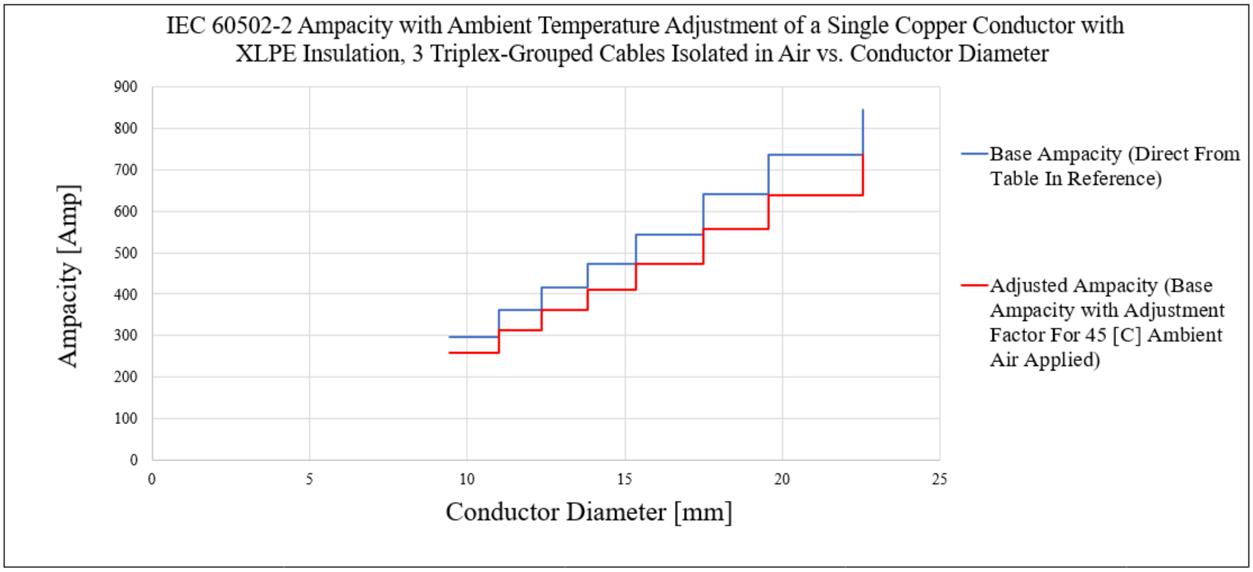


Figure 155: Example Ampacity Adjustment Factor [30]

7.3.1 Comparison of Ampacities

The legends of the figures in §7.3.1 contain each reference's ampacities' relevant parameters. The reference name, applicability (shipboard or land-based), system current (AC or DC), and applicable system voltage level (in [kV]) are shown in the legend of the following figures in the format shown below in Figure 156. Figure 157 displays the ampacities defined by the references compared to conductor diameter. Figure 158 displays the trendlines generated from the step-function nature of the references, following the method shown in §4.2 and §5.2. The average ampacity of all evaluated references for the range of conductor diameters is shown in Figure 159. The supporting data from each reference is discussed and shown following these figures.

Format:	Reference	(Applicability,	System Current Type,	System Voltage Level)
Options:	All Refs.	Land or Ship	AC or DC	# (in [kV])
Example:	IEC Stds. 60092-503/201 (Ship, AC, 1-15)			

Figure 156: Key for Legends in §7.3.2

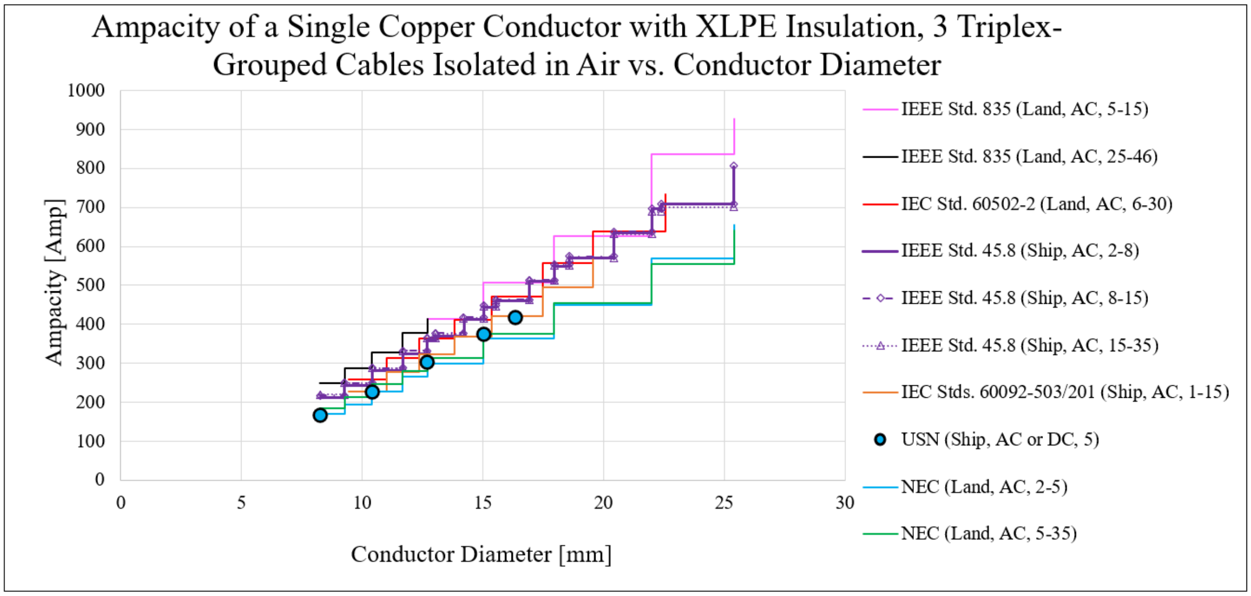


Figure 157: Ampacity vs. Conductor Diameter for Medium Voltage Cables, 90 [°C] Maximum Conductor Temperature and 45 [°C] Ambient Temperature

While both the shipboard IEEE and IEC standards define lower ampacities than their land-based equivalents, they give no explanation as to why. At a quick glance, the shipboard standard ampacities almost appear to be the land-based ampacities with a constant derating factor applied, as the IEEE shipboard ampacities are consistently 87-88% of the land-based ampacities and the IEC's are 88-89%. To be clear nowhere is this stated explicitly, rather this near proportional decrease in ampacity values is simply an observation by dividing the shipboard standard ampacities by the corresponding condition land-based ampacities.

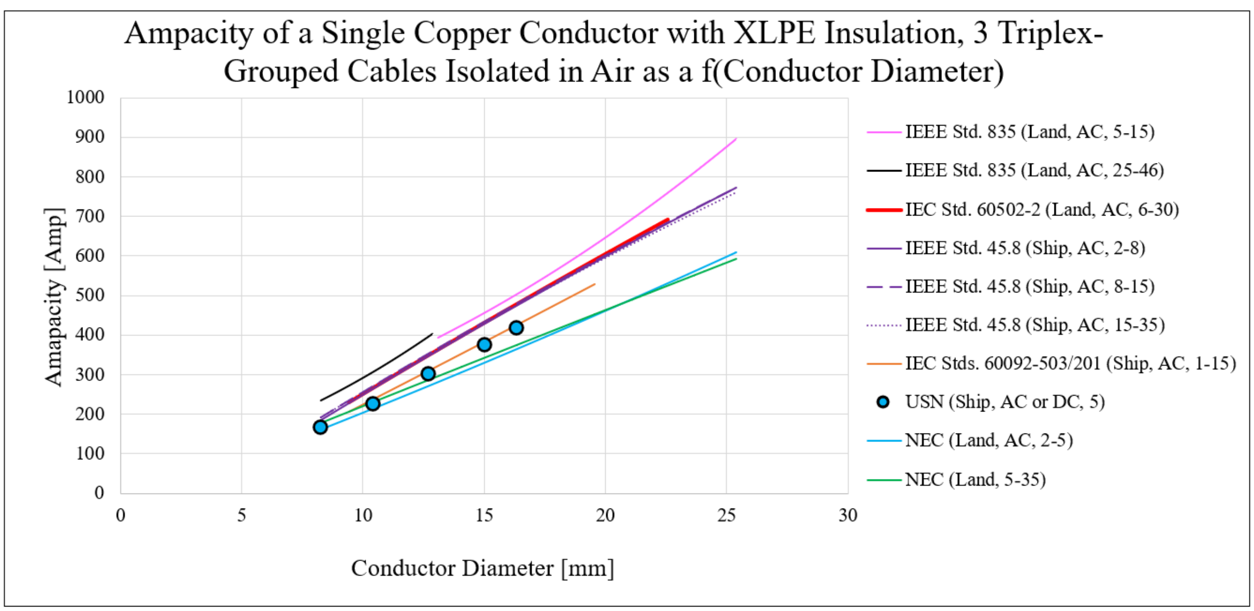


Figure 158: Trendline Comparison of Ampacity vs. Conductor Diameter for Medium Voltage Cables, 90 [°C] Maximum Conductor Temperature and 45 [°C] Ambient Temperature

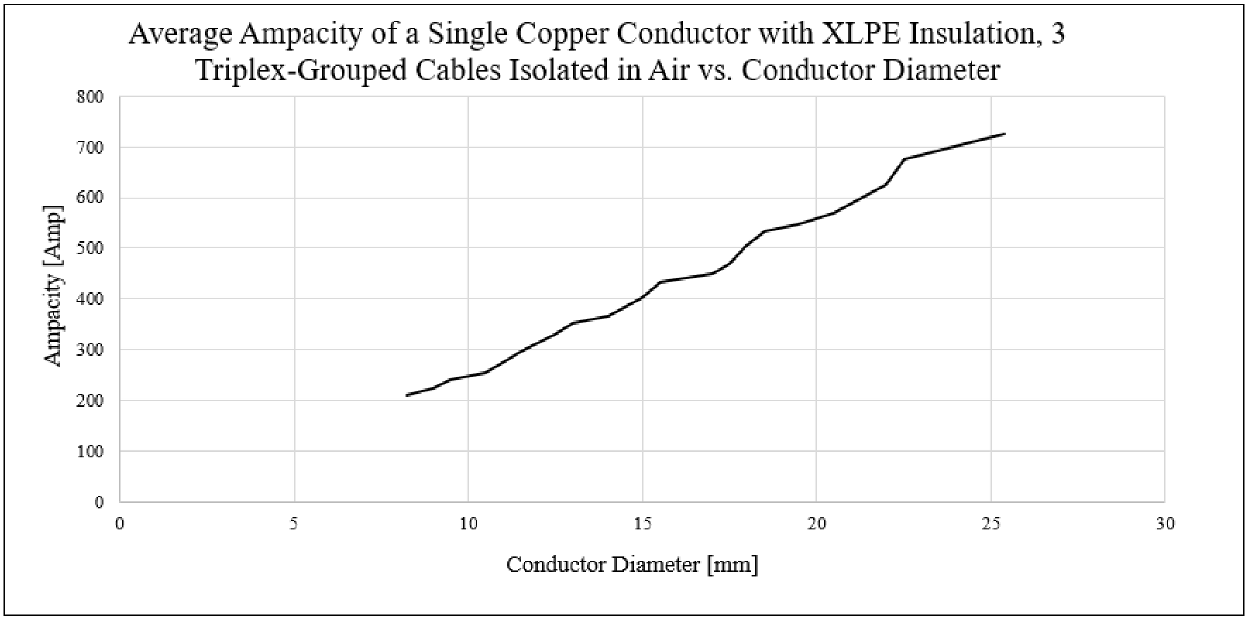


Figure 159: Average Ampacity of All Evaluated References vs. Conductor Diameter for Medium Voltage Cables, 90 [°C] Maximum Conductor Temperature and 45 [°C] Ambient Temperature

The averages shown above in Figure 159 include all evaluated references. As this study seeks to evaluate shipboard systems, the separated averages for ampacity for shipboard and land-based references are provided below in juxtaposition in Figure 160.

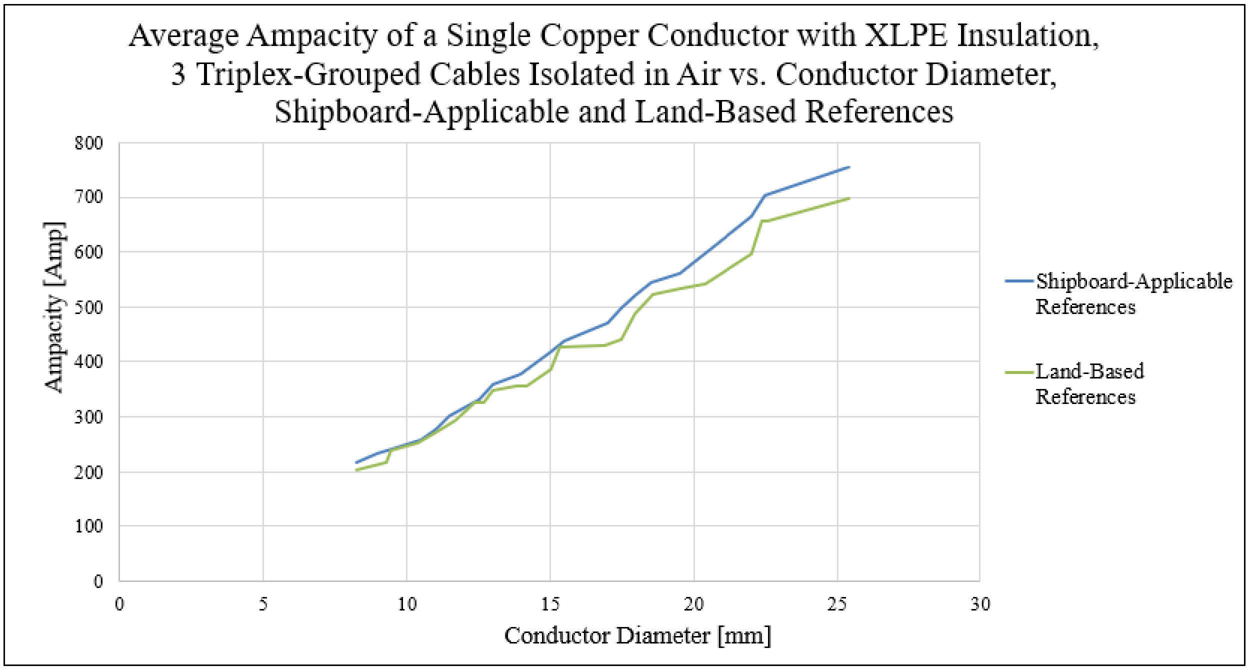


Figure 160: Average Ampacity of Shipboard-Applicable and Land-Based References vs. Conductor Diameter for Medium Voltage Cables, 90 [°C] Maximum Conductor Temperature and 45 [°C] Ambient Temperature

Note in contrast to IEEE and IEC values alone, the shipboard-applicable ampacity average is higher than the overall land-based ampacity average, due to the relatively low ampacity values outlined by the NEC. Both the IEEE's and IEC's shipboard-ampacities are lower than their corresponding condition land-based ampacity.

The remainder of §7.3.1 discusses the sources of information presented in Figure 157 through Figure 160.

IEC Std. 60092-503 covers shipboard electrical installations with 1-15 [kV] U_n AC supply systems. §5.5.4 of this standard dictates that ampacity ratings shall be in accordance with IEC Std. 60092-201 Table 6, with a 10% derating factor [39]. The base cable characteristics for IEC Std. 60092-201 are shown in Table 17. The values of the base ampacities, as well as the correction factors and corrected ampacity are shown in Table 18.

Characteristic	Value
Diameter of Conductors	9.44-19.54 [mm]
Maximum Allowable Conductor Temperature	85 [°C]
Ambient Temperature	45 [°C]
Nominal System Voltage	1-15 [kV]

Table 17: IEC Stds. 60092-503/201 Base Cable Characteristics [62]

Conductor Diameter [mm]	**Base AC Ampacity [Amp]**	**Max. Conductor Temperature Adjustment Factor**	**Adjusted AC Ampacity [Amp]**
9.44	203	1.125[a]	228
11.00	248	1.125[a]	278
12.36	288	1.125[a]	324
13.82	329	1.125[a]	370
15.35	374	1.125[a]	420
17.48	441	1.125[a]	496
19.54	504	1.125[a]	567

[a] IEC Std. 60092-201 gives adjustment factors for maximum allowable conductor temperatures for 85 [°C] and 95 [°C], the average of the two factors is shown here to approximate 90 [°C]

Table 18: IEC Stds. 60092-503/201 Base and Corrected Cable AC Ampacities [62]

IEC Std. 60502-2 covers land-based power cables with extruded insulation within the range of 6-30 [kV] U_n AC. The base cable characteristics for IEC Std. 60502-2 are shown in Table 19, found in Table B.2 of the standard [30]. The values of the base AC ampacities, as well as the correction factors and corrected ampacity are shown in Table 20.

Characteristic	Value
Diameter of Conductors	9.44-22.56 [mm]
Maximum Allowable Conductor Temperature	90 [°C]
Ambient Temperature	30 [°C]
Nominal System Voltage	6-30 [kV]

Table 19: IEC Std. 60502-2 Base Cable Characteristics [30]

Conductor Diameter [mm]	Base AC Ampacity [Amp]	Ambient Temperature Adjustment Factor	Adjusted AC Ampacity [Amp]
9.44	296	0.87	258
11.00	361	0.87	314
12.36	417	0.87	363
13.82	473	0.87	412
15.35	543	0.87	472
17.48	641	0.87	558
19.54	735	0.87	639
22.57	845	0.87	735

Table 20: IEC Std. 60502-2 Base and Corrected Cable AC Ampacities [30]

IEEE Std. 45.8 Recommended Practice for Electrical Installations on Shipboard Cable Systems §5.7 outlines cable AC ampacities for marine cables in 2-35 [kV] U_n systems [27]. The base cable characteristics for IEEE Std. 45.8 are shown in Table 21, found in Table 6 of the standard [27]. The values of the base ampacities, as well as the correction factors and corrected ampacities for the given ranges of U_n are shown in Table 22 through Table 24.

Characteristic	Value
Diameter of Conductors	8.25-25.40 [mm]
Maximum Allowable Conductor Temperature	90 [°C]
Ambient Temperature	45 [°C]
Nominal System Voltage	2-35 [kV]

Table 21: IEEE Std. 45.8 Base Cable Characteristics [27]

Conductor Diameter [mm]	Base AC Ampacity, No Adjustment Required [Amp]
8.25	212
9.27	244
10.41	281
11.68	325
12.70	360
13.02	371
14.21	413
15.02	444
15.52	460
16.93	510
17.86	549
18.58	570
20.42	635
22.00	697
22.40	709
25.40	805

Table 22: IEEE Std. 45.8 Base and Corrected Cable AC Ampacities, 2-8 [kV] Nominal System Voltage (U_n) [27]

Conductor Diameter [mm]	Base AC Ampacity, No Adjustment Required [Amp]
8.25	217
9.27	250
10.41	288
11.68	332
12.70	366
13.02	377
14.21	418
15.02	448
15.52	464
16.93	514
17.86	554
18.58	574
20.42	638
22.00	697
22.40	709
25.40	808

Table 23: IEEE Std. 45.8 Base and Corrected Cable AC Ampacities, 8-15 [kV] Nominal System Voltage (U_n) [27]

Conductor Diameter [mm]	Base AC Ampacity, No Adjustment Required [Amp]
8.25	220
9.27	250
10.41	288
11.68	332
12.70	366
13.02	376
14.21	416
15.02	446
15.52	462
16.93	512
17.86	551
18.58	570
20.42	632
22.00	689
22.40	701
25.40	798

Table 24: IEEE Std. 45.8 Base and Corrected Cable AC Ampacities, 15-35 [kV] Nominal System Voltage (U_n) [27]

IEEE Std. 835 Standard Power Cable Ampacities contains ampacity tables for power cables in systems with a Nominal System Voltage range of 0.6-500 [kV] [60]. The tabulated ampacities with the set parameters defined by this study (single conductor, XLPE insulation, triplex, in free air) for 5-15 [kV] U_n systems and 25-46 [kV] U_n systems are found on pages 502 and 845 of this standard, respectively [60]. The base cable characteristics for IEEE Std. 835 are shown in Table 25. The values of the base ampacities, as well as the correction factors and corrected ampacities for the given ranges of Un are shown in Table 26 and Table 27.

Characteristic	Value
Diameter of Conductors	8.25-25.40 [mm]
Maximum Allowable Conductor Temperature	90 [°C]
Ambient Temperature	40 [°C]
Nominal System Voltage	5-15, 25-46 [kV]

Table 25: IEEE Std. 835 Base Cable Characteristics [60]

Conductor Diameter [mm]	Base AC Ampacity [Amp]	Ambient Temperature Adjustment Factor	Adjusted AC Ampacity [Amp]
12.72	437	0.95	415
15.03	536	0.95	508
17.96	661	0.95	627
22.00	882	0.95	837
25.40	977	0.95	927

Table 26: IEEE Std. 835 Base and Corrected Cable AC Ampacities, 5-15 [kV] Nominal System Voltage (U_n) [60]

Conductor Diameter [mm]	Base AC Ampacity [Amp]	Ambient Temperature Adjustment Factor	Adjusted AC Ampacity [Amp]
8.25	263	0.95	250
9.26	302	0.95	287
10.40	346	0.95	328
11.67	397	0.95	377
12.72	436	0.95	414

Table 27: IEEE Std. 835 Base and Corrected Cable AC Ampacities, 5-15 [kV] Nominal System Voltage (U_n) [60]

MIL-DTL-24643\22E Table 1 provides conductor sizes for cables within 5 [kV] U_n USN ship systems [57]. MIL-HDBK-299 specifies the ampacity for each conductor, applicable to DC or 60 [Hz] AC in Table VI(a)(1) [63]. The base characteristics of the USN cables are listed in Table 28. The values of the base ampacities, as well as the correction factors and corrected ampacities for the USN cable are shown in Table 29.

Characteristic	Value
Diameter of Conductors	8.25-16.34 [mm]
Maximum Allowable Conductor Temperature	90 [°C]
Ambient Temperature	40 [°C]
Nominal System Voltage	5 [kV]

Table 28: USN Base Cable Characteristics [63]

Conductor Diameter [mm]	Base AC or DC Ampacity [Amp]	Ambient Temperature Adjustment Factor	Adjusted AC or DC Ampacity [Amp]
8.25	174	0.96[a]	167
10.40	235	0.96[a]	226
12.70	315	0.96[a]	302
15.02	391	0.96[a]	375
16.34	435	0.96[a]	418

[a] MIL-HDBK-299 gives ampacity for 40 [°C] and 50 [°C] ambient temperature which has a constant adjustment factor applied to the 40 [°C] ambient temperature ampacities of 0.92 to arrive at the 50 [°C] ambient temperature ampacity. The average of the adjustment factors (1 and 0.92) is applied to the 40 [°C] ambient temperature ampacities to approximate a 45 [°C] ambient temperature.

Table 29: USN Base and Corrected Cable AC or DC Ampacities, 5 [kV] U_n [63]

The National Electrical Code, NEC, is an internationally recognized standard that sets the foundation for electrical safety for residential, commercial, and industrial occupancies [64]. Table 311.60(C)(73) of this reference outlines ampacities for land-based AC conductors in 2-35 [kV] U_n systems [59]. The base characteristics for the NEC cables are shown in Table 30. The values of the base ampacities, as well as the correction factors and corrected ampacities for the given ranges of U_n are shown in Table 31 and Table 32.

Characteristic	Value
Diameter of Conductors	8.25-25.4 [mm]
Maximum Allowable Conductor Temperature	90 [°C]
Ambient Temperature	40 [°C]
Nominal System Voltage	2-35 [kV]
Spacing Between Cables	> 1 Cable Diameter

Table 30: NEC Base Cable Characteristics [59]

Conductor Diameter [mm]	Base AC Ampacity [Amp]	Ambient Temperature Adjustment Factor	Adjusted AC Ampacity [Amp]
8.25	180	0.9487[a]	171
9.26	205	0.9487[a]	194
10.40	240	0.9487[a]	228
11.67	280	0.9487[a]	266
12.70	315	0.9487[a]	299
15.02	385	0.9487[a]	365
17.96	475	0.9487[a]	451
22.00	600	0.9487[a]	569
25.40	690	0.9487[a]	655

[a] Calculated from Equation 311.60(D)(4) within the reference.

Table 31: NEC Base and Corrected Cable AC Ampacities, 2-5 [kV] Nominal System Voltage (U_n) [59]

Conductor Diameter [mm]	Base AC Ampacity [Amp]	Ambient Temperature Adjustment Factor	Adjusted AC Ampacity [Amp]
8.25	195	0.9487[a]	185
9.26	225	0.9487[a]	213
10.40	260	0.9487[a]	247
11.67	295	0.9487[a]	280
12.70	330	0.9487[a]	313
15.02	395	0.9487[a]	375
17.96	480	0.9487[a]	455
22.00	585	0.9487[a]	555
25.40	675	0.9487[a]	640

[a] Calculated from Equation 311.60(D)(4) within the reference.

Table 32: NEC Base and Corrected Cable AC Ampacities, 5-35 [kV] Nominal System Voltage (U_n) [59]

7.3.2 Effect of Ampacity

Ampacity ratings of power cables have a major impact on cable system sizing. The required total current can be split into different numbers of parallel cables creating a tradeoff between conductor size and number of cables that can be optimized for the overall required spatial allocation. A brief example of this is given in the following paragraph, and a more complete example for an MVDC system is worked through in §9.

Example: A 10 [MW] AC system is being designed for a ship using 5 [kV] Nominal System Voltage (U_n) (Phase-to-Phase voltage). Using the base equation for power of a 3-cable group in a 3-phase AC system (Equation 1 below), with the power of the cable group being 3 times that of a single cable, this system would require a total of 1155 [Amp]. The cable size versus ampacity rating for an AC system is obtained from IEEE Std. 45.8 (shown in Table 33) for groups of 3 conductors in triplex configuration, with the minimum 100% insulation level (2.29 [mm]) for the 5 [kV] U_n AC system voltage. The results are shown in Table 33 [27].

$$I_{AC_{SingleCable}} = Current\ Per\ Cable\ in\ an\ AC\ System\ [Amp]$$

$$V_{PG}(Phase - to - Ground\ Voltage) = \frac{U_n\ (Phase - to - Phase\ Voltage)}{\sqrt{3}}\ [V]$$

$$P_{AC_{SingleCable}}(Power\ of\ a\ Single\ Cable\ in\ a\ 3 - Phase\ AC\ System) = \frac{U_n * I_{AC_{SingleCable}}}{\sqrt{3}}\ [W]$$

$$P_{AC_{ThreeCableGroup}}(Power\ of\ a\ 3 - Cable\ Group\ in\ a\ 3 - Phase\ AC\ System) = 3 * P_{AC_{SingleCable}}\ [W]$$

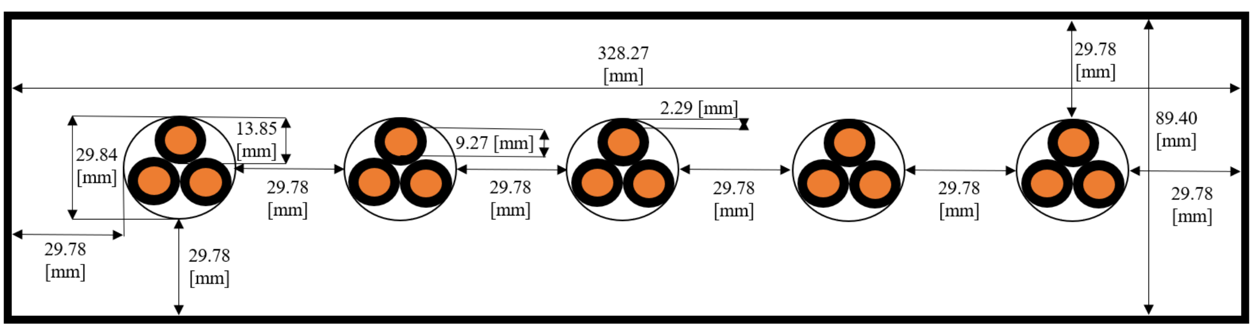
$$P_{AC_{ThreeCableGroup}} = \frac{3 * I_{AC_{SingleCable}} * U_n}{\sqrt{3}} = \sqrt{3} * I_{AC_{SingleCable}} * U_n \qquad (1)$$

Equation 1: AC Power for a 3-Cable Group from Single Cable Current and Phase-to-Phase System Voltage

IEEE Std. 45.8 directs a spacing distance between cable groups of at least 2.15 times a single insulated conductor diameter [27]. Assuming a rectangular grid, and the cables are in a rectangular cable way with the IEEE required minimum spacing between any cable group, and this spacing is also applied between any cable group and the cable way, the total cross-sectional area required for each cable system is shown in the far-right column of Table 33. Of note this is a simplified example, that does not include all components required in cable construction, such as semi-conductive tape thickness, shielding thickness, and jacket thickness. Table 33 shows that the required area for a cable system is dependent on the total current required, ampacity of the conductors, insulation thickness for the U_n, and the required spacing between cables. An example 1 x 5 cable way with a 9.27 [mm] diameter cable (simplified to be only conductor + 2x insulation thickness) corresponding to the highlighted row of Table 33 is shown below Table 33 in Figure 161.

Conductor Diameter	Single Cable Ampacity [27]	Power per 3-Cable Group	Number of Cable Groups Required	Cable Grid Geometry	Total Single Cable Diameter (Includes 2x Insulation Thickness)	Cable Way Height	Cable Way Width	Cable Way Cross-sectional Area
[mm]	[Amp]	[MW]	#	Row x Column	[mm]	[m]	[m]	[m^2]
8.25	199	1.7234	6	2 x 3	12.83	0.1380	0.1935	0.0267
9.27	232	2.0092	5	1 x 5	13.85	0.0894	0.3283	0.0293
10.40	244	2.1131	5	1 x 5	14.98	0.0967	0.3551	0.0343
11.68	287	2.4855	5	1 x 5	16.26	0.1050	0.3854	0.0404
12.70	317	2.7453	4	2 x 2	17.28	0.1859	0.1862	0.0346
15.03	386	3.3429	3	1 x 3	19.61	0.1266	0.2958	0.0374
16.06	422	3.6546	3	1 x 3	20.64	0.1332	0.3113	0.0415
17.96	489	4.2349	3	1 x 3	22.54	0.1455	0.3400	0.0495
19.67	528	4.5726	3	1 x 3	24.25	0.1565	0.3658	0.0573
21.25	570	4.9363	3	1 x 3	25.83	0.1667	0.3896	0.0650
22.00	594	5.1442	2	1 x 2	26.58	0.1716	0.2864	0.0491
22.72	636	5.5079	2	1 x 2	27.3	0.1762	0.2941	0.0518
24.10	662	5.7331	2	1 x 2	28.68	0.1851	0.3090	0.0572
25.40	677	5.8630	2	1 x 2	29.98	0.1935	0.3230	0.0625

Table 33: Example 10 [MW] Cable Systems with a 5 [kV] Nominal System Voltage



Note: This is a simplified example that does not include all components required in cable construction

Figure 161: Example Cable Way Cross-Section For a 5 [kV] U_n AC System with a 10 [MW] Capacity, See Table 33

8.0 Impact of Standards on MV Power Cables

8.1 Cable Insulation Electric Stress

One method of comparing the presented standards is to examine the electric stress in the insulation of the cables. Comparing the electric stress within the insulation at Cable Nominal Voltage (U_o), Withstand Voltage (U_w), and BIL results in the range of currently acceptable stress levels. The resultant stresses from U_o, U_w, and BIL are notably different, with higher stresses allowed when there is a shorter duration of the applied stress. Also, comparing the stress levels between references for each type of voltage leads to the range of currently acceptable stress levels. This evaluation aids in the goal of producing prospective shipboard MVDC design and test values by providing context to the stresses within the prospective systems as to how they would compare to the existing MVAC stresses.

The electric stress within cable insulation were calculated using Equation 2-Equation 5 below. These equations solve for the maximum, minimum, and average electrical stresses within a given cable insulation. These stresses are dependent on the diameter of the conductor, thickness of insulation, and the magnitude of the voltage inducing the stress. The voltages used in this section are the line-to-ground values of Cable Nominal Voltage (U_o), Withstand Test Voltage (U_w), and BIL.

$$a = Radius\ of\ Conductor\ [mm]$$

$$t_{ins} = Thickness\ of\ Insulation\ [mm]$$

$$b = a + t_{ins}\ (Radius\ of\ Insulated\ Conductor)[mm] \qquad (2)$$

Equation 2: Radius of Insulated Conductor

$$E = Electric\ Stress\ Experienced\ by\ Insulation\ [\frac{kV}{mm}]$$

$$V_{PG} = Phase - to - Ground\ Voltage\ [kV]\ (U_o, U_w, or\ BIL)$$

$$E_{max} = \frac{V_{PG}}{a * \ln\left(\frac{b}{a}\right)}\ [\frac{kV}{mm}] \qquad (3)$$

Equation 3: Maximum Electric Stress Within Insulation [65]

$$E_{min} = \frac{V_{PG}}{b * \ln\left(\frac{b}{a}\right)}\ [\frac{kV}{mm}] \qquad (4)$$

Equation 4: Minimum Electric Stress Within Insulation [65]

$$E_{ave} = \frac{V_{PG}}{t_{ins}}\ [\frac{kV}{mm}] \qquad (5)$$

Equation 5: Average Electric Stress Within Insulation [65]

The maximum stress within insulation occurs at the interface between the center conductor and the insulation, and the minimum occurs at the outer edge of the insulation. An example of the stress gradient within cable insulation is shown below in Figure 162. This figure shows the resultant stress gradient within cable insulation for a 12 [kV] U_n 3-Phase AC system. The stress within a single cable's insulation at Nominal System Voltage is from the phase-to-ground RMS voltage known as the Cable Nominal Voltage (U_o) (6.928 [kV] RMS for a 12 [kV] U_n system). The insulation thickness is in accordance with IEEE Std. 1580 100% rating, which is 4.45 [mm] for a cable within a 12 [kV] U_n system [28]. The conductor size of AWG 1/0 (8.25246 [mm] diameter) is selected for this example.

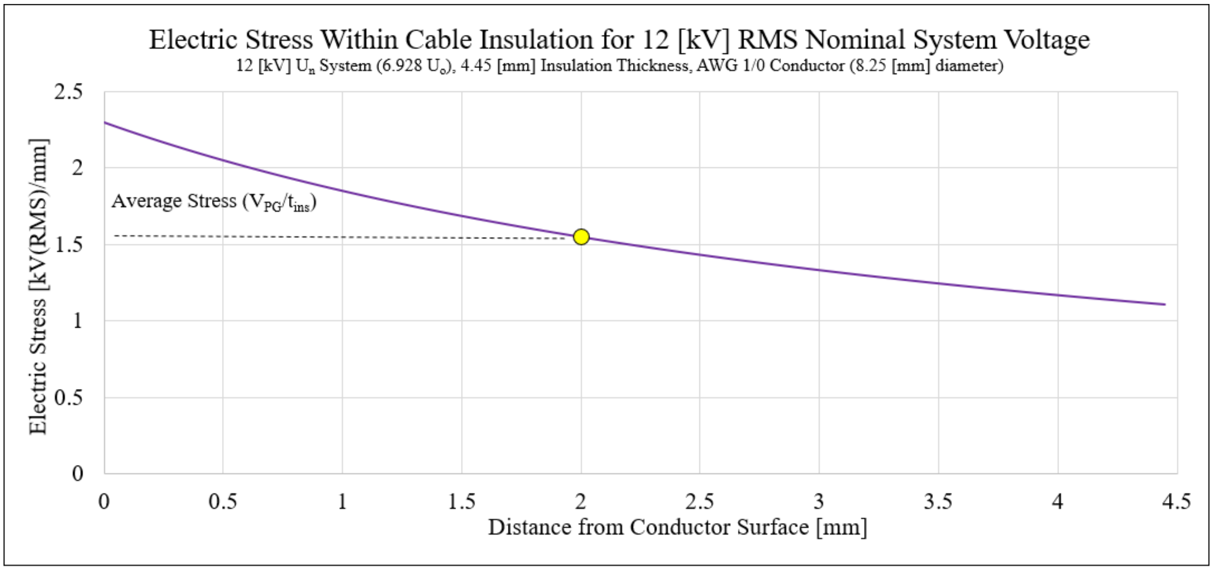


Figure 162: Stress Gradient Within Cable Insulation at U_o, showing 2x Change in Electric Stress from Inner to Outer Edges of Insulation

An example of typical average electric stress in a cable's insulation is depicted in Figure 163. Because the insulation thickness is determined by the system voltage, and according to MV system standards insulation thickness takes step increases as system voltage is increased, the average electric stress takes a "saw-tooth" shape. A corresponding trendline for the average stress is also depicted by the dashed line in Figure 163. The trendlines within this section were generated using a similar method of least squares regression to what was done in §4.2 and §5.2. This is done using the high and low electric stresses at each insulation thickness transitions and the electric stress in-between transition points as points for regression.

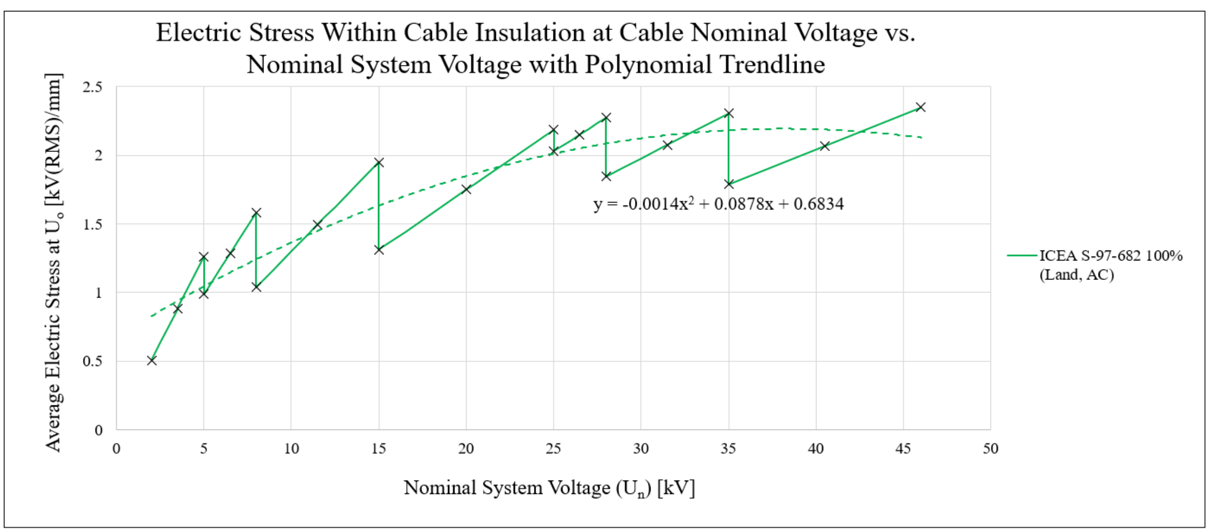


Figure 163: Example Average Electric Stress Within Cable Insulation at U_o vs. U_n, and Generated Trendline

The legends of the figures in §8.1 contain each reference's parameters. The reference name, applicability (shipboard or land-based), system current (AC or DC), and if the standard governing the insulation thickness is different than the standard governing the voltage are shown in the legend of the following figures in the format shown in Figure 164. The supporting data from each reference are discussed and shown following these figures.

Format:	Reference (Applicability, System Current Type, If Insulation Thickness Comes from Another Standard)			
Options:	All Refs.	Land or Ship	AC or DC	Blank or All Refs.
Example:	IEC Std. 60502-2 (Land, AC, IEC. Std. 60502-2)			

Figure 164: Key for Legends in §8.1

Figure 166 - Figure 189 show 6 figures for each type of voltage, each versus Nominal System Voltage (U_n); the calculated average electrical stresses, generated trendlines of the average stresses, the range of electrical stresses for each type of voltage, maximum and minimum stress bounds from connecting the endpoints of the range bars in the preceding figure, the average of the evaluated references average electric stresses, and finally the average of the evaluated references split into shipboard-applicable and land-based references. The minimum and maximum stresses that are plotted were calculated with Equation 3 using the smallest conductor (53.5 [mm^2]) for the maximum stress, and the minimum stress with Equation 4 using the largest conductor (506.7 [mm^2]). Of note, the shipboard-applicable standard IEC Std. 60092-354 contains identical guidance in terms of insulation thickness, Withstand Test Voltage, and BIL as the land-based standard IEC Std. 60502-2 and so they are graphed as a single line [40] [30]. IEC Std. 60502-2 states ground fault clearing times that meet the definition of both the IEEE 100% and 133% insulation levels for the given values, and so it is averaged into both respective categories [30]. IEEE Std. 835 and IEC. Std. 60092-354 do not state what ground fault clearance times are required, so for this study they are assumed to be at the 100% level [60] [40].

Figure 165 below shows typical values for electrical stresses from BIL, U_w, and U_o to give a reference of scale to the reader for the following figures.

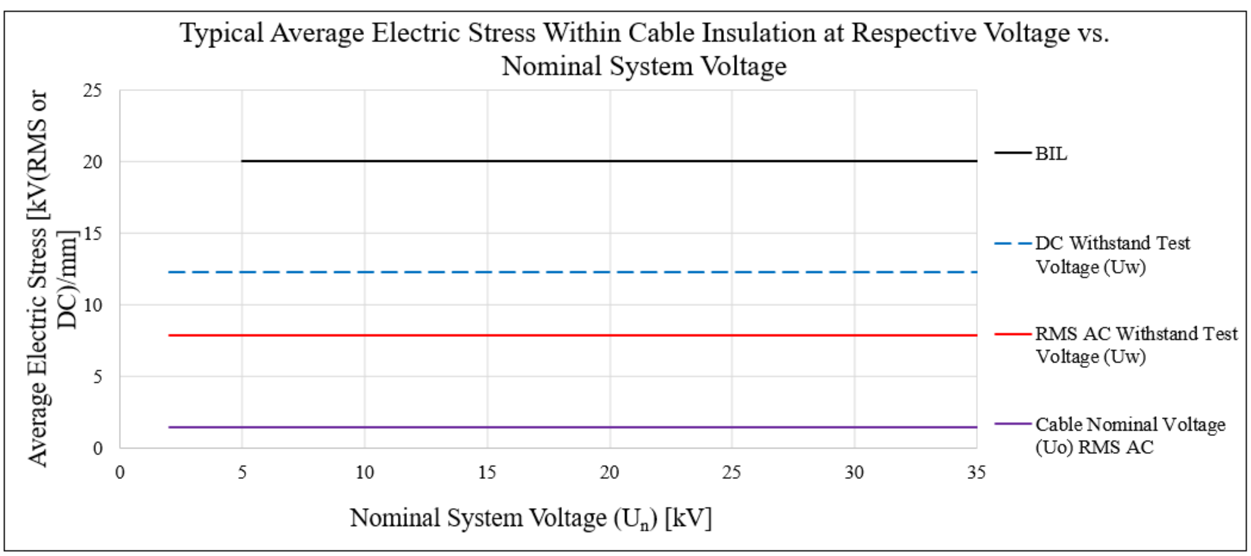


Figure 165: Typical Average Electric Stress Within Cable Insulation at U_o, U_w, and BIL vs. U_n for AC or DC Systems

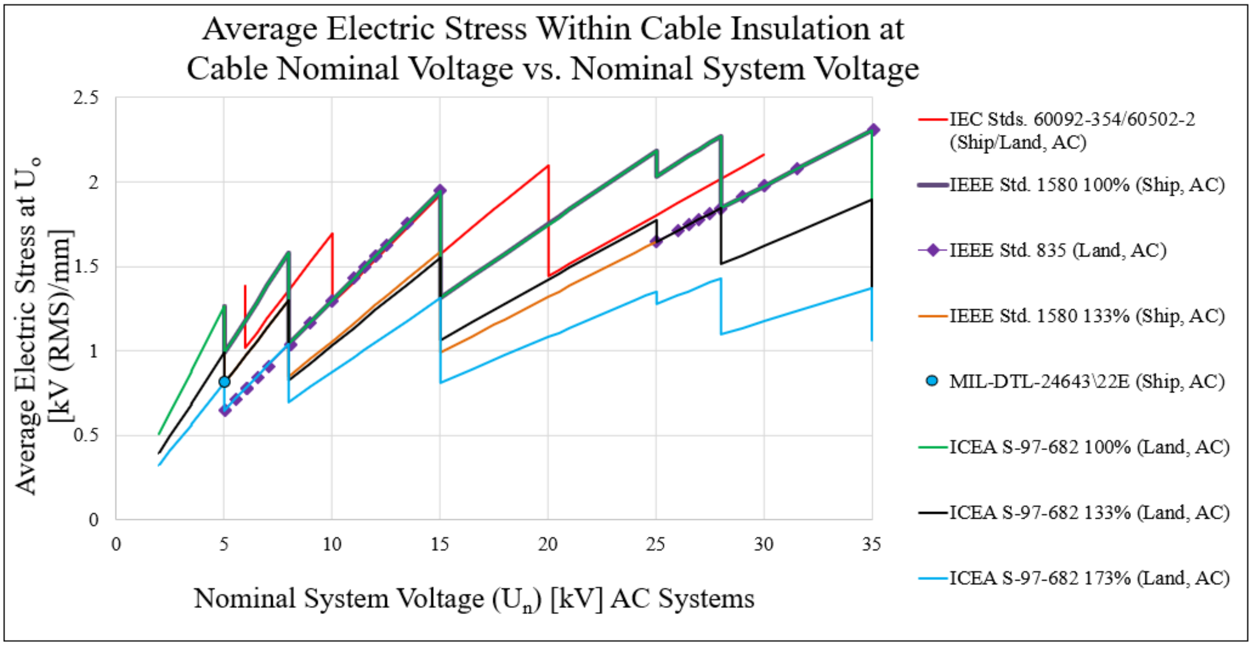


Figure 166: Average Electric Stress Within Cable Insulation at U_o vs. U_n for AC Systems

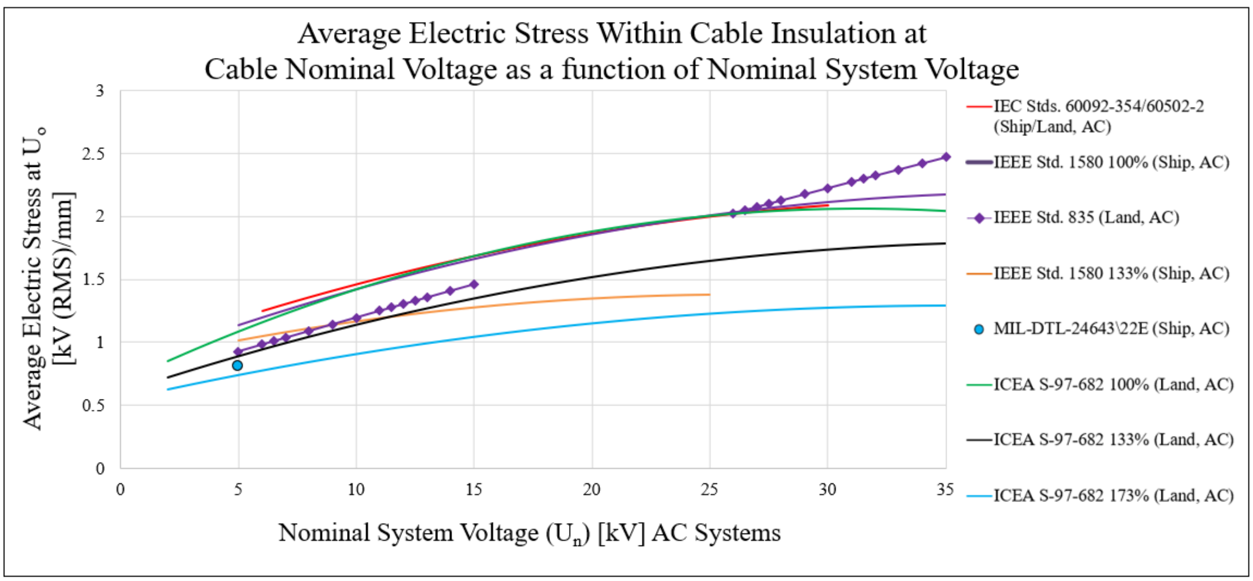


Figure 167: Trendlines of Average Electric Stress Within Cable Insulation at U_o vs. U_n for AC Systems

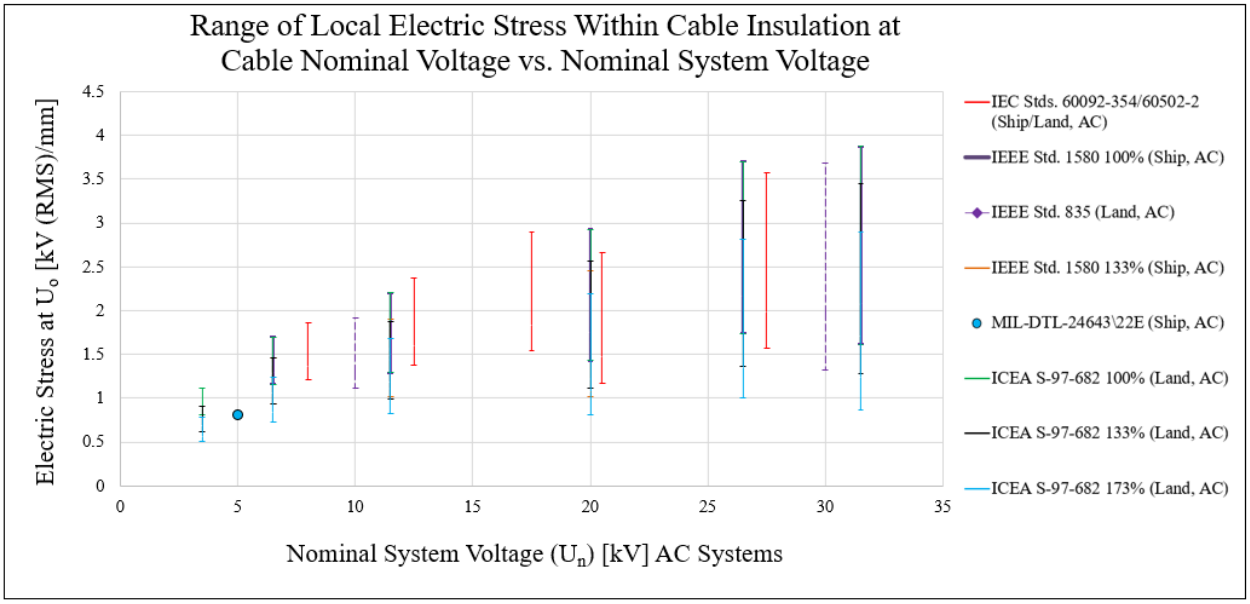


Figure 168: Range of Electric Stress Within Cable Insulation at U_o vs. U_n for AC Systems

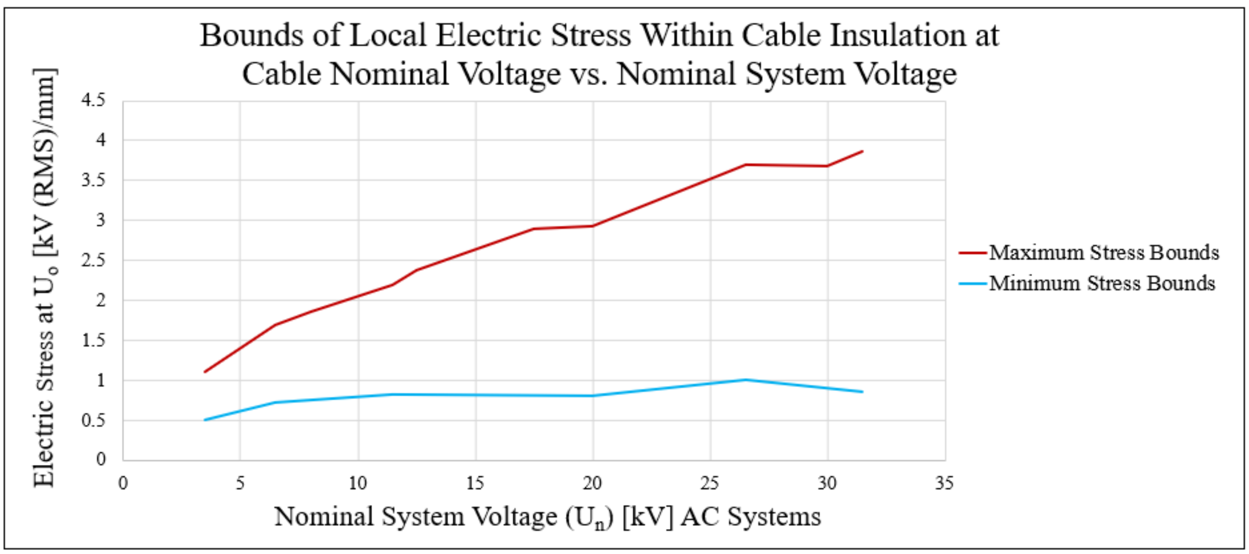


Figure 169: Bounds of Electric Stress Within Cable Insulation at U_o vs. U_n for AC Systems

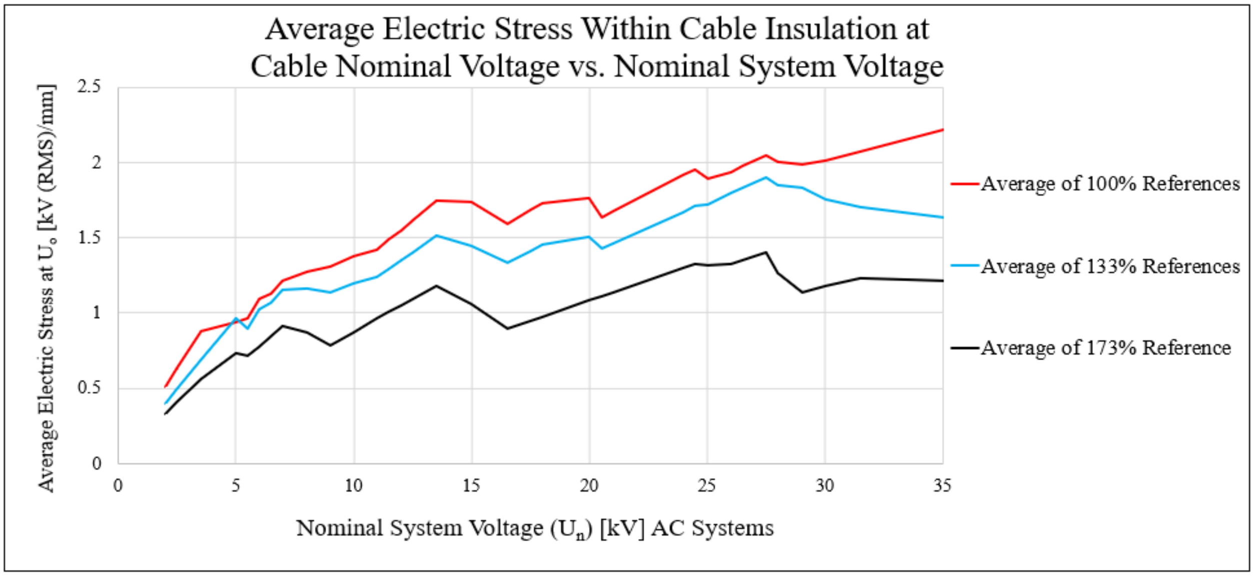


Figure 170: Average of Evaluated References' Average Electric Stress Within Cable Insulation at U_o vs. U_n for AC Systems

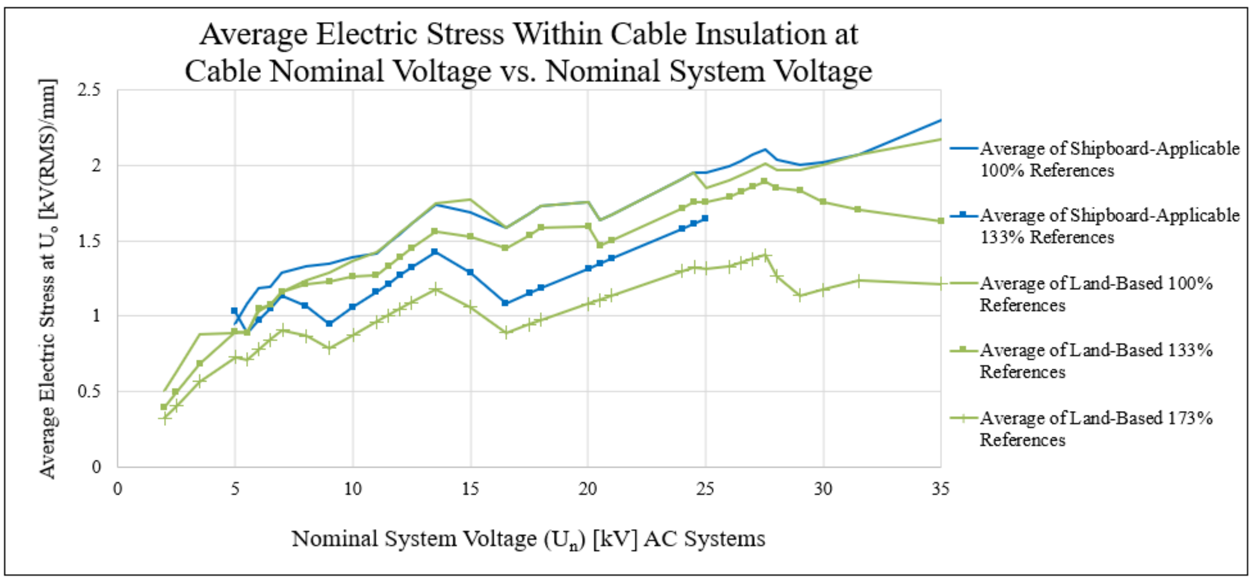
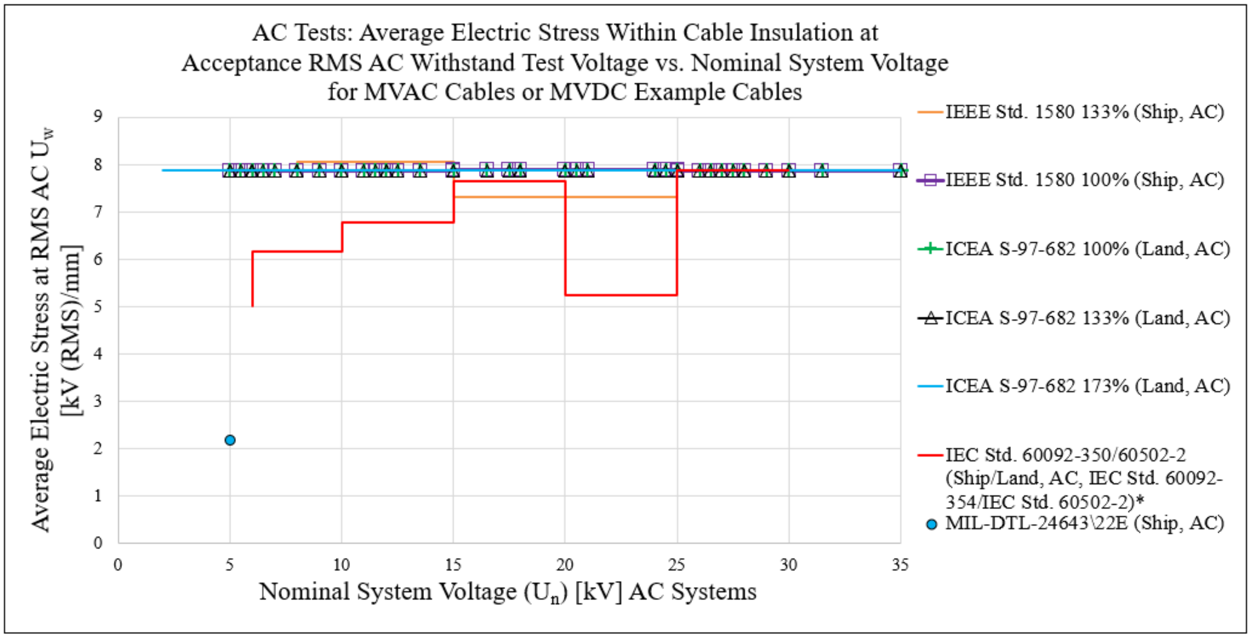
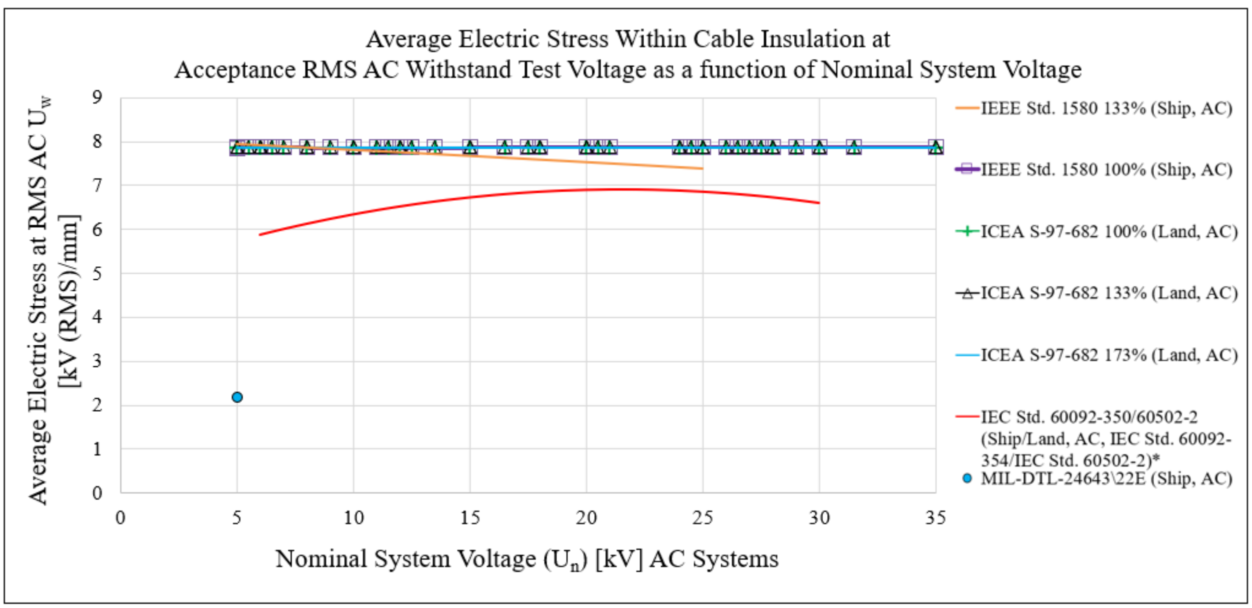


Figure 171: Comparison of Shipboard-Applicable and Land-Based References' Average Electric Stress Within Cable Insulation at U_o vs. U_n for AC Systems



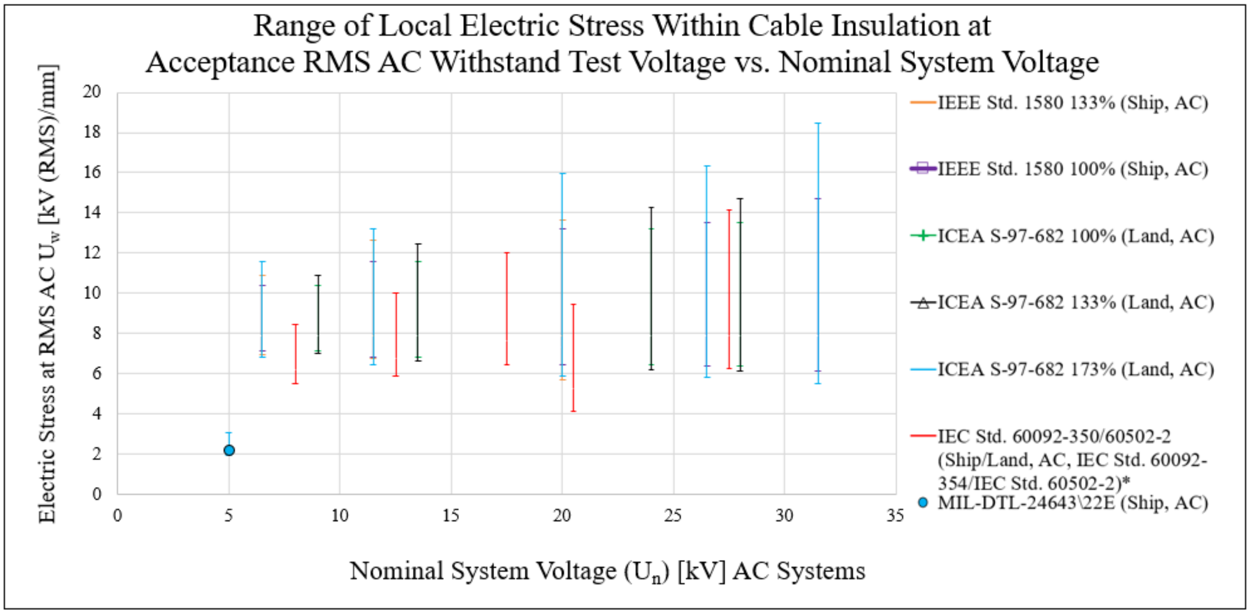
*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 172: Average Electric Stress Within Cable Insulation at AC RMS U_w vs. U_n for AC Systems



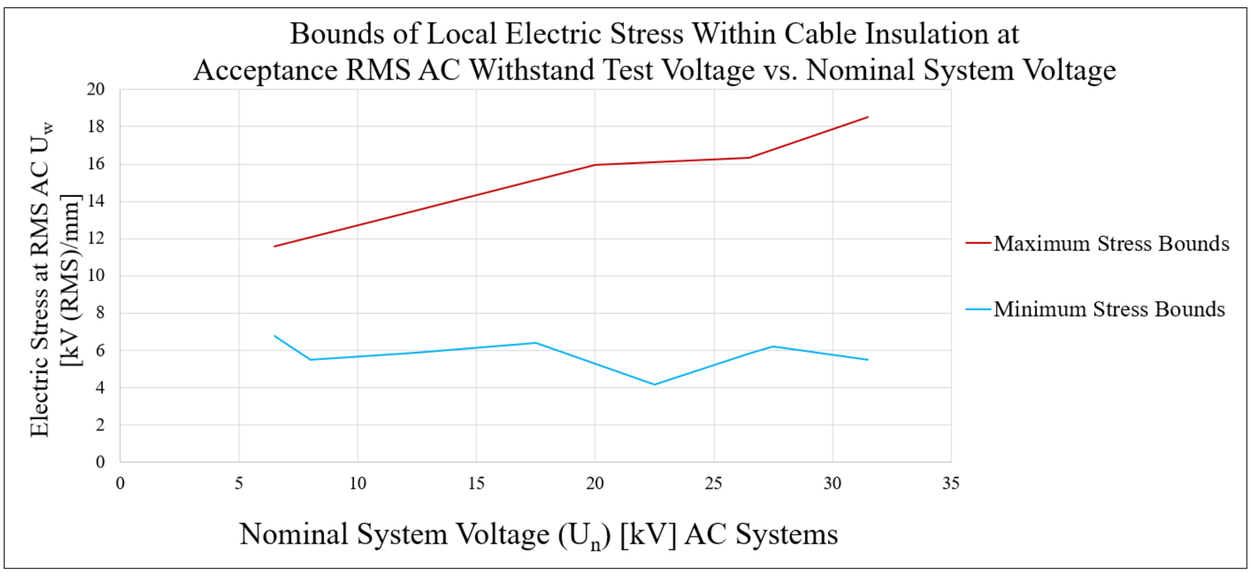
*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 173: Trendlines of Average Electric Stress Within Cable Insulation at AC RMS U_w vs. U_n for AC Systems



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 174: Range of Electric Stress Within Cable Insulation at AC RMS U_w vs. U_n for AC Systems



Note: MIL-DTL-24643\22E range data is excluded from bounds

Figure 175: Bounds of Electric Stress Within Cable Insulation at AC RMS U_w vs. U_n for AC Systems

Within the evaluated references, the electrical stress within cable insulation at withstand voltage test levels does not vary considerably due to the increase of Nominal System Voltage or percent insulation level. This is due to the test voltages increasing at the same intervals as the prescribed Nominal System Voltages, resulting in minimal changes to the electrical stress. Additionally, at each Nominal System Voltage there are levels of Withstand Test Voltages corresponding to percent insulation level.

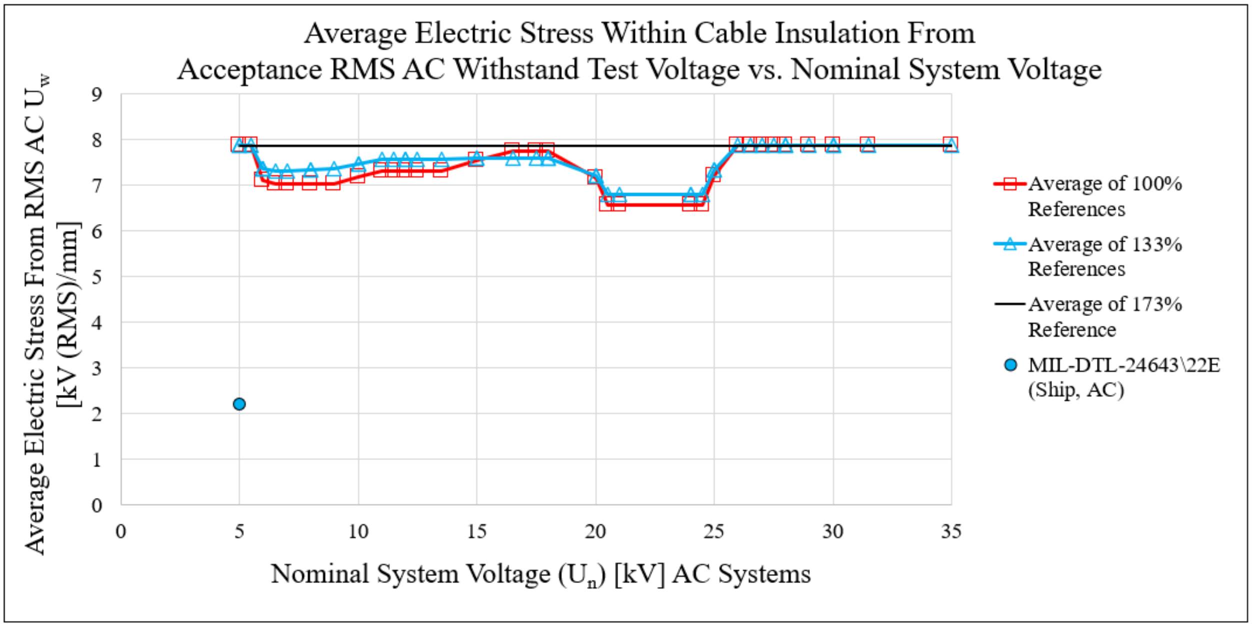


Figure 176: Average of Evaluated References' Average Electric Stress Within Cable Insulation at AC RMS U_w vs. U_n for AC Systems

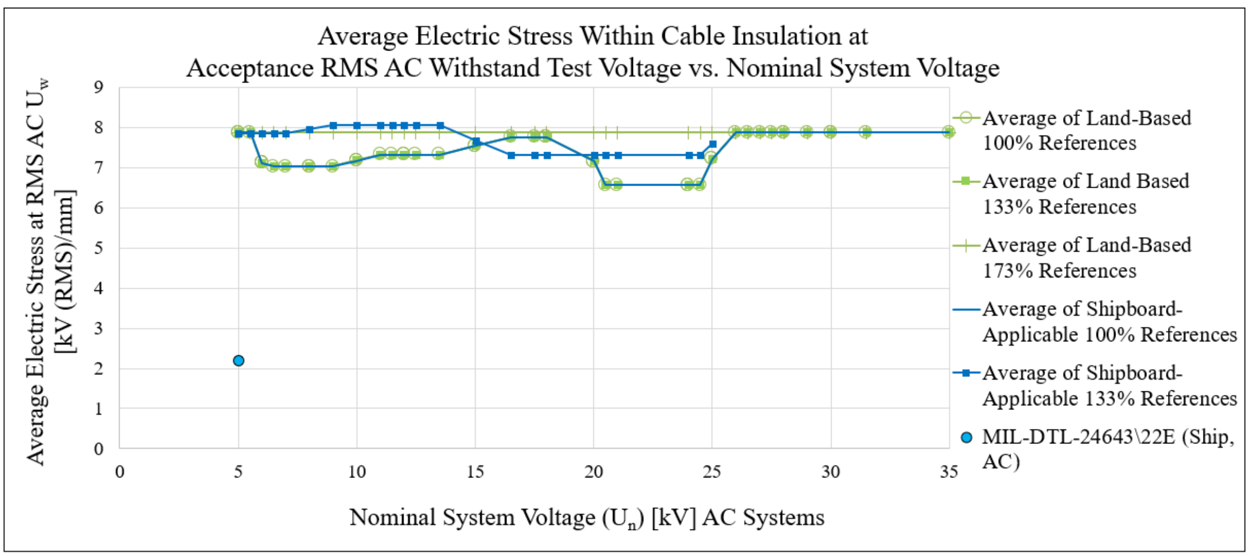
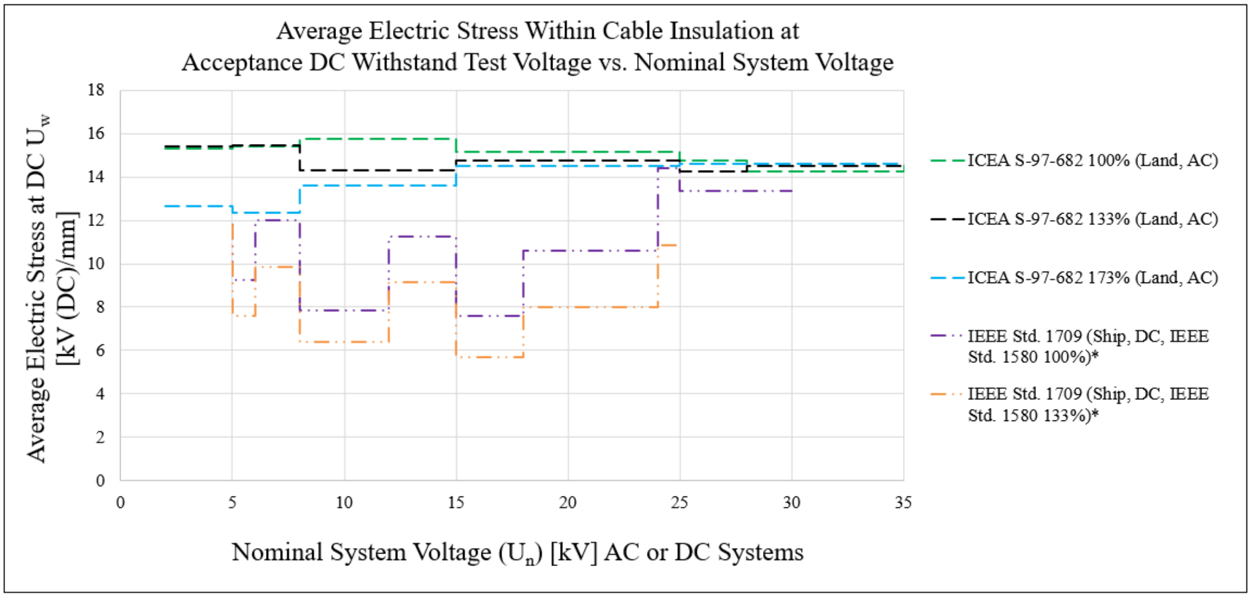
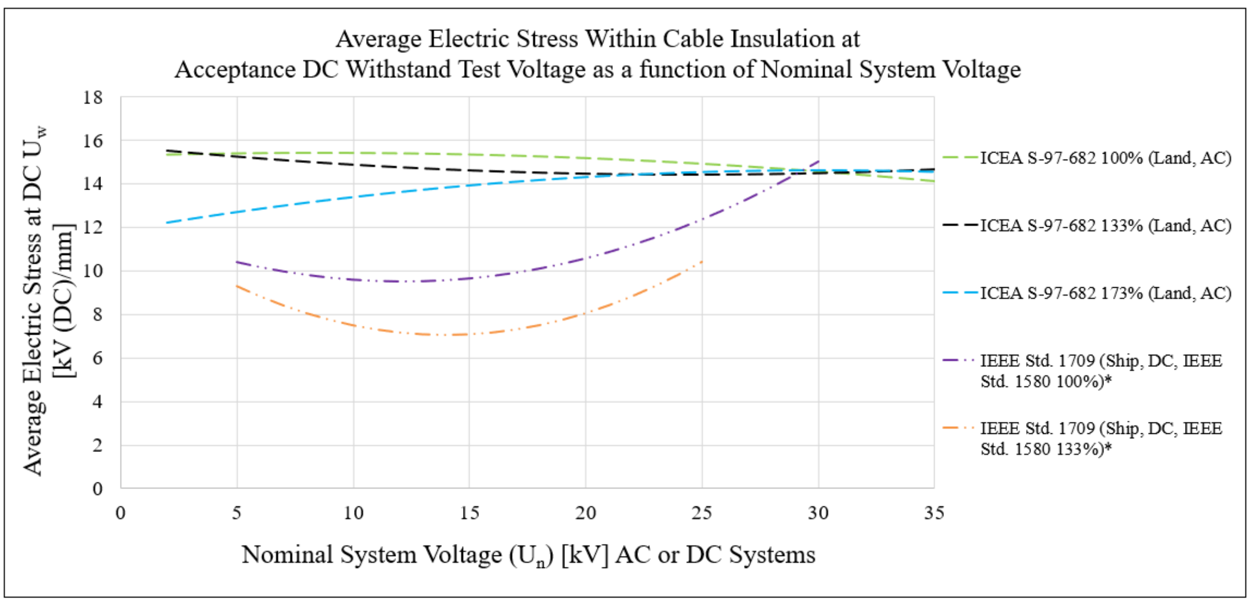


Figure 177: Comparison of Shipboard-Applicable and Land-Based References' Average Electric Stress Within Cable Insulation at AC RMS U_w vs. U_n for AC Systems



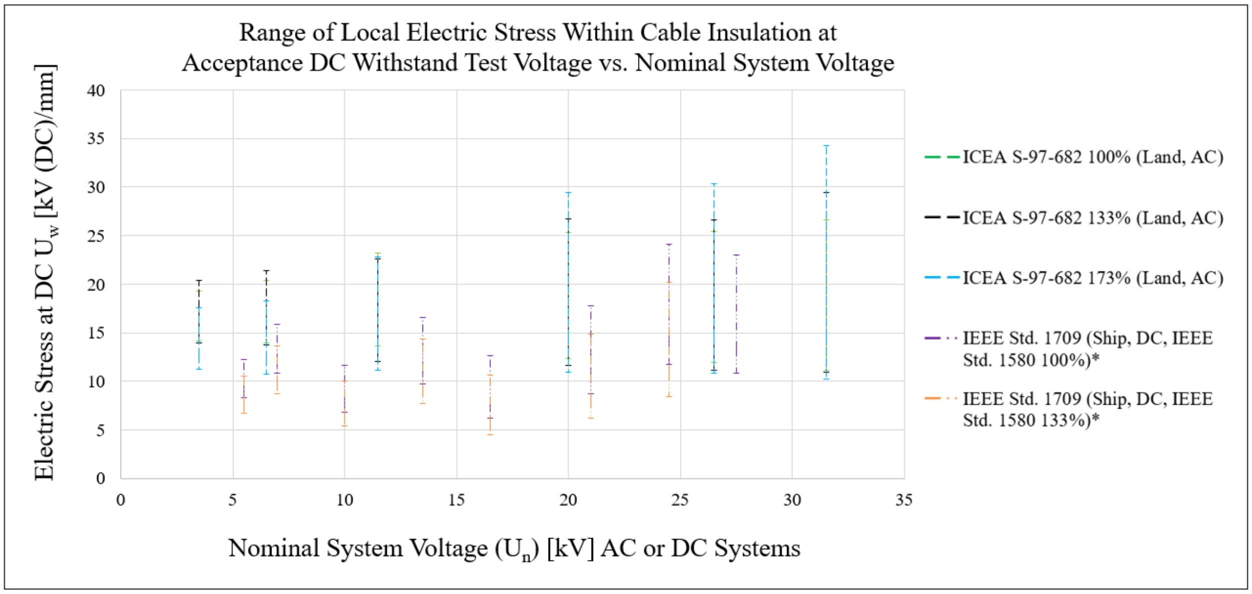
*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 178: Average Electric Stress Within Cable Insulation at DC U_w vs. U_n for AC or DC Systems



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 179: Trendlines of Average Electric Stress Within Cable Insulation at DC U_w vs. U_n for AC or DC Systems



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 180: Range of Electric Stress Within Cable Insulation at DC U_w vs. U_n for AC or DC Systems

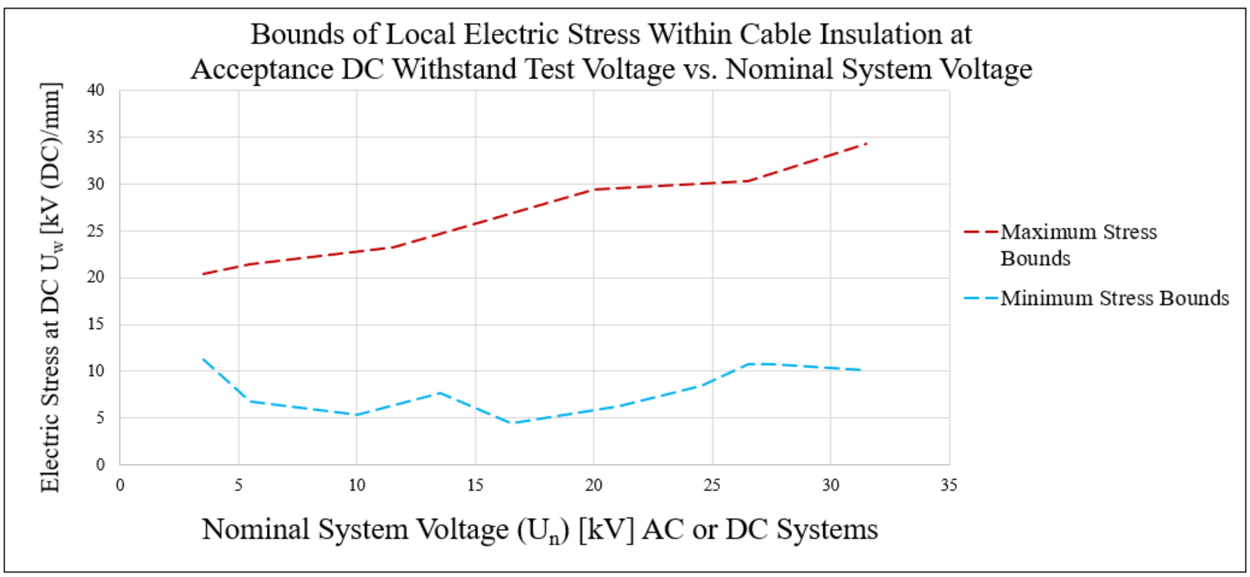


Figure 181: Bounds of Electric Stress Within Cable Insulation at DC U_w vs. U_n for AC or DC Systems

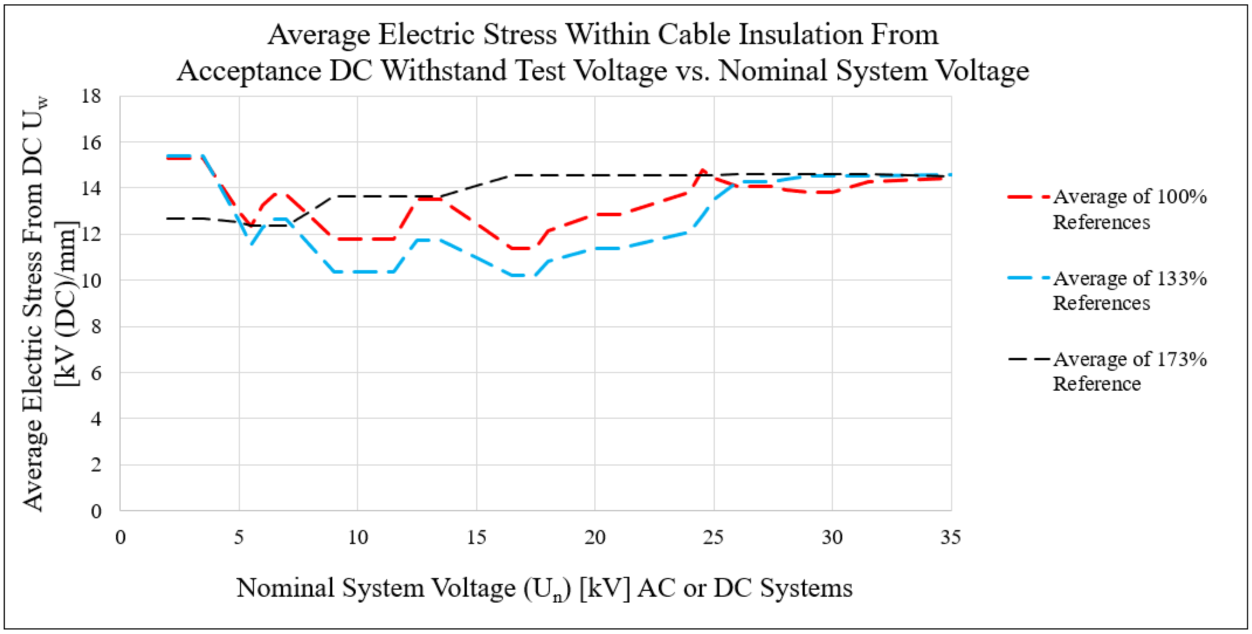


Figure 182: Average of Evaluated References' Average Electric Stress Within Cable Insulation at DC U_w vs. U_n for AC or DC Systems

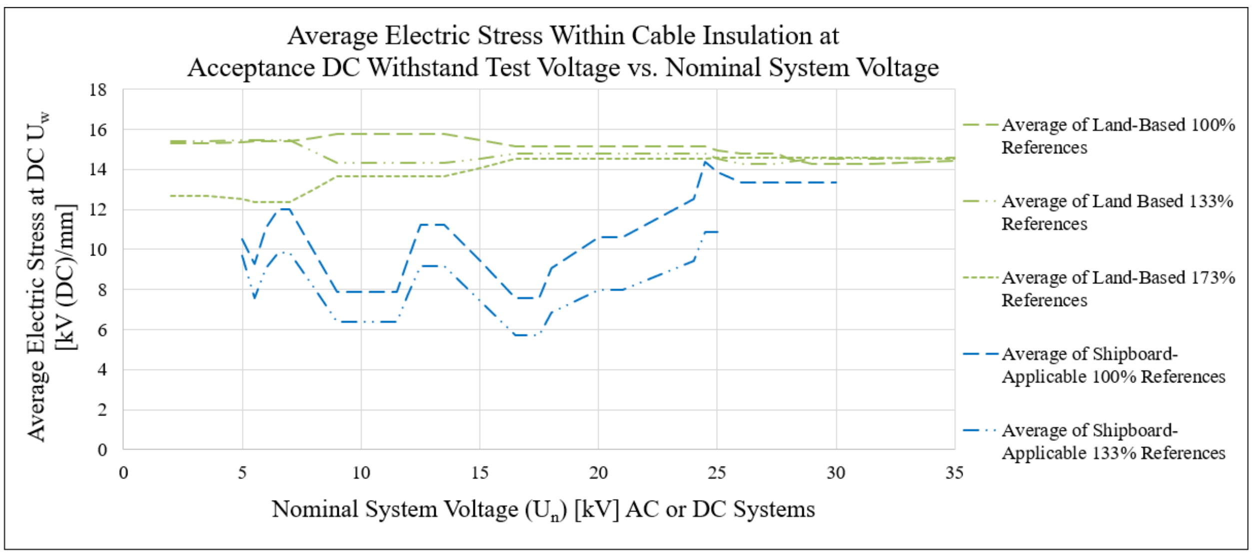
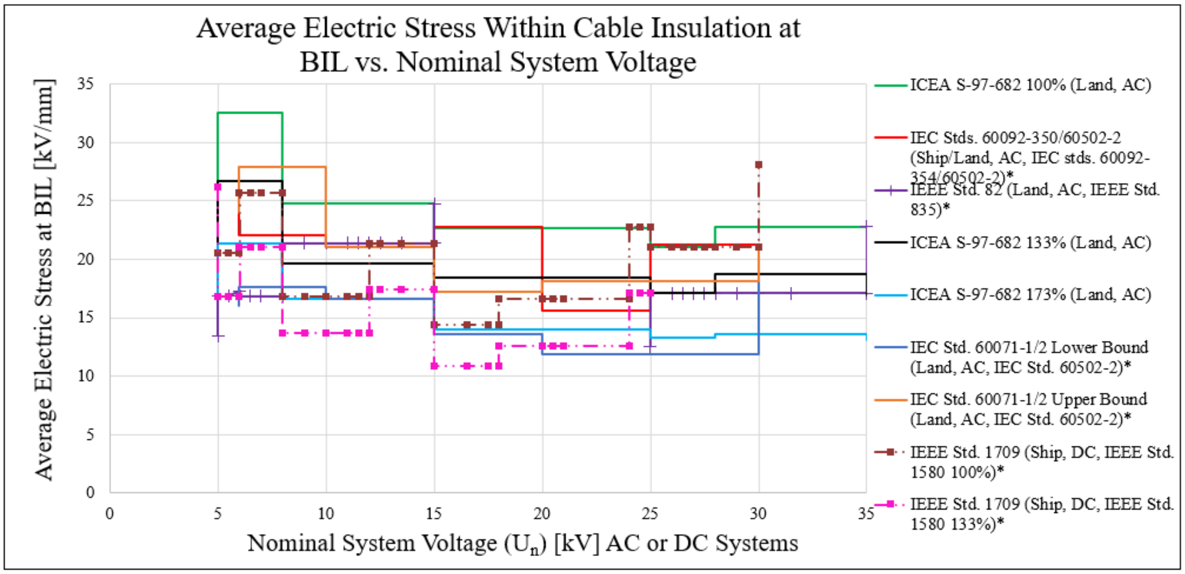
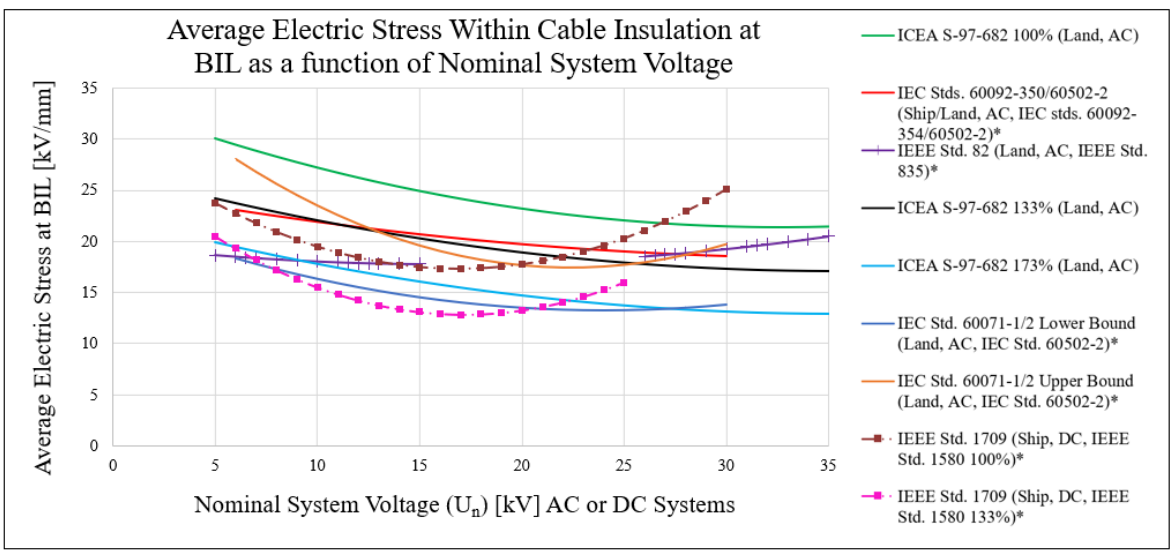


Figure 183: Comparison of Shipboard-Applicable and Land-Based References' Average Electric Stress Within Cable Insulation at DC U_w vs. U_n for AC or DC Systems



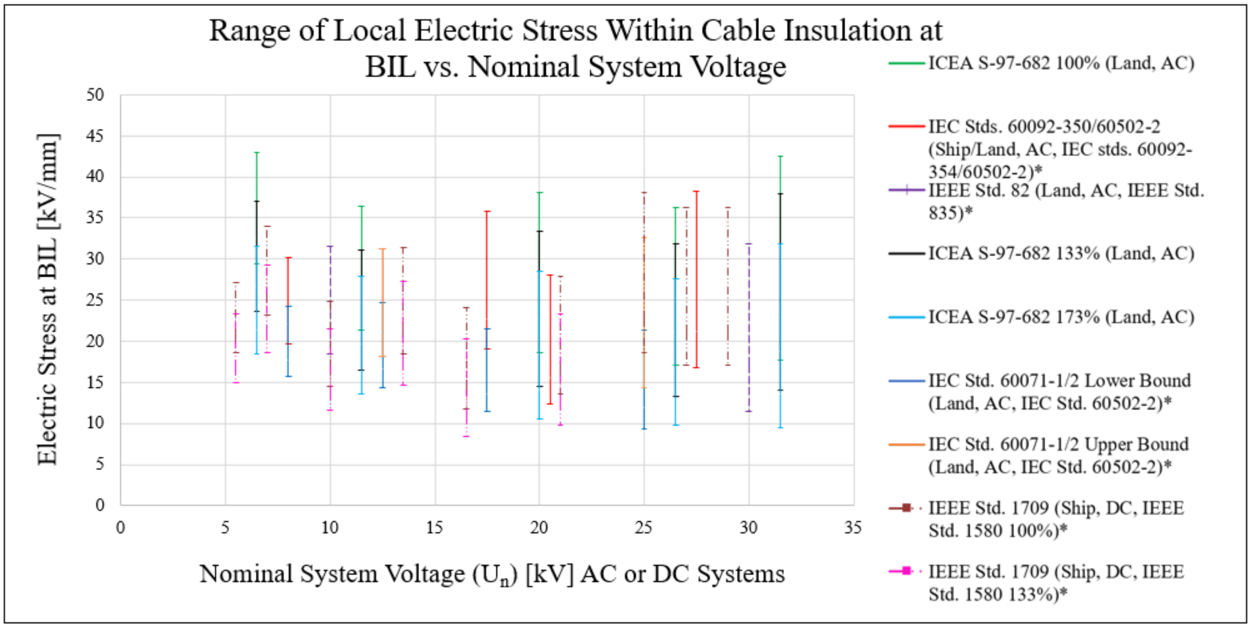
*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).
Note: Insulation thickness used for the shipboard-applicable BIL from IEEE Std. 1709, which presents recommendations for MVDC cables, comes from IEEE Std. 1580, the shipboard-applicable AC reference from the IEEE as there are no current MVDC insulation thickness recommendations. The average stress from both the 100% and the 133% insulation levels are shown.

Figure 184: Average Electric Stress Within Cable Insulation at BIL vs. U_n for AC or DC Systems



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).
Note: Insulation thickness used for the shipboard-applicable BIL from IEEE Std. 1709, which presents recommendations for MVDC cables, comes from IEEE Std. 1580, the shipboard-applicable AC reference from the IEEE as there are no current MVDC insulation thickness recommendations. The average stress from both the 100% and the 133% insulation levels are shown.

Figure 185: Trendlines of Average Electric Stress Within Cable Insulation at BIL vs. U_n for AC or DC Systems



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).
Note: Insulation thickness used for the shipboard-applicable BIL from IEEE Std. 1709, which presents recommendations for MVDC cables, comes from IEEE Std. 1580, the shipboard-applicable AC reference from the IEEE as there are no current MVDC insulation thickness recommendations. The average stress from both the 100% and the 133% insulation levels are shown.

Figure 186: Minimum and Maximum Electric Stress Within Cable Insulation at BIL vs. U_n for AC or DC Systems

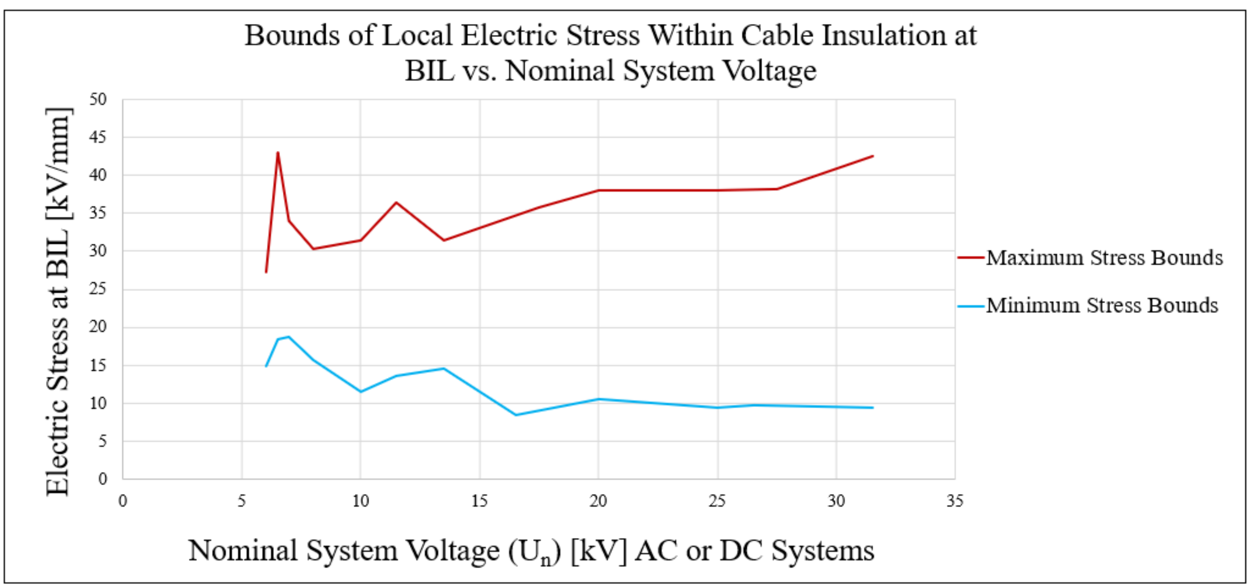


Figure 187: Bounds of Electric Stress Within Cable Insulation at BIL vs. U_n for AC or DC Systems

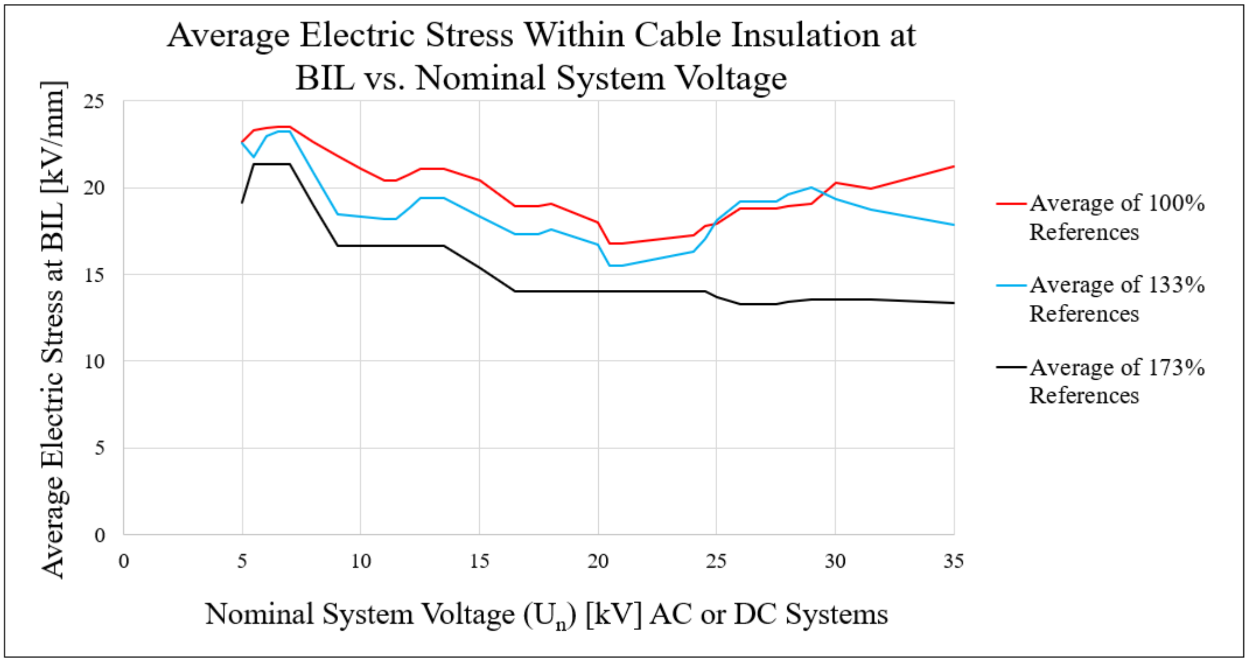


Figure 188: Average of Evaluated References' Average Electric Stress Within Cable Insulation at BIL vs. U_n for AC or DC Systems

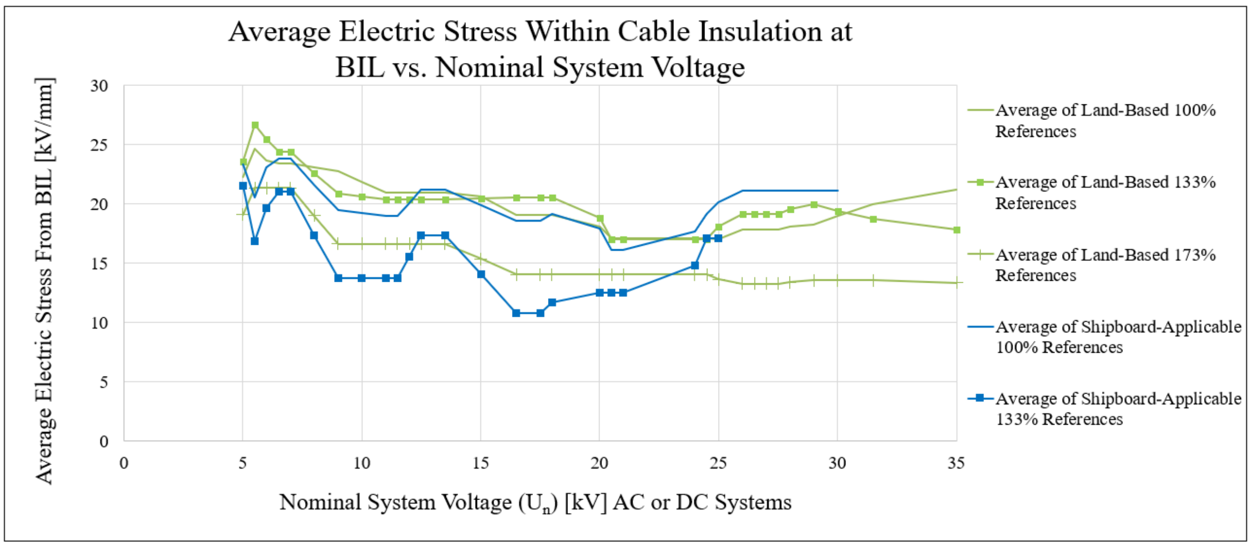
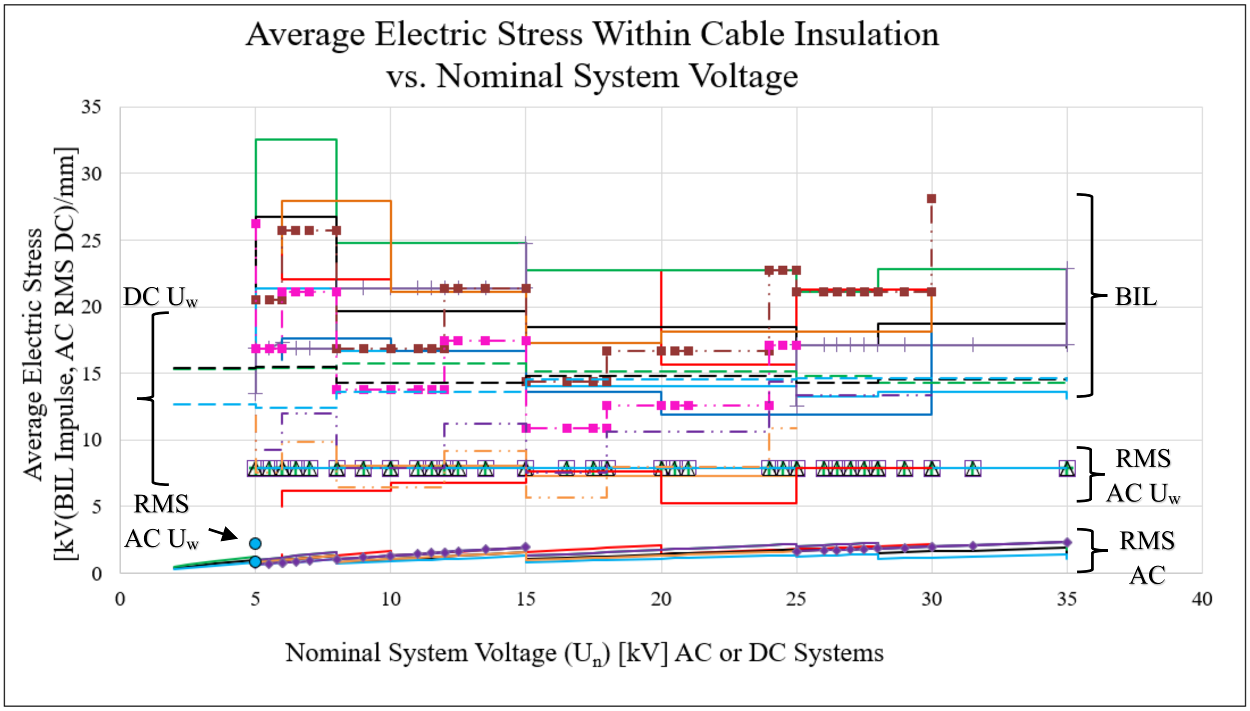


Figure 189: Comparison of Shipboard-Applicable and Land-Based References' Average Electric Stress Within Cable Insulation at BIL vs. U_n for AC or DC Systems

The average electric stresses presented in this section are shown collectively below in Figure 190. The Average of all reference's averages is shown in the following This figure shows the clear difference in scale of stresses caused by Cable Nominal Voltage, Withstand Test Voltage, and BIL.



Note: Legend not shown due to legibility, plotted data is in accordance with preceeding figures.

Figure 190: Average Electric Stress Within Cable Insulation at U_o, RMS AC or DC U_w, and BIL vs. U_n for AC or DC Systems

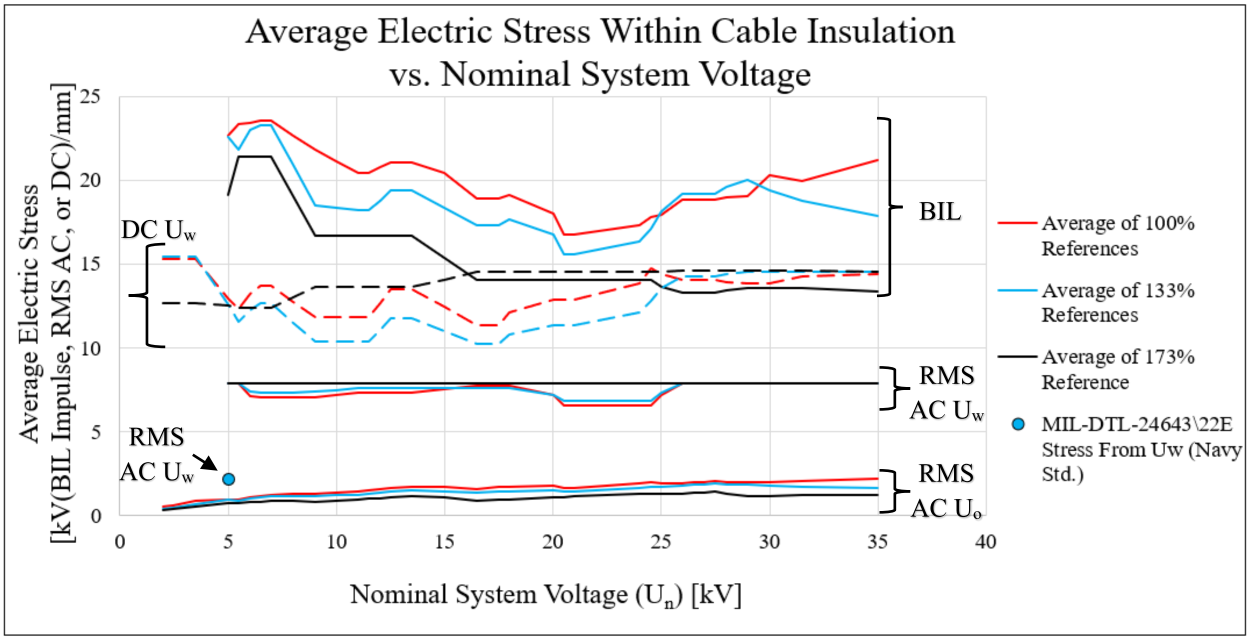


Figure 191: Average of Evaluated References' Average Electric Stress Within Cable Insulation at U_o, RMS AC or DC U_w, and BIL vs. U_n for AC or DC Systems, Three Insulation Levels: 100%, 133% and 173%

A more digestible version of Figure 191 is shown in Figure 192, displaying only the average electrical stresses for the 133% insulation level.

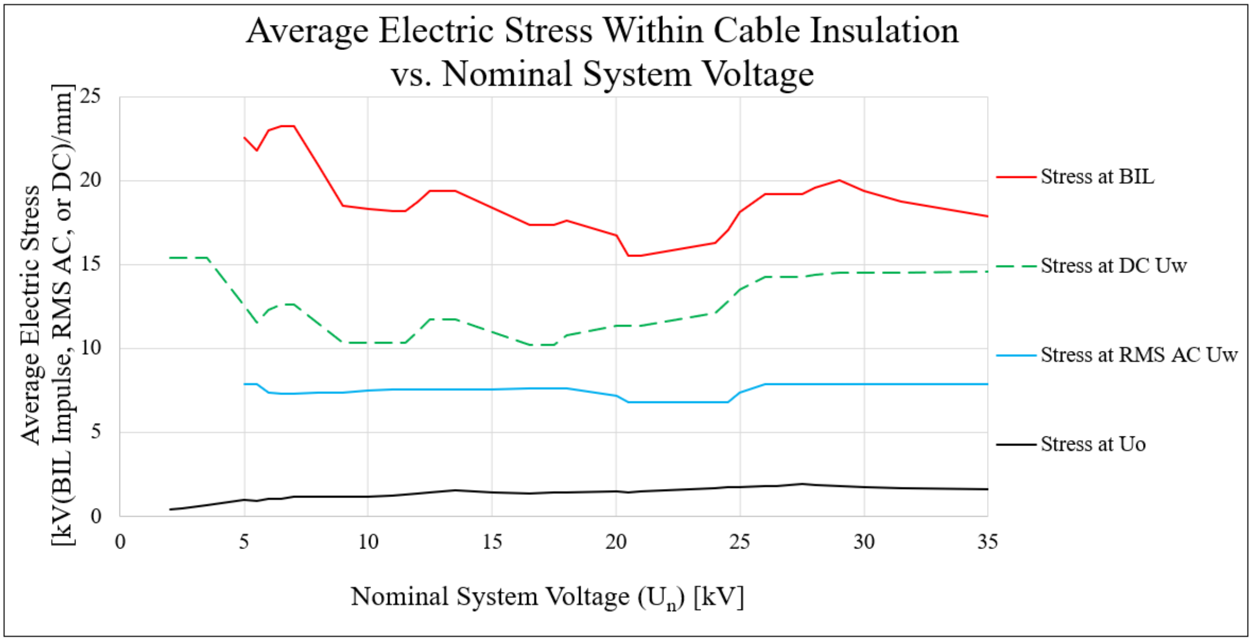


Figure 192: Average of Evaluated References' Average Electric Stress Within Cable Insulation at U_o, RMS AC or DC U_w, and BIL vs. U_n for AC or DC Systems, 133% Insulation Level

The remainder of this section contains the tabulated stresses that has been plotted in Figure 165 - Figure 190. For quick reference, the specified BIL and U_w from IEEE Std. 1580, IEC Std. 60092-354, and ICEA S-97-682 are shown below in Table 34. The cells not highlighted in gray are the test voltages in [kV] for the test and standard described by the gray cells in the same row, with the Nominal system voltage highlighted gray at the top of the column. These values can be found in; Figure 4, Figure 8, Figure 14, Figure 17, Figure 36, Figure 51, Figure 53, Figure 55, and Table 6. Of note ICEA S-97-682, and IEEE Std. 1580 do not specify BIL, nor does the other IEEE shipboard AC standard, IEEE Std. 45.8.

Test Voltage Levels for Acceptance Withstand Tests and BIL Tests [kV] For a 12 [kV] Nominal System Voltage (U_n) RMS AC or DC System				
Reference	Applied Voltage Information			Test Voltage [kV]
IEEE Std. 1580 [28]	RMS AC U_w [kV]	Acceptance, 5 [min]	100%	35
			133%	44
IEEE Std. 82 [34]	BIL [kV]			110
IEEE Std. 1709 [2]	BIL [kV]			75
	DC U_w [kV]	Acceptance, 1 [min]		50
IEC Std. 60092-350/60502-2 [31] [30]	RMS AC U_w [kV]	Acceptance, 5 [min]		30.5
	BIL [kV]			95
IEC Std. 60071-1/2 [4] [32]	BIL [kV]	Lower Bound		75
		Upper Bound		95
ICEA S-97-682 [35]	RMS AC U_w [kV]	Acceptance, 5 [min]	100%	35
			133%	44
			173%	52
	DC U_w [kV]	Acceptance, 15 [min]	100%	70
			133%	80
			173%	90
	BIL [kV]			110

Table 34: BIL, RMS AC and DC U_w Values for a 12 [kV] U_n AC or DC System

The cable insulation electric stress of a cable in a system with a Nominal System Voltage of 12 [kV] due to Cable Nominal Voltage (RMS AC), RMS AC U_w, DC U_w, and BIL shown in Figure 166 through Figure 191 are tabulated in Table 35.

Electric Stress of Insulation in 12 [kV] U_n 3-RMS AC or DC System					
Source of Stress	Reference	Insulation Thickness %	Minimum Stress [kV/mm]	Average Stress [kV/mm]	Maximum Stress [kV/mm]
Cable Nominal Voltage (U_o)	IEEE Std. 1580[a]	100	1.34	1.56	2.29
		133	1.07	1.27	1.99
	IEEE Std. 835[b]	100	1.35	1.56	2.30
	IEC Stds. 60092-354/60502-2[c]	100	1.32	1.54	2.28
	ICEA[d]	100	1.35	1.56	2.30
		133	1.04	1.24	1.96
		173	0.86	1.05	1.76
DC Withstand Voltage (U_w)	IEEE Std. 1709[e]	100	6.79	7.87	11.59
		133	5.39	6.41	10.06
	ICEA[d]	100	13.60	15.75	23.20
		133	12.00	14.32	22.64
		173	11.13	13.63	22.82

Source of Stress	Reference	Insulation Thickness %	Minimum Stress [kV/mm]	Average Stress [kV/mm]	Maximum Stress [kV/mm]
RMS AC Withstand Voltage (U_w)	IEEE Std. 1580[a]	100	6.79	7.87	11.59
		133	6.78	8.06	12.65
	IEC Stds. 60092-350/ 60092-354/ 60502-2[c]	100	5.85	6.78	10.02
	ICEA[d]	100	6.80	7.87	11.60
		133	6.60	7.87	12.45
		173	6.43	7.87	13.19
BIL	IEEE Std. 1709[e]	100	14.56	16.85	24.84
		133	11.55	13.74	21.56
	IEEE Std. 82[b]	100	18.46	21.37	31.49
	IEC Stds. 60092-350/ 60092-354/ 60502-2[c]	100	18.21	21.11	31.22
	IEC Std. 60071-1/2[f]	Lower Bound	14.38	16.67	24.65
		Upper Bound	18.21	21.11	31.22
	ICEA[d]	100	21.38	24.75	36.46
		133	16.50	19.69	31.13
		173	13.61	16.66	27.89

Note: Cable Nominal Voltage (U_o) is defined as the phase-to-ground RMS voltage for AC Systems, or the line-to-ground voltage for DC systems.

[a] Insulation thickness and RMS AC U_w are in accordance with IEEE Std. 1580 [28].

[b] Insulation thickness is in accordance with IEEE Std. 835, BIL is in accordance with IEEE Std. 82 [60] [34].

[c] Insulation thicknesses are in accordance with IEC Stds. 60092-354/60502-2, RMS AC U_w, and BIL are in accordance with IEC Stds. 60092-350/60502-2 [40] [31] [30].

[d] Insulation thickness, RMS AC and DC U_w, and BIL are in accordance with ICEA S-97-682 [35].

[e] Insulation thickness is in in accordance with IEEE Std. 1580, DC U_w and BIL are accordance with IEEE Std. 1709 [28] [2].

[f] Insulation thickness is in accordance with IEC Std. 60502-2, BIL is in accordance with IEC Stds. 60071-1/2 [4] [32] [30].

Table 35: Cable Insulation Electric Stress of Shipboard 12 [kV] U_n (RMS AC and DC) from Nominal System Voltage (U_n), RMS AC and DC Withstand Test Voltage (U_w), and BIL

8.2 Cable System Sizing

Cable system sizing is dependent on multiple parameters. These parameters include the power rating of the system, Nominal System Voltage (U_n), diameter of conductors, thickness of insulation, number of conductors per cable group, cable geometry, and spacing between each cable and their surroundings. The process of cable system design requires selecting values for some parameters, and allowing other parameter set points to be determined by set constraints. This section evaluates the main constraints on cable sizing and outlines a nominal cable design process.

8.2.1 Cable Sizing

By convention and as reflected in all evaluated standards, international and local, the power cable insulation thickness for MV systems is fixed at specific values defined within the standards. These cable insulation thickness values are fixed according to three users selected quantities: the conductor diameter, the Nominal System Voltage (U_n), and the expected ground fault clearing time which forces an increase in insulation thickness often expressed as a percent insulation level. This third quantity by convention has 3 levels if expressed as a percentage: 100% (to be used in systems where ground faults will be cleared within 1 [min]), a larger thickness of 133% (to be used in systems where ground fault clearing times exceed 1 [min] but are less than 60 [min]), and a larger still thickness of 173% (to be used in systems where ground fault clearing times exceed 60 [min]) [27]. Within all evaluated references insulation thickness for a given Nominal System Voltage and percent insulation level was constant for conductor diameters within the range of 8.25-25.4 mm (AWG 1/0-1000 kcmil), and so this range of conductor diameters was used within this study to reduce variables.

By the analysis presented in §7.2 the standardized cable insulation thicknesses result in very similar amounts of electric stress within the cable insulation for each type of test voltage. For example, essentially all the different cables at the various Nominal System Voltages result in average insulation electric stresses for BIL impulse voltage tests that are close to 20 [kV/mm] (shown in Figure 184). While short-term Factory Withstand voltage tests result in insulation electric stresses that are close to 8 [kV/mm] (Figure 166). Furthermore, operation at nominal system voltages cause insulation electric stresses that are close to 1 - 2 [kV/mm] (Figure 172). Furthermore, within the evaluated standards the BIL and Withstand Voltage Test Voltage levels do not impact the size of the MVAC cables. However, the standards seem to imply a linkage between test voltage levels (BIL and U_w) and the insulation thickness, as the step-increases of insulation thickness and test voltage levels occur at the same Nominal System Voltage.

One additional variable is DC versus AC. The MV power cable standards evolved initially for AC systems and have more recently been applied to DC systems. There is less overall in-service experience with DC cables than AC cables, so there may be some future adjustments to standards for DC cable systems. But as of the present the existing MVDC cable standard does not suggest there be any change to the standardization of fixed cable insulation thickness values according to system voltage as is done with MVAC cable systems. Thus, according to the applicable standards, the insulation thicknesses of MV power cables are predetermined by the selection of the Nominal System Voltage (U_n), conductor size, and percent insulation level.

The result of the standardized fixed cable insulation thickness according to nominal system voltage, conductor diameter, and ground fault clearing time is that any change in testing voltage for either BIL or Withstand will only result in a change in electric stress within the cable insulation during that test. If a greater test voltage is chosen, the electric stress will be higher and thereby cause a more severe test. Whereas if a lower test voltage is chosen, a less severe test will result. Without some strong reason and foundation for a change, it appears the standards have converged to acceptable cable insulation thicknesses and test stresses that detect cable weaknesses, yet do not do damage to the cable for MV system voltages.

8.2.2 Cable System Size Design Process

From the evaluations conducted within this study, a sequence of design steps for cable systems that account for key parameters important to cable performance has been developed. This sequence of steps, listed below, provides a suggested cable system design process applicable to shipboard MVDC power cables.

1. **Select design power level.** Typically based on the output requirements of the system, how much power is needed for the equipment the power system is being designed for.
2. **Select Nominal System Voltage.** Selected by considering the output requirements of the system, such as matching the equipment operating voltage or a higher voltage to reduce the required current.
3. **Determine insulation thickness.** Minimum thickness is set by the Nominal System Voltage for a given reference. The percent insulation level (100%, 133% or 173%) is selected based on the expected ground fault clearing time of the system.
4. **Selected cable environment, insulation material, number of cables per group, and spacing.** The ambient temperature, insulation material, number of cables per group, and cable group spacing from other cable groups and surfaces.
5. **Calculate conductor ampacities.** Based on the selected cable group environment, the ampacity of a single cable group can be calculated for each size of conductor.
6. **Determine maximum length of cable system.** Determined by the system the cables will be used within. For a shipboard system, this would be the longest cable required for the design.
7. **Select maximum allowable voltage drop.** The maximum voltage drop is a systems requirement and impacts the allowed series resistance of the conductor and hence the required conductor area according to the length of cable.
8. **Calculate number of cable groups required**. Calculated by dividing the maximum power of the cable system by the maximum power per cable group. Can be calculated for each size of conductor being evaluated.
9. **Determine cross-sectional and volumetric requirements**. The cable way cross-sectional area for each conductor size is calculated using the calculated number of cables, the selected cable group geometry, and cable group spacing. This area is multiplied by the selected maximum length of cable system for an estimate of the total volume required for the cable system.
10. **Select testing voltage levels and calculate resultant electrical stresses.** A Withstand Test Voltage level and BIL are selected, as well as the duration of the withstand test. It is then determined if the resultant calculated electrical stresses within the insulation are acceptable.

During this design process there is the potential to optimize the resultant dimensions of the full cable system. The resultant system size can be calculated and compared for each conductor size within the range of allowable conductor sizes to find a local minimum.

9.0 Example MVDC Shipboard Cable Designs

This section works through an MVDC Shipboard cable design example, following the 10 steps outlined in §8.2.2 with a subsection for each step.

9.1 Selection of Design Power Level

With the growing power demand from nearly every onboard system of future warships, particularly the electric propulsion and high-load weapon systems, a future MVDC ship would likely need significantly more power available than current warships. To meet this need, this example will be of a ship with 75 [MW] maximum power available.

9.2 Selection of Design Nominal System Voltage

Potential future Nominal System Voltages for USN shipboard bus power cable systems include 6, 12, and 18 [kV] systems [5]. The focus of this study is to evaluate and make potential recommendations for bus power cables with a 12 [kV] Nominal System Voltage, and so 12 [kV] is selected for this example.

9.3 Determination of Insulation Thickness

USN shipboard cable systems have the potential for ground fault clearing times to exceed 1 [min]. Additionally, an increased factor of safety to reduce the chance of insulation failure is beneficial as replacing cables is not possible while deployed and difficult while in port. Due to these factors, a 133% insulation level is selected for this example. The average of MVAC shipboard 133% insulation levels from §7.2 is used for this example, 4.98 [mm].

9.4 Selection of Cable Environment, Insulation Material, Number of Cables per Group, and Spacing

For this example, the cable environment is selected to be the overhead area of an internal ship deck, with an ambient temperature of 45 [°C] and insulated with XLPE. These parameters are selected to correspond to standard ampacity values as established in §7.3. To reduce electro-magnetic signatures, 4-cable (2 pairs of +/- conductor pairs) groups are used [5]. Cable groups are spaced in accordance with IEEE Std. 45.8, with 2.15 times the diameter of a single cable between any 2 groups [27]. Cables are spaced half this distance (1.075 times a single cable diameter) from any surface of the ship, approximating appropriate spacing using the method of imaging. With the spacing guidelines from IEEE Std. 45.8 being for MVAC 3-cable groups, a thorough heat transfer analysis and adjustment of spacing is warranted. Table 36 summarizes these selected values.

Cable Parameter	Selected Value
Ambient Temperature	45 [°C]
Cable Insulation Material	XLPE
Number of Cables per Group	4
Spacing of Cable Groups from other Cable Groups	2.15 x Single Cable Diameter
Spacing of Cable Groups from Surfaces	1.075 x Single Cable Diameter

Table 36: Selected Cable Environment, Insulation Material, Number of Cables per Group, and Spacing

9.5 Calculation of Conductor Ampacities

For the number of cables per cable grouping, this example evaluates 4-cable groups. 4-cable groups (2 pairs of 2 cables of opposite polarities) are likely to be used for future USN shipboard MVDC systems to minimize magnetic signatures [5]. Evaluated references such as IEEE Std. 45.8 provide ampacity ratings for MVAC cables with the specified environmental factors in Table 36, but only for single cables or 3 cable groups [27]. An adjustment factor or equation is not given to determine the ampacity for a 4-cable group, or for DC cables. Some reports address this issue with an adjustment factor based on equal heat produced per cable group [5]. Thus the 4-cable DC group is constrained to have the same ampacity as a corresponding 3-cable AC group. This appears to be a conservative constraint. This example utilizes a similar the heat per cable group approach, outlined below.

1. Calculate the heat per cable group produced in an equivalent U_n AC system with a 3-cable group, using Equation 6 below. Resistance values based on conductor size from the National Electric Code adjusted to 90 [°C] operating temperature were used, as this is the maximum rated temperature for XLPE insulation [59].

$$I_{AC_{SingleCable}} = AC\ Current\ per\ Cable[Amp]$$

$$R_{AC} = Cable\ Resistance\ to\ AC\ Current\ [\frac{\Omega}{km}]$$

$$HeatProduced_{AC_{ThreeCableGroup}}\ [\frac{W}{km}] = 3 * I^2_{AC_{SingleCable}} * R_{AC} \tag{6}$$

Equation 6: Heat Produced Per AC Cable Group

2. Set up the base equation for the heat per cable group produced from a DC 4-cable group. Resistance values based on conductor size from the National Electric Code adjusted to 90 [°C] operating temperature were used [59].

$$I_{DC_{SingleCable}} = DC\ Current\ per\ Cable[Amp]$$

$$R_{DC} = Cable\ Resistance\ to\ DC\ Current\ [\frac{\Omega}{km}]$$

$$HeatProduced_{DC_{FourCableGroup}}\ [\frac{W}{km}] = 4 * I^2_{DC\_SingleCable} * R_{DC} \tag{7}$$

Equation 7: Heat Produced Per DC Cable Group

3. Set Equation 6 equal to Equation 7 to solve for I_{DC} for each conductor diameter that would result in a similar heat production.

$$3 * I^2_{AC_{SingleCable}} * R_{AC} = 4 * I^2_{DC_{SingleCable}} * R_{DC}$$

$$I^2_{DC_{SingleCable}} = \frac{3 * R_{AC}}{4 * R_{DC}} * I^2_{AC_{SingleCable}}$$

$$I_{DC_{SingleCable}} = \sqrt{\frac{3R_{AC}}{R_{DC}}} * \frac{I_{AC_{SingleCable}}}{2} \tag{8}$$

Equation 8: I_{DC} proportional relationship to I_{AC} for MV Cables

4. Resistance to alternating current is different than resistance to direct current due to the skin effect, a phenomenon in which more current flows at the outer surface of the conductor than in the center [5]. MIL-HDBK-299 presents a method of calculating a skin effect ratio for AC resistance based on the DC resistance of the conductor and the frequency of the AC [63]. Using this method, for conductors with diameters in the range of 8.25 [mm] – 25.4 [mm] and a 60 [Hz] frequency, the AC resistance is equivalent to the DC resistance. This results in Equation 9 below.

$$I_{DC_{SingleCable}} = \frac{\sqrt{3}}{2} * I_{AC_{SingleCable}} \tag{9}$$

Equation 9: $I_{DCSingleCable}$ proportional relationship to $I_{ACSingleCable}$, with 8.25-25.4 [mm] Diameter Conductors and 60 [Hz] AC

5. The total power of a MVDC 4-cable group is obtained by multiplying the Nominal System Voltage by double the I_{DC} calculated in Equation 9, as there are 2 pairs of the 2 required cables of each polarity within each 4-cable group. This results in Equation 10 below.

$$I_{DC_{SingleCable}} = Current\ Per\ Cable\ [Amp]$$

$$V_{LL}(Line - to - Line\ Voltage) = Nominal\ System\ Voltage\ (U_n)\ [V]$$

$$P_{DC_{SingleCablePair}}(Power\ of\ a\ Pair\ of\ Cables\ in\ a\ DC\ System) = I_{DC_{SingleCable}} * U_n\ [W]$$

$$P_{DC_{FourCableGroup}}(Power\ of 2\ Pairs\ of\ 2\ Cables\ in\ a\ DC\ System) = 2 * P_{DC_{SingleCablePair}}\ [W]$$

$$P_{DC_{FourCableGroup}} = 2 * I_{DC_{SingleCable}} * U_n = 2 * \frac{\sqrt{3}}{2} * I_{AC_{SingleCable}} * U_n = \sqrt{3} * I_{AC_{SingleCable}} * U_n \tag{10}$$

Equation 10: Power of a 4-Cable Group in an MVDC Cable System, with 8.25-25.4 [mm] Diameter Conductors and 60 [Hz] AC

Based on this approximation for DC cable ampacity keeping the heat produced per cable constant, Equation 1 equals Equation 10. This conservative approach means the power carried by an AC 3-cable group is equivalent to a DC 4-cable group.

The resultant amount of power carried by a DC 4-cable group can thus be determined from Equation 10. Table 37 below shows the calculated MVDC single cable ampacities, using the average shipboard MVAC ampacity ratings for 3-conductor cables from §7.3.1 Figure 160, the single cable ampacity for a DC cable in a 4-cable group using Equation 9, and the resultant power of a DC 4-cable group in a 12 [kV] U_n system using Equation 10.

Individual Conductor AWG Size	Individual Conductor Diameter [mm]	Single Cable AC Ampacity for a 3-Cable Group ($I_{ACSingleCable}$ [Amp]), From §7.3.1 Shipboard Average	Single Cable DC Ampacity for a 4-Conductor Cable Group, $I_{DCSingleCable}$ [Amp]	Total 4-Cable Group Power, $P_{DC4CableGroup}$ [MW]
1/0	8.25	216	187	4.49
2/0	9.27	243	210	5.05
3/0	10.4	257	223	5.34
4/0	11.68	300	260	6.24
250	12.70	332	288	6.90
350	15.03	416	360	8.65
400	16.06	456	395	9.48
500	17.96	523	453	10.87
600	19.67	561	486	11.66
700	21.25	635	550	13.20
750	22.00	665	576	13.82
800	22.72	703	609	14.61
900	24.10	734	636	15.26
1000	25.40	755	654	15.69

Table 37: MVDC Cable Ampacities and Resultant 4-Cable Group Power Based on Average of Evaluated References' MVAC 3-Cable Group Ampacities

9.6 Determination of Maximum Length of Cable System

Modern USN Destroyers are ~183 [m] (600 [ft]) in length [66]. While a cable would not run the full length from bow to stern of the vessel, using this length as a maximum length may be appropriate. The longest cables run from the engine rooms to the furthest corners of the ship, but do not do so in a straight line. For this study a maximum cable length of 200 [m] is used.

9.7 Selection of Maximum Allowable Voltage Drop

The only standard evaluated that contained guidance for maximum allowable voltage drop is IEC Std. 60092-201. This general standard for shipboard electrical system design specifies in §36.1 that "the cross-sectional areas of conductors shall be so determined that the drop in the voltage from the main or emergency switchboard bus-bars to any and every point on the installation when conductors are carrying the maximum current under normal conditions of service, does not exceed 6 % of the nominal [system] voltage" [62]. Therefore, this example will use a conductor size such that the voltage drop in a 12[kV] system with 8334 [Amp] over 180 [m] is ≤ 6%, or 0.72 [kV].

The National Electric Code contains Table 8, which provides direct current resistance for conductors operating at 75 [°C] based on the conductor size with and without a coating [59]. For this example, a maximum allowable operating temperature of 90 [°C] will be used. An equation for adjusting the operating temperature is given in the notes of the table. The resistances are given with units of [Ω/km], equivalent to [V/Amp-km]. A summary of these DC resistances for tin coated copper conductors operating at 90 [°C] are provided below in Table 38.

Individual Conductor AWG Size	Individual Conductor Diameter [mm]	R_{DC} [Ω/km]
1/0	8.25	0.4351
2/0	9.27	0.3449
3/0	10.4	0.2736
4/0	11.68	0.2149
250	12.70	0.1838
350	15.03	0.1313
400	16.06	0.1137
500	17.96	0.0911
600	19.67	0.0767
700	21.25	0.0652
750	22.00	0.0607
800	22.72	0.0570
900	24.10	0.0504
1000	25.40	0.0455

Table 38: NEC Direct Current Resistances for Coated Copper Conductors Operating at 90 [°C] [59]

Using these NEC DC resistance values, Equation 11 below can be used to calculate the percentage voltage drop within a conductor. This equation has a factor of 2 to account for the voltage drop in both the positive and negative poles.

$$L = Maximum\ Length\ of\ Cable\ [km]$$

$$I_{DC_{SingleCable}} = Maximum\ Current\ Per\ Conductor\ [Amp]$$

$$R_{DC} = DC\ Resistance\ [\frac{\Omega}{km}]$$

$$U_n = Nominal\ System\ Voltage\ [V]$$

$$\%VD = \frac{2 * L * I_{DC_{SingleCable}} * R_{DC}}{U_n} * 100\% \tag{11}$$

Equation 11: Percentage Voltage Drop

Using the maximum length of the cable system determined in §9.6 (0.2 [km]) and maximum current per conductor determined in §9.5 (single cable DC ampacities), the percentage voltage drop can be calculated. If the calculated percentage voltage drop exceeds 6 %, then the DC Resistance (R_{DC}) exceeds the allowable resistance for this system, and that size of conductor will not be feasible. Table 39 below shows the percentage voltage drop for this system with conductor diameters in the range of 8.25-25.4 [mm].

AWG Size	Conductor Diameter [mm]	Voltage Drop (%)
1/0	8.25	0.266
2/0	9.27	0.243
3/0	10.4	0.222
4/0	11.68	0.202
250	12.70	0.191
350	15.03	0.168
400	16.06	0.151
500	17.96	0.134
600	19.67	0.122
700	21.25	0.107
750	22.00	0.111
800	22.72	0.115
900	24.10	0.103
1000	25.40	0.106

Table 39: Percent Voltage Drop for Conductors in a 75 [MW], 12 [kV] U_n System, With a 200 [m] Maximum Cable Length, and DC Ampacities from Table 37

Table 39 above shows that any conductor with diameters between 8.25-25.4 [mm] would result in ≤ 6% voltage drop within this example system and be in compliance with IEC Std. 60092-201 [62].

9.8 Calculation of Number of Required Cable Groups

The number of required cable groups is determined by dividing the maximum power required for the cable system by the calculated maximum power per 4-cable group. The maximum power required for the cable system was determined to be 75 [MW] in §9.1. The maximum power per 4-cable group is shown in the far-right column of Table 37 in §9.5. The resultant number of required 4-cable groups for cables with a diameter within the range of 8.25-25.4 [mm] are shown below in Table 40.

AWG Size	Conductor Diameter [mm]	Power Per 4-Cable Group [MW]	Required Number of 4 – Conductor Cable Groups
1/0	8.25	4.49	17
2/0	9.27	5.05	15
3/0	10.4	5.34	15
4/0	11.68	6.24	13
250	12.70	6.90	11
350	15.03	8.65	9
400	16.06	9.48	8
500	17.96	10.87	7
600	19.67	11.66	7
700	21.25	13.20	6
750	22.00	13.82	6
800	22.72	14.61	6
900	24.10	15.26	5
1000	25.40	15.69	5

Table 40: Required Number of 4-Cable Groups for 75 [MW] System Power at 12 [kV] U_n, Power Per 4-Cable Group from Table 32

9.9 Determination of Cross-Sectional Area

For this example, the IEEE Std. 45.8 spacing guidance is used, requiring a spacing between cable groups of 2.15 times the diameter of a single insulated cable [27]. Additionally, “Installation of cables beyond double banking is not recommended for any cables”, so only single and double-banked geometries are used [27].

The diameter of a single insulated cable, and a resultant 4-cable group is calculated for each conductor size using the construction guidance within MIL-DTL-24643/86, which outlines the construction of a 3-cable group in a 5 [kV] U_n 3-phase MVAC system. [58]. Each conductor will be wrapped in the following concentric layers:

- Semi-conducting tape, assumed to be 5 [mils] (0.127 [mm]) [5]
- XLPE insulation, with thickness determined in §9.3
- Silicone rubber or fiberglass tape, with a minimum thickness of 0.08 [in] (2.032 [mm]) [58]
- Two or more cross-lapped semi-conducting tapes, with a total minimum thickness of 0.01 [in] (0.254 [mm]) [58]

Each 4-cable group diameter is calculated in a similar manner, following the construction requirements of a 3-cable group outlined by MIL-DTL-24643/86, adjusted for a 4-cable group. Each 4-cable group will be wrapped in the following concentric layers [58]:

- Semi-conducting tape, assumed to be 5 [mils] (0.127 [mm]) [5]
- Braided 34 AWG shielding, 16 [mils] (0.4064 [mm]) [5]
- Polyester tape, assumed to be 5 [mils] (0.127 [mm]) [5]
- Cross-linked polyolefin jacket, with a minimum thickness of 0.09 [in] (2.286 [mm]) [58]

Figure 193 shows a cross-sectional view of a cable group constructed according to the above guidance.

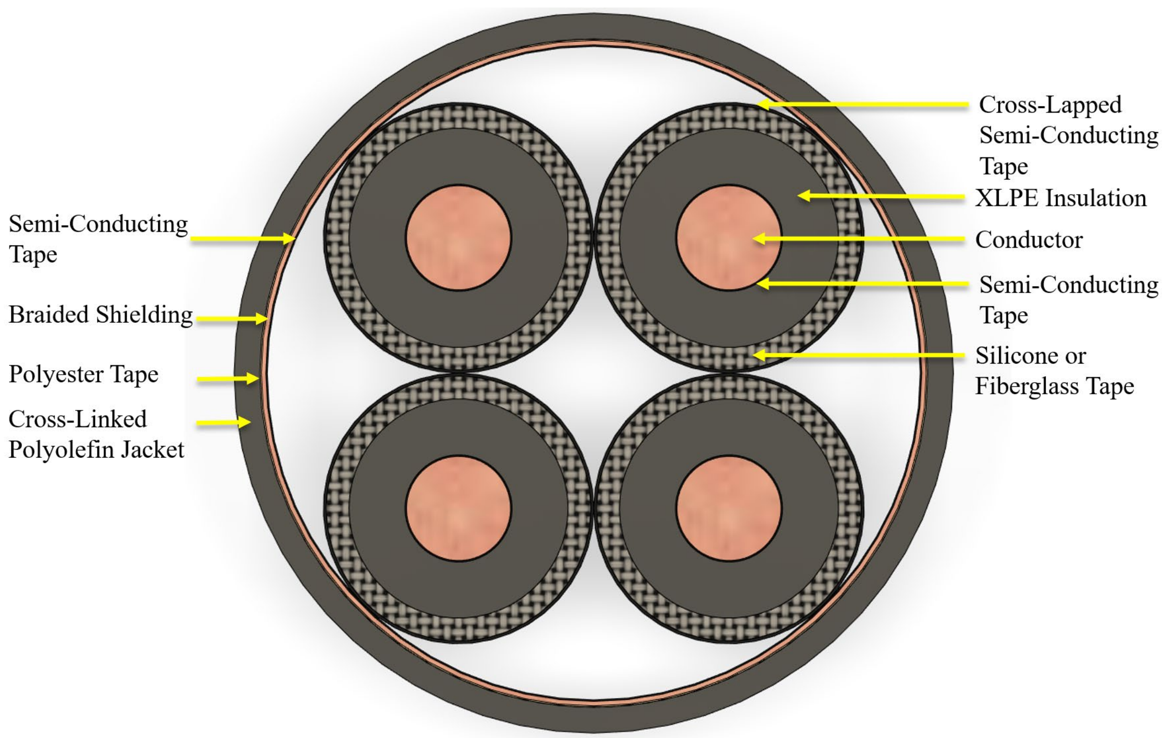
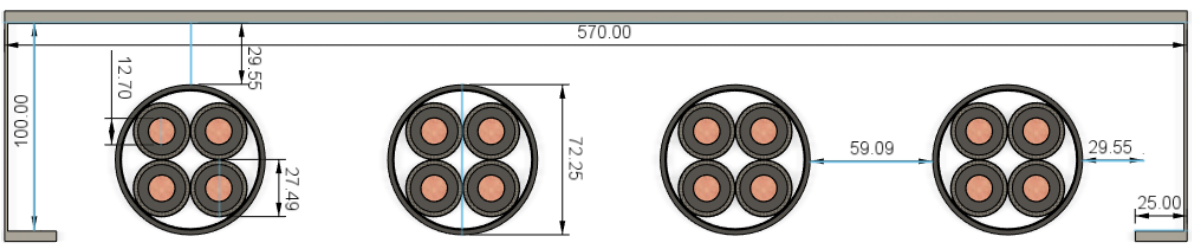


Figure 193: Cross-Sectional View of Completed Cable Group

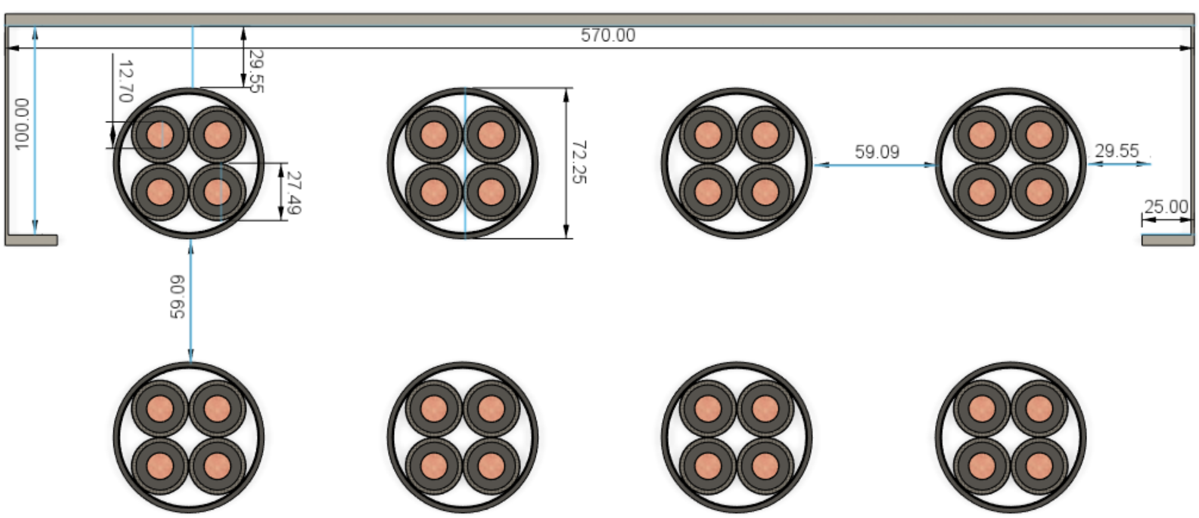
On a typical ship, cable ways run in-between either the overhead or bulkhead stiffeners. Therefore, the width of a shipboard cableway can be constrained by the spacing of these stiffeners when cables are placed in this region. This spacing varies considerably depending on the ship in question, and so for this example the overhead stiffener spacing of 570 [mm] is used, with a stiffener web length of 100 [mm] and flange length of 50 [mm]. For this example, the cable way will be restricted to the 2 areas between 3 adjacent stiffeners.

The area required for the cable system is determined by taking the number of required cable groups and creating a rectangular grid of cable groups with the required spacing. As covered in §9.4, cable groups are spaced 2.15 times the diameter of a single insulated cable from other cable group and 1.075 times the diameter of a single cable from any surface (the deck plate and stiffener web in this example). For this example, if possible it is considered ideal to keep the cable bank between a single pair of stiffeners, with the total area minimization being the second priority. If a single-banked (single row) configuration is wider than the stiffener spacing of 0.575 [m], the cable way will be double-banked between stiffeners (a grid of two rows and as many columns as required). As IEEE Std. 45.8 does not allow for more than 2 rows of banked cable groups, if a third or fourth row is required then the area between the next adjacent stiffener will be used for the required cables. If a fifth or more rows are needed for a given conductor size, that design is considered invalid. "Region-1" and "Region-2" for this example refer to the area between the 1st and 2nd adjacent stiffeners, and the 2nd and 3rd adjacent stiffeners, respectively. These configurations are illustrated below in Figure 194, for cables with a 12.7 [mm] conductor diameter in 12 [kV] U_n Systems with 25, 50, 75, and 100 [MW] power levels and all required spacing shown.



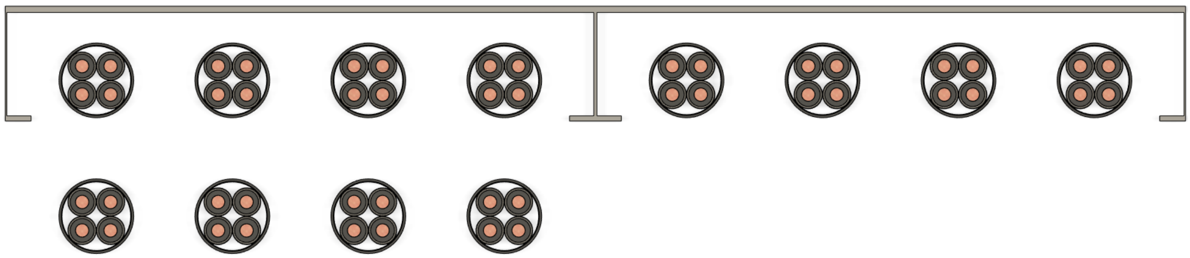
Note: All units measurements in [mm]

(a) Cable Group System with a Single-Banked Geometry, 12.7 [mm] conductor, 12 [kV] U_n, 25 [MW] Power Level

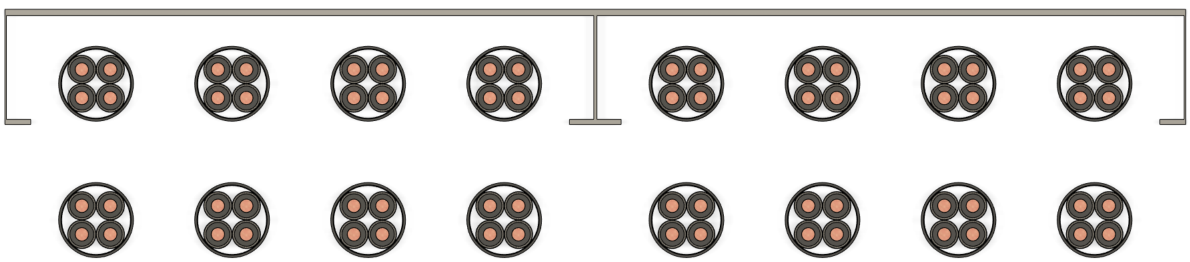


Note: All units measurements in [mm]

(b) Cable Group System with a Double-Banked Geometry, 12.7 [mm] conductor, 12 [kV] U_n, 50 [MW] Power Level



(c) Cable Group System with a Double-Banked Geometry, 12.7 [mm] conductor, 12 [kV] U_n, 75 [MW] Power Level



(d) Cable Group System with a Double-Banked Geometry, 12.7 [mm] conductor, 12 [kV] U_n, 100 [MW] Power Level

Figure 194: Cable Grid Geometry Constraints for a 12 [kV] U_n, 25 and 50 [MW] System

An estimate for the total volume required is then calculated by multiplying the required cross-sectional area of the cable way by the maximum length of the cable system. The resultant area and volume required for each conductor diameter within the range of 8.25-25.4 [mm] is calculated and shown with the characteristics of each size conductor's cable system is shown in Table 41. In this table any designs that could fit within a single pair of stiffeners, Region-1, are the highest priority (as seen in the Cable Grid Geometry column, with the Region-2 geometry listed as "N/A"). The second priority is minimum required cross-sectional area. Minimum area is desired for this example, as space on a ship is extremely limited and the extra space between the stiffeners could be put to another use. The best design following these given constraints is highlighted in blue in Table 41. The calculations for the cable grid geometry resulting in minimum cross-sectional area or minimum height, and resultant system mass are shown in Appendix A.

Conductor Diameter	Number of Cable Groups Required	Cable Grid Geometry	Minimum Cable Spacing	Cable Way Heights	Cable Way Widths	Total Cable Way Cross-sectional Area	Total Cable System Volume
[mm]	#	Row x Column (Region-1, Region-2)	[mm]	[m] (Region-1, Region-2)	[m] (Region-1, Region-2)	[m^2] (Total)	[m^3]
8.25	17	2x5, 2x4	49.52	0.197, 0.197	0.556, 0.444	0.197	39.43
9.27	15	2x4, 2x4	51.72	0.206, 0.206	0.463, 0.463	0.190	38.04
10.4	15	2x4, 2x4	54.15	0.215, 0.215	0.483, 0.483	0.208	41.50
11.68	13	2x4, 2x3	56.90	0.225, 0.225	0.507, 0.380	0.199	39.89
12.70	11	2x4, 1x3	59.09	0.233, 0.102	0.525, 0.394	0.163	32.52
15.03	9	2x4, 1x1	64.10	0.252, 0.110	0.570, 0.142	0.159	31.73
16.06	8	2x3, 1x2	66.32	0.260, 0.114	0.440, 0.293	0.148	29.56
17.96	7	2x3, 1x1	70.40	0.276, 0.120	0.466, 0.155	0.147	29.41
19.67	7	2x3, 1x1	74.08	0.289, 0.126	0.490, 0.163	0.162	32.43
21.25	6	2x3, N/A	77.47	0.302, N/A	0.511, N/A	0.154	30.87
22.00	6	2x3, N/A	79.09	0.308, N/A	0.521, N/A	0.161	32.12
22.72	6	2x3, N/A	80.64	0.314, N/A	0.531, N/A	0.167	33.34
24.10	5	2x3, N/A	83.60	0.325, N/A	0.550, N/A	0.179	35.75
25.40	5	2x3, N/A	86.40	0.335, N/A	0.568, N/A	0.191	38.10

Note: Region-1 and Region-2 correspond to the areas between the 1st and 2nd adjacent stiffeners, and the 2nd and 3rd adjacent stiffeners, respectively.

Table 41: Volumetric Requirements of a 75 [MW] 12 [kV] U_n Shipboard Cable System based on Conductor Sizing, 200 [m] Cable Way Length

The data shown in Table 41 is displayed graphically in Figure 195.

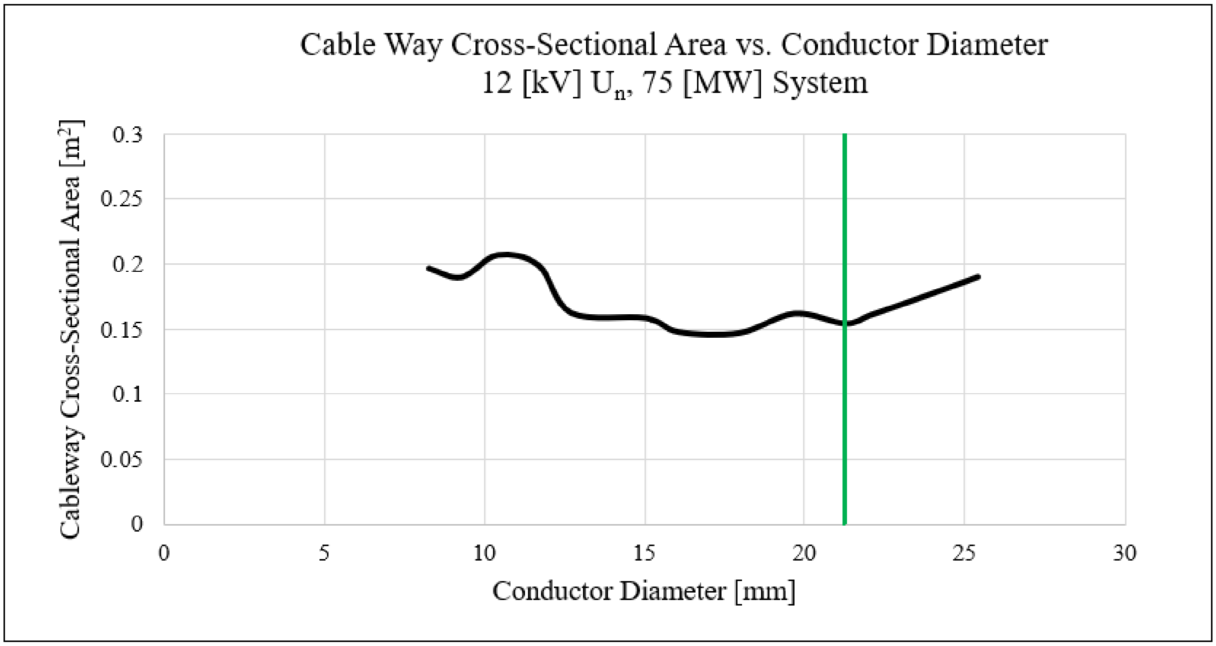


Figure 195: Cableway Cross-Sectional Area for a 12 [kV] U_n 75 [MW] System versus Conductor Diameter

The vertical green line in Figure 195 highlights the cableway cross-sectional area corresponding to a 21.25 [mm] diameter conductor, which is the selected size for this example with the given prioritizations and constraints. There are other conductor diameters that result in a slightly lower total area (e.g., 16.06 [mm] which results in a 0.148 [m^2] cableway area), however this size was not selected due to the prioritization of limiting the cables to region-1 if possible. The area monotonically increasing starting at 21.25 [mm] indicates that the selected conductor diameter is the first size in which it is possible to meet the power requirements within a single area. At conductor sizes smaller than 21.25 [mm], the heights and widths of both region-1 and region-2 have steps corresponding to a change in the cable grid geometry, causing the inconsistent changes in the cableway's cross-sectional area.

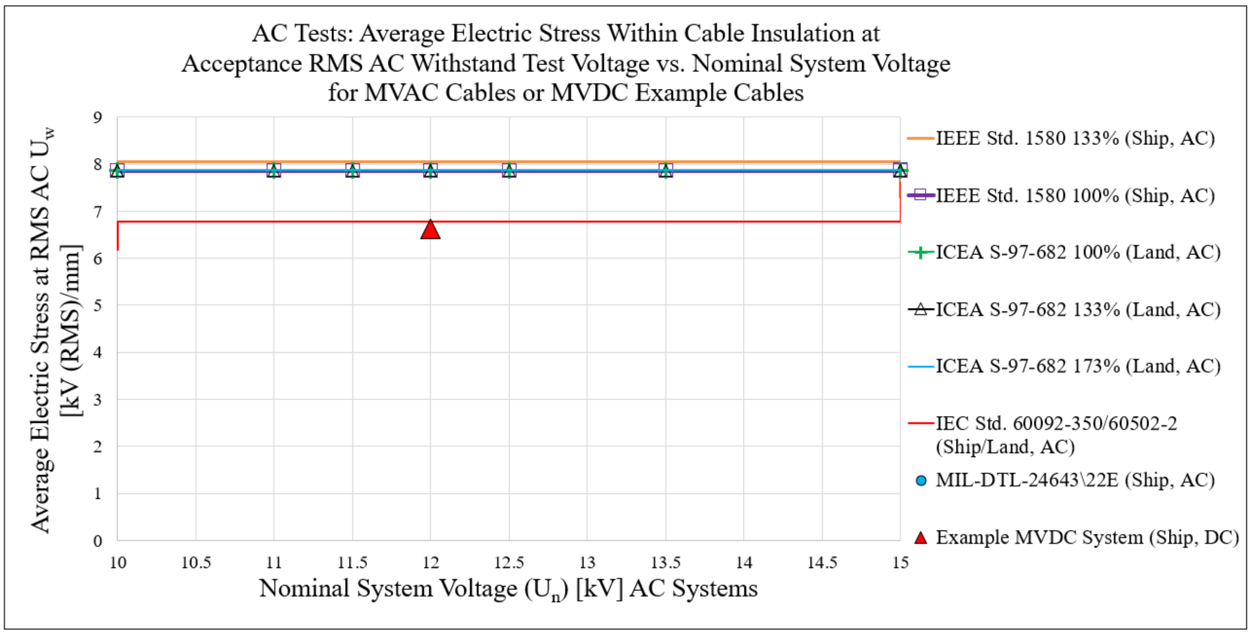
9.10 Selection of Test Voltages and Resultant Electrical Stress

For this example cable system, the test voltages for BIL and factory Acceptance RMS AC and DC Withstand Tests were determined by taking the average of the minimum and maximum voltages from the shipboard-applicable test voltages shown in Table 12a and Table 13a in §6.0, with BIL rounded to the nearest 5 [kV]. This calculation results in a BIL of 95 [kV], and factory Acceptance RMS AC and DC Withstand Test Voltages of 33 and 43.9 [kV], respectively. The recommended duration for both factory Acceptance Withstand Tests is 5 [min], based on the duration of the maximum shipboard-applicable factory Acceptance Withstand Test durations from Table 12a.

These test voltages were used to calculate the electrical stresses within the cable insulation at each respective voltage. The minimum and maximum voltages from the shipboard-applicable test voltages shown in Table 12a and Table 13a in §6.0, as well as the calculated average voltage were used with Equation 5 to calculate the resultant stresses within the cable insulation at these voltages and displayed in Table 42. This example is constrained to use the insulation thickness of 4.98 [mm] determined in §9.3 from the average of all shipboard 133% insulation thickness references. Figure 196 through Figure 198 show how the average stresses at BIL and U_W compare to those of the standards presented in §8.1. The legends of these figures contain the name of the references plotted, as well as the applicability of the reference to either land-based or shipboard systems, the current type of the system being designed (AC or DC), and if the insulation thickness used comes from a different standard.

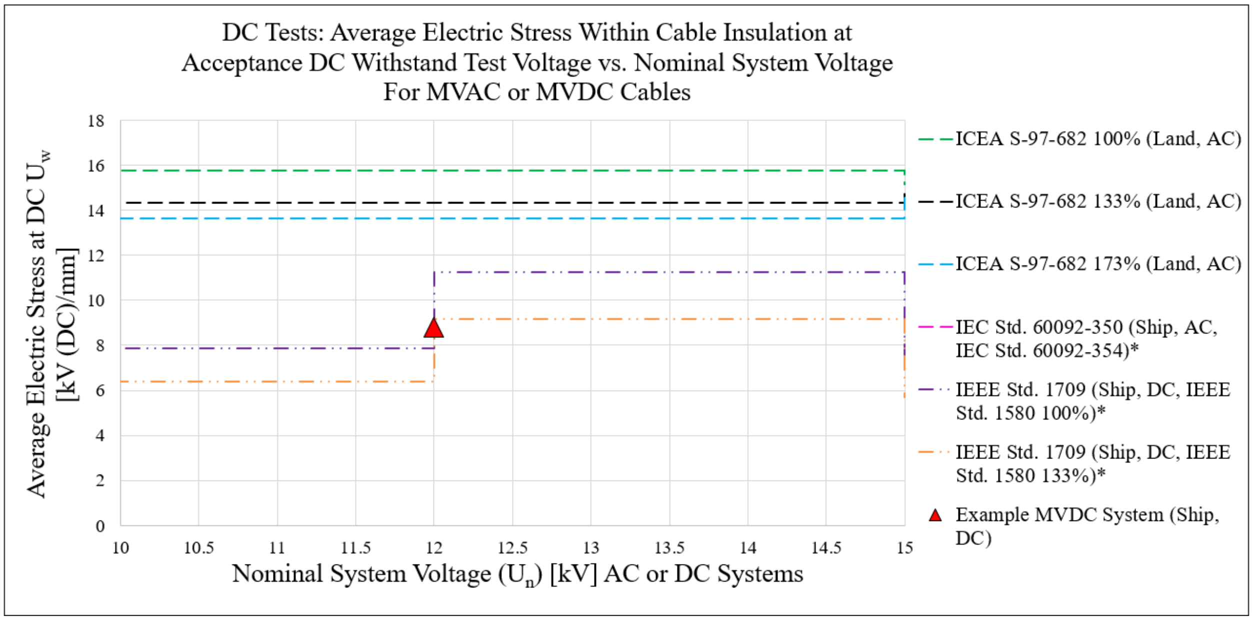
Average Electric Stresses Within Insulation for Example MVDC Cable System with a 12 [kV] U_n								
Average Electric Stress Within Insulation at Acceptance RMS AC U_W [kV/mm]			Average Electric Stress Within Insulation at Acceptance DC U_w [kV/mm]			Average Electric Stress Within Insulation at BIL [kV/mm]		
Min. Standard (22 [kV]) [31]	Average (33 [kV])	Max. Standard (44 [kV]) [28]	Min. Standard (35 [kV]) [2]	Average (43.9 [kV])	Max. Standard (52.8 [kV]) [31]	Min. Standard (75 [kV]) [36]	Average (95 [kV])	Max. Standard (110 [kV]) [2]
4.42	6.63	8.84	7.03	8.82	10.60	15.06	19.08	22.09

Table 42: Average Electric Stresses Within Insulation at Acceptance AC U_w and BIL for Example MVDC Shipboard Cable System with a 12 [kV] Nominal System Voltage



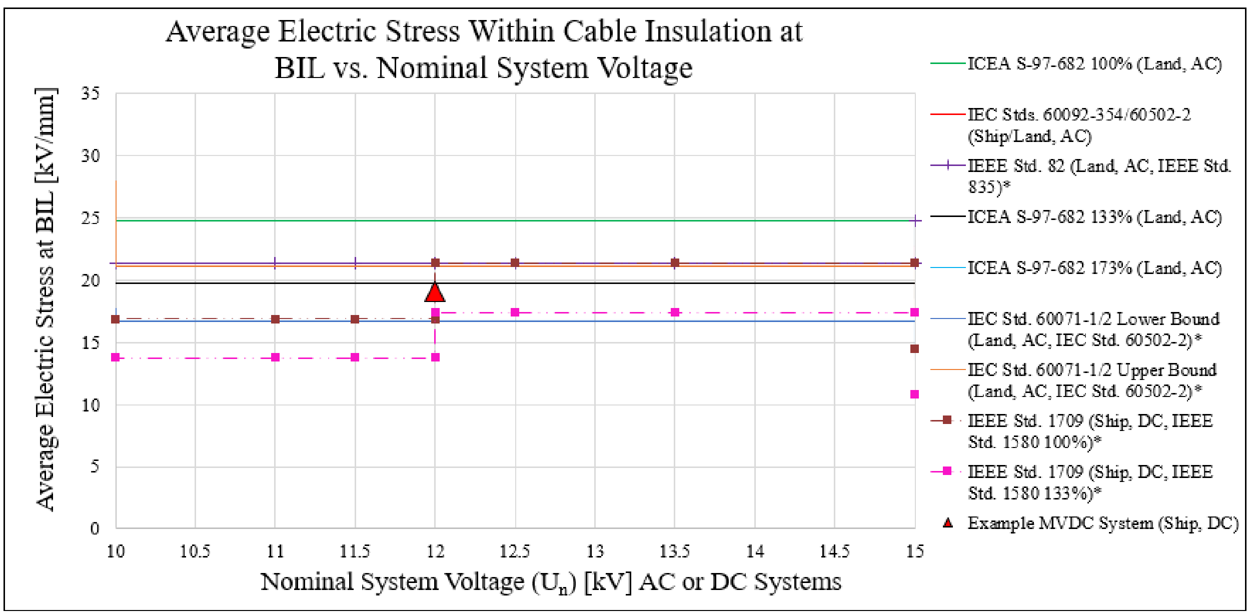
*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 196: Average Electric Stress Within Insulation at Acceptance RMS AC U_w for Example MVDC Cable Compared to Other References Shown in §8.1



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 197: Average Electric Stress Within Insulation at Acceptance DC U_w for Example MVDC Cable Compared to Other References Shown in §8.1



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 198: Average Electric Stress Within Insulation at BIL for Example MVDC Cable System Compared to Other References Shown in §8.1

9.11 Results

The parameters selected/calculated within each of the 10 steps of this example MVDC system are shown below in Table 43. Each parameter is listed beside its corresponding step of the system design process.

Cable System Design Step		Value [Units]
1. Selection of Maximum Power		75 [MW]
2. Selection of Nominal System Voltage		12 [kV]
3. Determination of Insulation Thickness		4.98 [mm]
4. Selected Cable Environment	Ambient Temperature	45 [°C]
	Spacing of Cable Groups	2.15x Single Cable Diameter from Other Cables, 1.075x from Any Other Surface [mm]
	Insulation Material	XLPE
5. Calculation of Conductor Ampacity		550 [Amp]
6. Maximum Length of Cable System		200 [m]
7. Selection of Maximum Allowable Voltage Drop		6%
8. Calculation of Number of Required Cable Groups		6
9. Calculation of Cross-Section and Volume		0.154 [m^2], 30.9 [m^3]
10. Corresponding Test Voltages and Resultant Average Electric Stress	At BIL (105 [kV])	21.08 [kV/mm]
	At U_w (33 [kV])	6.63 [kV/mm]

Table 43: Example MVDC System Parameters Alongside Corresponding System Design Step

The cable way cross-section of the example MVDC cable system designed in §9.1-9.10 is shown below in Figure 199.

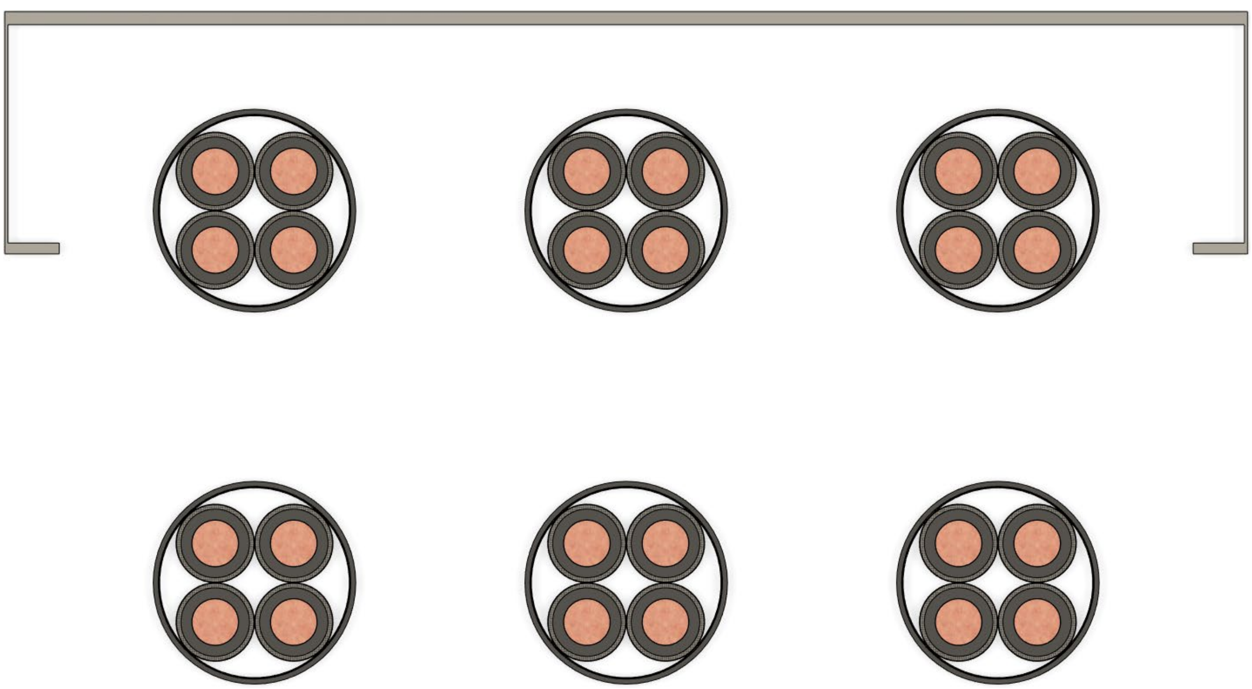
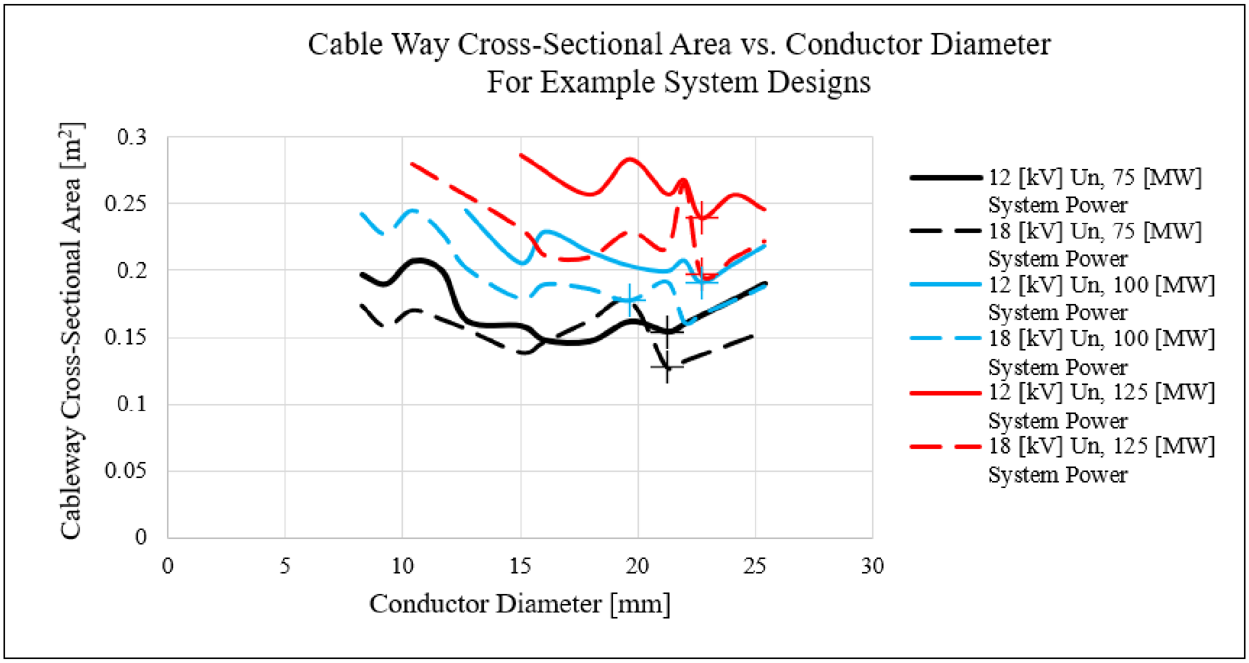


Figure 199: Selected MVDC System Cable Way Cross-Section, 75 [MW] 12 [kV] U_n

9.12 More Example System Design Results for Various Power and Voltage Levels

The example cable system designed in §9.1-9.10 outlined the process for a 75 [MW] cable system with at 12 [kV] Nominal System Voltage. This process has been completed for all combinations of 75, 100, and 125 [MW] cable systems with 12 or 18 [kV] Nominal System Voltages. The area required for each design is shown in Figure 200 for visual comparison, with the Nominal System Voltage and system power of each design shown in the legend. The results of each step of the design process are tabulated in Table 44, with the results of each step shown as a separate column. The height and width of each area, as well as the overall cableway area and volume for each system design are shown in Appendix B. Of note, the insulation thickness, selected cable environment, maximum length of cable system, maximum allowable voltage drop, and average electric stress at AC U_w and BIL were constant at the values shown at the bottom of Table 44. Additionally, for the steps that produce a range of values (ampacity of conductors, voltage drop, number of required cables, volumetric requirements, and resultant electric stress) only the values corresponding to the cable system with the minimum volumetric requirement are shown. This conductor diameter is shown in the far-right column of the table.



Note: Selected conductor diameter for each example system is indicated by '+' on the figure.

Figure 200: Cableway Cross-Sectional Area for Example System Designs versus Conductor Diameter, with Sold Lines and Dashed Lines for 12 and 18 [kV] U_n Systems, Respectively

Step 1	Step 2	Step 5	Step 8	Step 9	
Design Power [MW]	**Design System Voltage (U_n) [kV]**	**Single Conductor Ampacity [Amp] [a]**	**Number of Required Cable Groups**	**Cable Way Cross-Sectional Area [m^2] [b]**	**Volumetric Req. [m^3]**
75	12	550	6	0.154	30.87
75	18	550	4	0.128	25.58
100	12	609	7	0.191	38.19
100	18	486	6	0.178	35.52
125	12	609	9	0.239	47.87
125	18	609	6	0.197	39.36

For each example system, the following steps were constant:

- Step 3[a]: Insulation Thickness- 4.98 [mm] for 12 [kV] systems, 7.13 [mm] for 18 [kV] systems.
- Step 4: Cable environment: ambient temperature - 45 [°C], cable spacing - cable groups 2.15x single cable diameter away from another cable and 1.075x from any other surface, insulation material - XLPE.
- Step 6: Maximum length of cable system - 200 [m].
- Step 7: Maximum allowable voltage drop - 6%.
- Step 10[d]: Average Stress- 6.63 [kV/mm] at RMS AC U_w, 8.82 [kV/mm] at DC U_w, and 19.08 [kV/mm] at BIL for 12 [kV] systems, 7.43 [kV/mm] at RMS AC U_w, 8.42 [kV/mm] at DC U_w, and 19.64 [kV/mm] at BIL for 18 [kV] systems.

[a] Range of values for single conductor in a 4-cable group based on conductor diameter not shown, values presented correspond to the conductor diameter resulting in the cable system with the minimum volumetric requirement.

[b] The height and width of each area, as well as the overall cableway area and volume for each system design are shown in Appendix B

[c] Values shown are the average of shipboard 133% insulation from §7.2.

[d] Test voltages for BIL and factory Acceptance AC Withstand Test were determined by taking the average of the minimum and maximum voltages from the shipboard-applicable test voltages shown in Table 12 and Table 13 in §6.0, with BIL rounded to the nearest 5 [kV].

Table 44: More Example System Design Results

Each example MVDC system from Table 44 above is shown comparatively to-scale in Table 45.

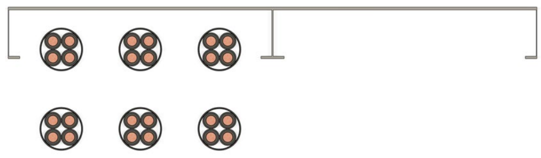
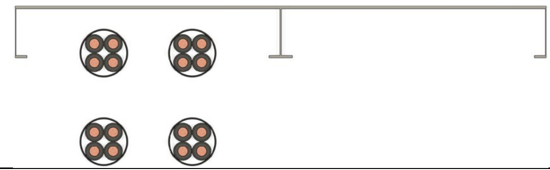
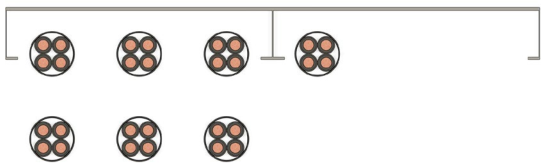
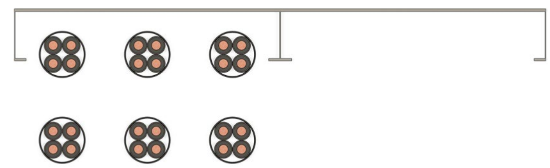
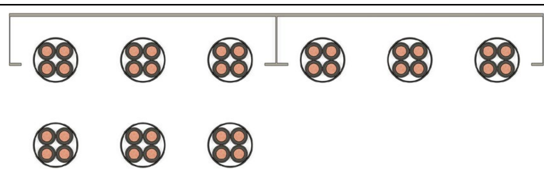
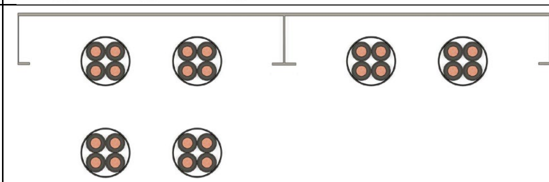
Visual Comparison of Example MVDC System Cableways		
System Power Level	**12 [kV] U_n Systems**	**18 [kV] U_n Systems**
75 [MW]		
100 [MW]		
125 [MW]		

Table 45: Visual Comparison of Example System Design Results

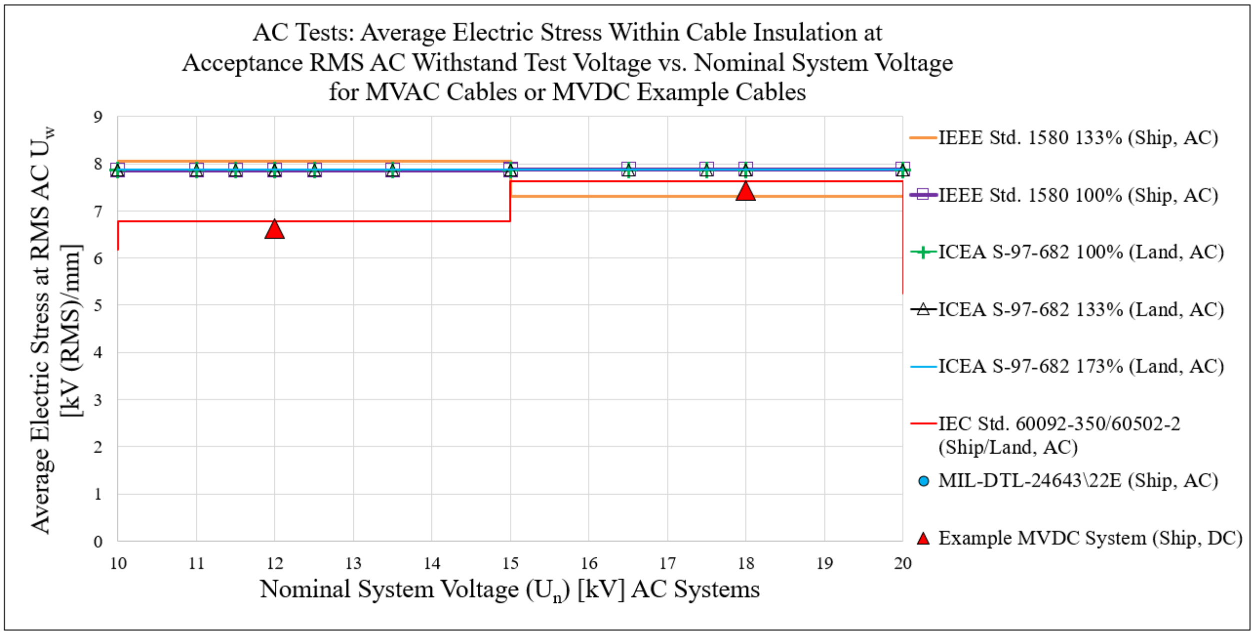
The resultant conductor sizes from the example systems shown in Table 45 are shown in Table 46. Additionally, as the resultant mass of a 200 [m] cable system (the maximum) of each example system is shown in the far-right column, using the following parameters:

- Solid copper conductor density of 0.00896 [g/mm^3] [67]
- Semi-conducting tape density of 0.000425 [g/mm^3] [68]
- Cable insulation and jacket XLPE density of 0.000965 [g/mm^3] [69]
- Fiberglass tape density of 0.00114 [g/mm^3] [70]
- Polyester tape density of 0.00075 [g/mm^3] [71]

Design Power [MW]	Design System Voltage (U_n) [kV]	Conductor Size [kcmil]	Mass of 200 [m] Cableway [MT]
75	12	700	20.4
75	18	700	14.6
100	12	800	26.7
100	18	600	19.4
125	12	800	34.3
125	18	800	24.3

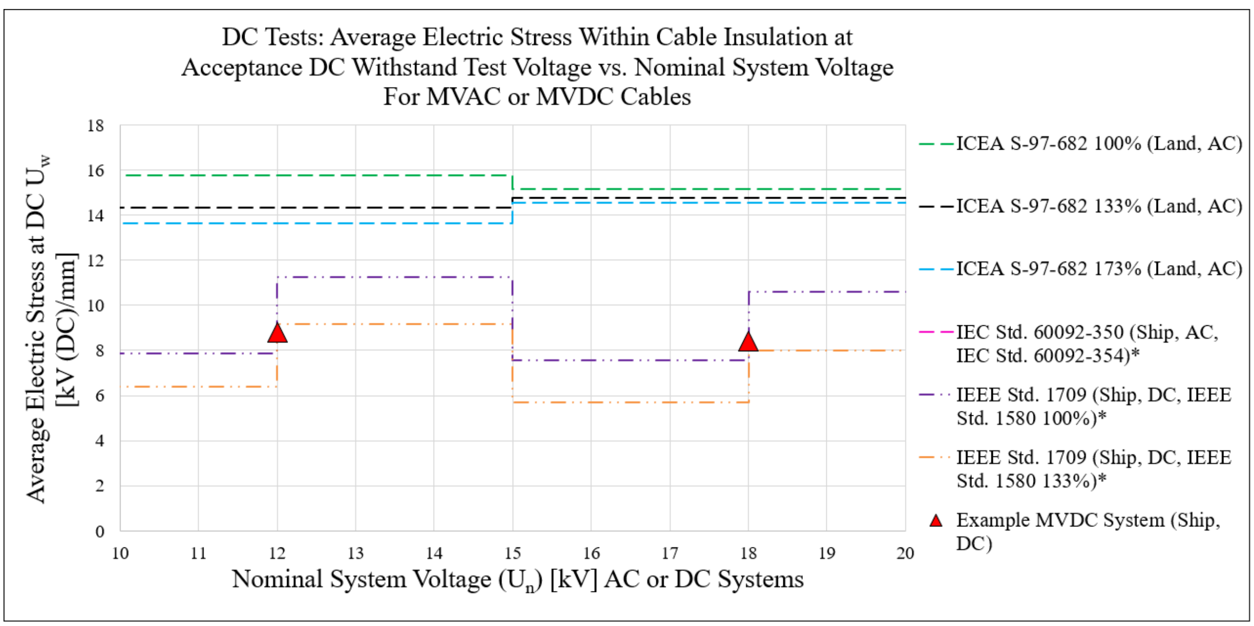
Table 46: Example System Design Conductor Sizes and Resultant Weight

Figure 201 through Figure 203 show how the average stresses at BIL and U_W compare to those of the standards presented in §8.1. The legends of these figures contain the name of the references plotted, as well as the applicability of the reference to either land-based or shipboard systems, the current type of the system being designed (AC or DC), and if the insulation thickness used comes from a different standard.



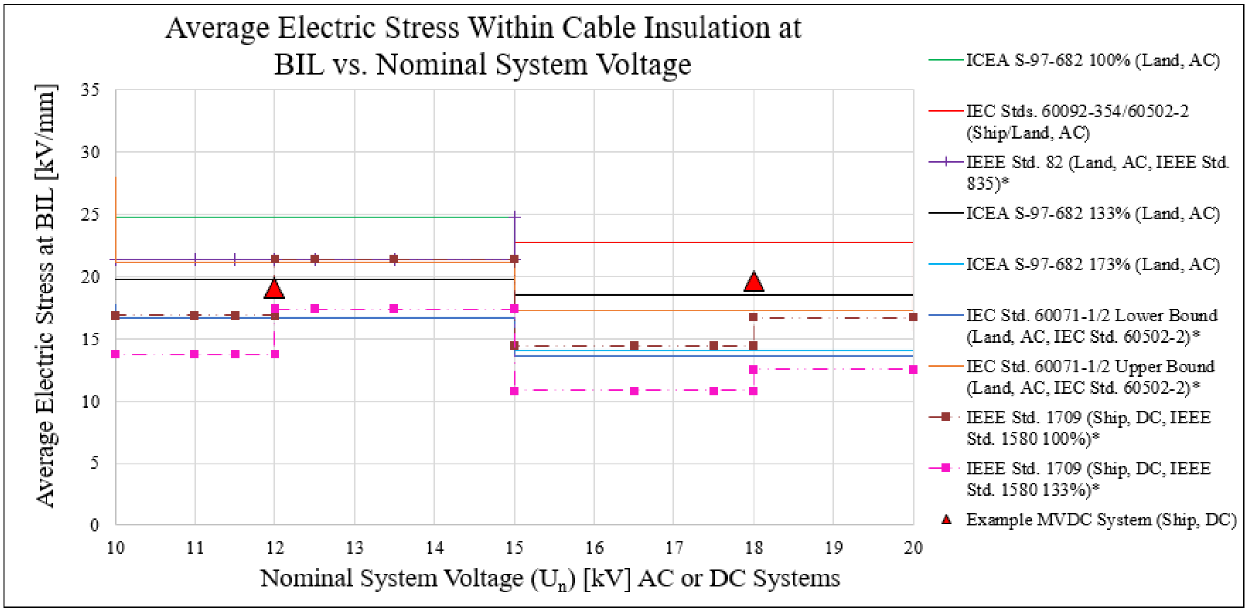
*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 201: Average Electric Stress Within Insulation at Acceptance RMS AC Withstand Test Voltage (U_w) for Example MVDC Cable Compared to Other References Shown in §8.1



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 202: Average Electric Stress Within Insulation at Acceptance DC Withstand Test Voltage (U_w) for Example MVDC Cable Compared to Other References Shown in §8.1



*The test voltage level and insulation thickness for this data come from separate standards, as shown in the legend and described in Figure 164. Both standards are from the same governing body (IEEE or IEC) and have the same applicability (shipboard or land-based).

Figure 203: Average Electric Stress Within Insulation at BIL for Example MVDC Cable System Compared to Other References Shown in §8.1

Based on the constraints of these example cable systems designs, the maximum power possible for 12 and 18 [kV] U_n systems was determined for cables constrained to Region-1, and to both Region-1 and Region-2. The MatLab script for calculations is shown in Appendix A, results are shown in Table 47.

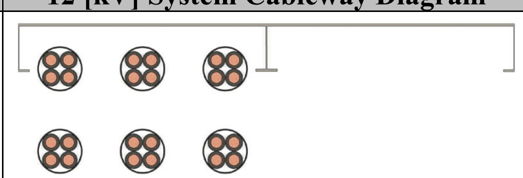
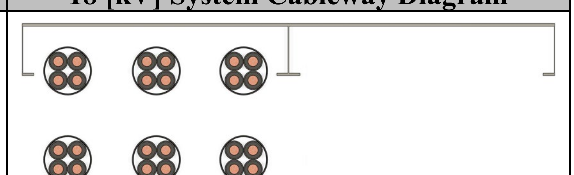
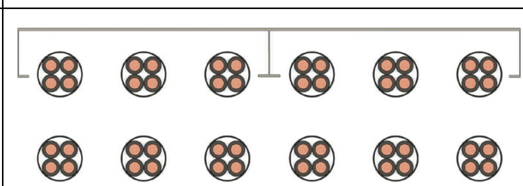
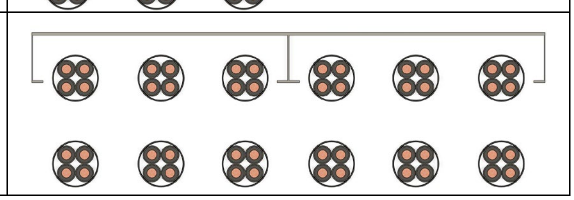
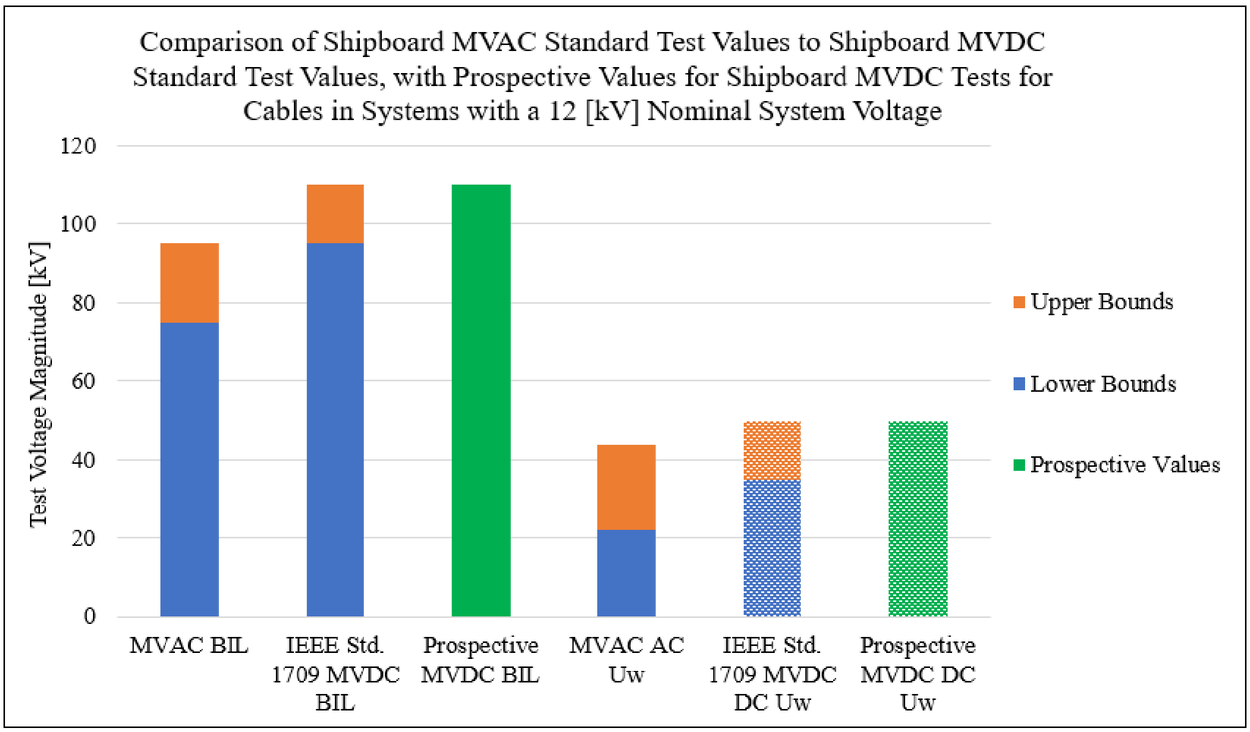
Region Allotted	Design System Voltage (U_n) [kV]	Maximum Power [MW]	Conductor Size [kcmil]	Mass of Cableway [MT]
1	12	94	1000	27.7
1 and 2	12	188	1000	55.3
1	18	118	700	21.9
1 and 2	18	237	700	43.7
	12 [kV] System Cableway Diagram		**18 [kV] System Cableway Diagram**	
1				
1 and 2				

Table 47: Maximum Power Within Fixed Size Cableway for 12 and 18 [kV] U_n Cable System Designs and Results

10.0 Summary of Shipboard MVAC Design Values and Prospective Shipboard MVDC Design Values

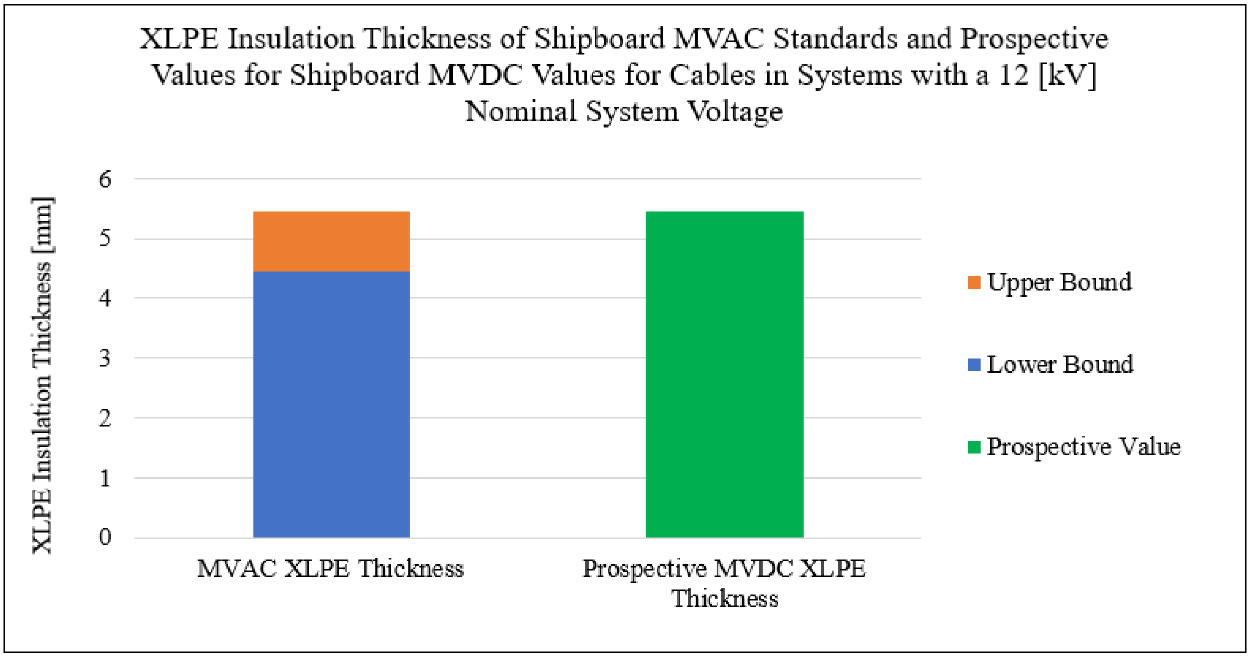
This section collects all data from this study to compare existing MVAC design and test values and resultant electrical stresses with the existing MVDC test values. The below graphs are used for ease of visual comparison of this study's prospective MVDC design and test values and resultant electrical stresses to the existing standards.

Figure 204 through Figure 211 show the range of BIL, AC Withstand Test Voltage (AC U_w), DC Withstand Test Voltage (DC U_w), XLPE insulation thicknesses, and resultant stresses for the evaluated MVAC standards, the sole MVDC standard (IEEE Std. 1709), and the resultant prospective MVDC design and test values from this study for a system with a 12 or 18 [kV] Nominal System Voltage (U_n). Within these figures, BIL and AC U_w are shown with solid bars, and DC U_w are shown with non-solid bars for ease of interpretation. Of note, IEEE std. 1709 shows a range of values despite being a single standard because it has a step-interval at 12 and 18 [kV] U_n for the given design values. Insulation thicknesses are not given within IEEE Std. 1709. For this evaluation, MVAC shipboard insulation thicknesses from IEEE Std. 1580 100% and 133% insulation levels are used to calculate stresses. The prospective shipboard MVDC design values resulting from this study are also shown within each figure. The graphed values are tabulated and shown in Table 48 through Table 57.



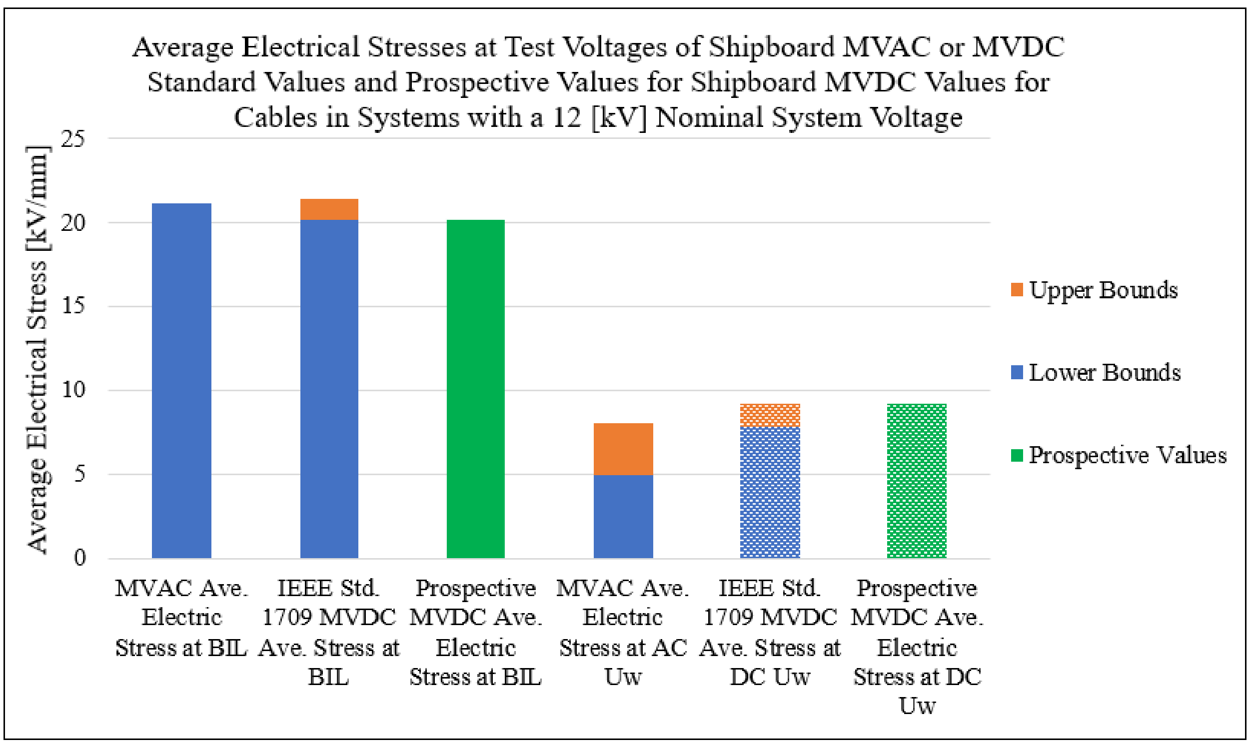
Note: DC tests voltages and stresses at DC test voltages are shown with non-solid bars

Figure 204: Comparison of Shipboard MVAC Standard Test Values to Shipboard MVDC Standard Test Values, with Prospective Values for Shipboard MVDC Tests for Cables in Systems with a 12 [kV] Nominal System Voltage



Note: IEEE Std. 1709 does not provide insulation thickness guidance.

Figure 205: XLPE Insulation Thickness of Shipboard MVAC Standards and Prospective Values for Shipboard MVDC Values for Cables in Systems with a 12 [kV] Nominal System Voltage



Note[1]: IEEE Std. 1709 test values shown with IEEE Std. 1580 100% and 133% insulation levels

Note[2]: DC tests voltages and stresses at DC test voltages are shown with non-solid bars

Figure 206: Average Electrical Stresses at Test Voltages of Shipboard MVAC Standard and Prospective Values for Shipboard MVDC Values for Cables in Systems with a 12 [kV] Nominal System Voltage

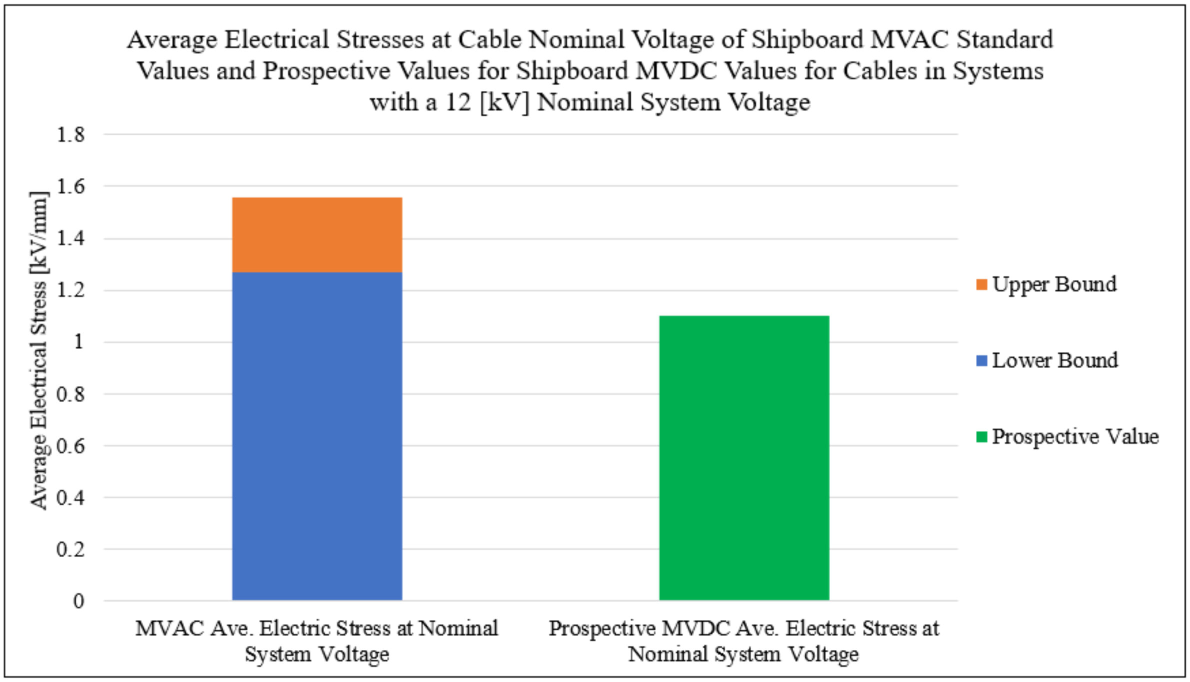
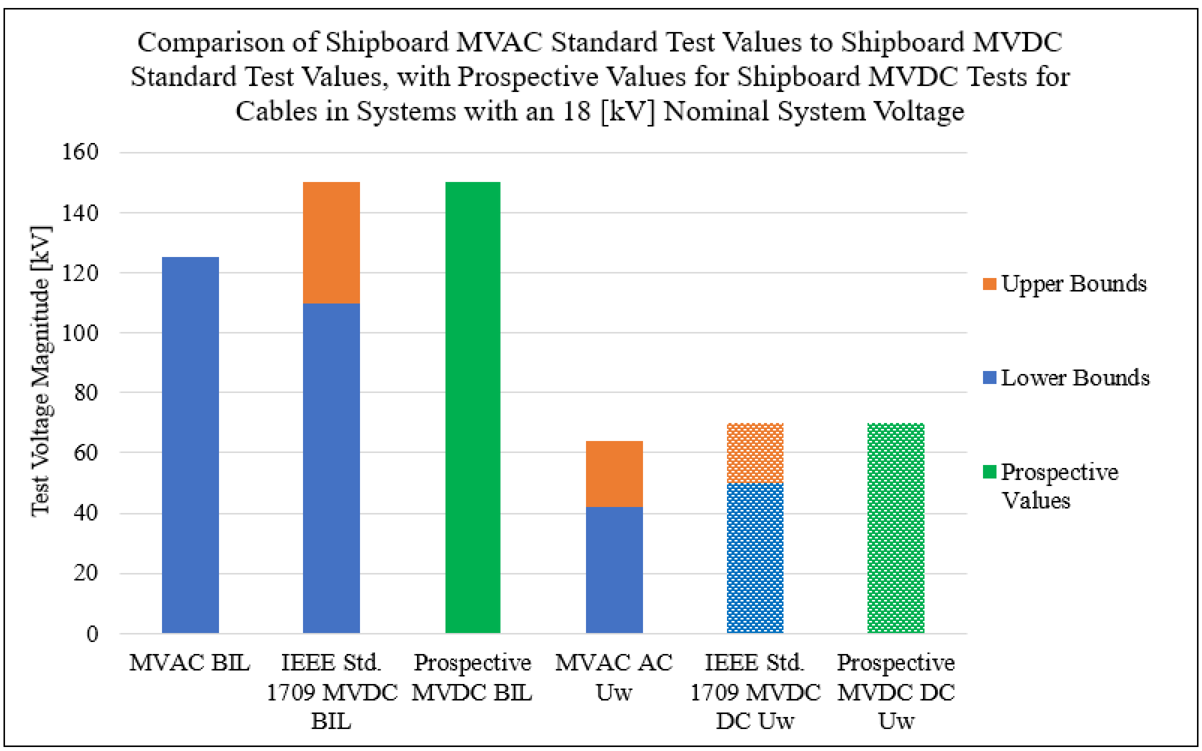
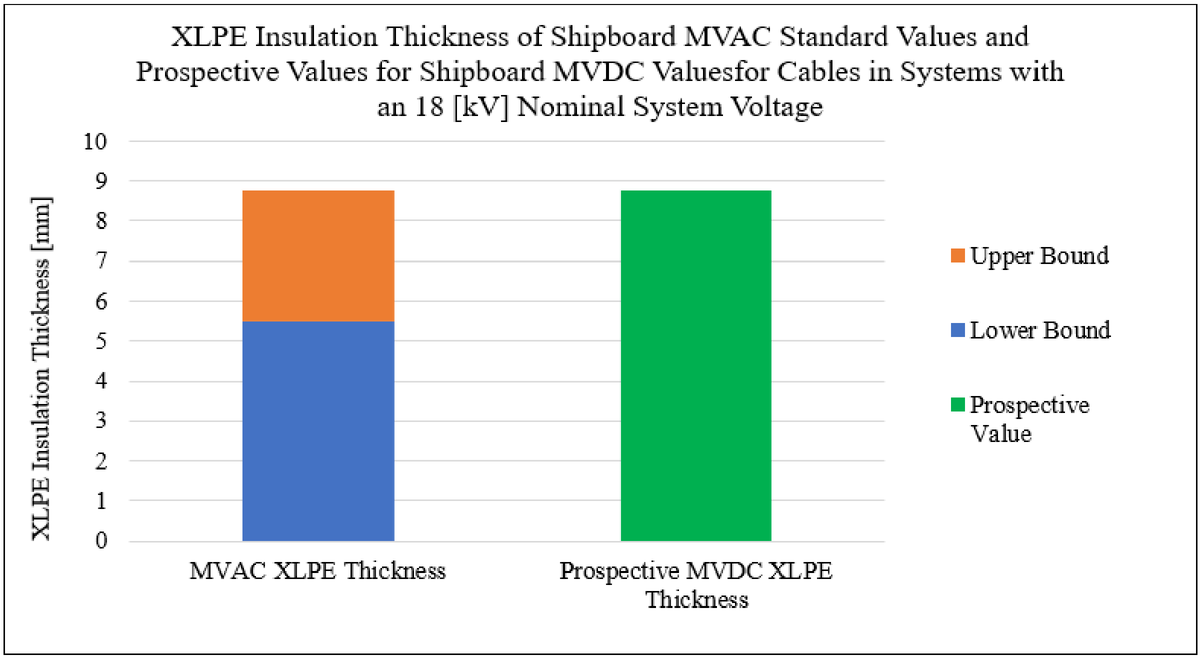


Figure 207: Average Electrical Stresses at Cable Nominal Voltage of Shipboard MVAC Standard Values and Prospective Values for Shipboard MVDC Values for Cables in Systems with a 12 [kV] Nominal System Voltage



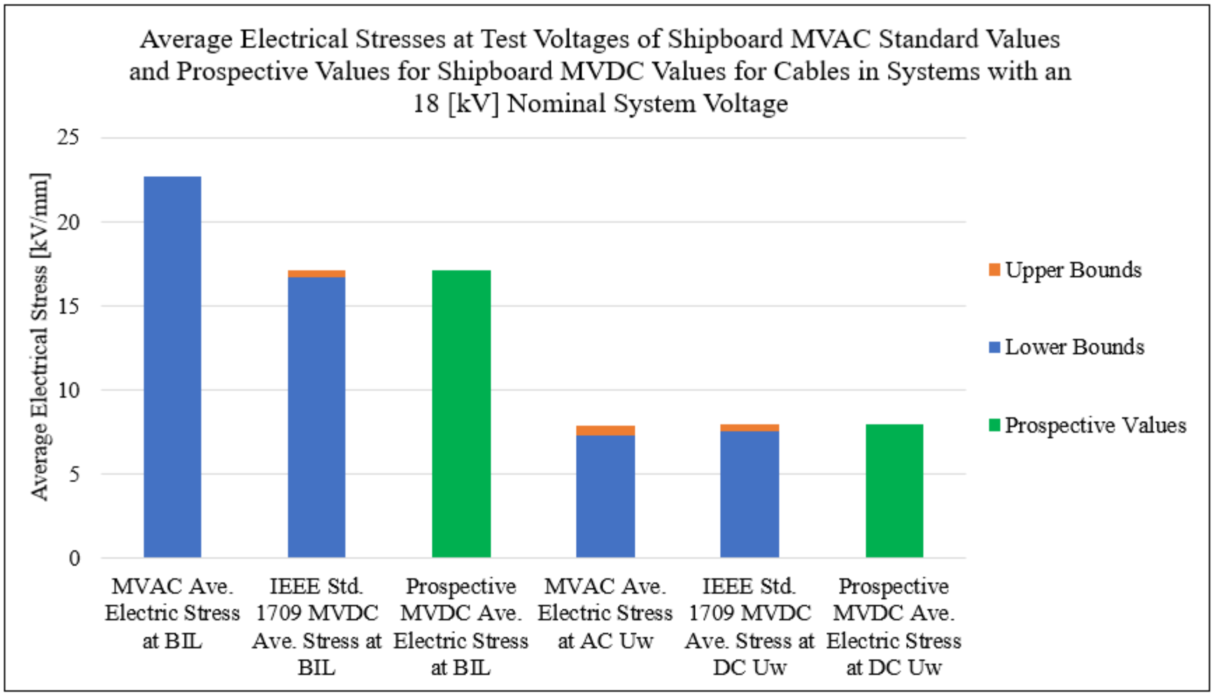
Note: DC tests voltages and stresses at DC test voltages are shown with non-solid bars

Figure 208: Comparison of Shipboard MVAC Standard Test Values to Shipboard MVDC Standard Test Values, with Prospective Values for Shipboard MVDC Tests for Cables in Systems with an 18 [kV] Nominal System Voltage



Note: IEEE Std. 1709 does not provide insulation thickness guidance.

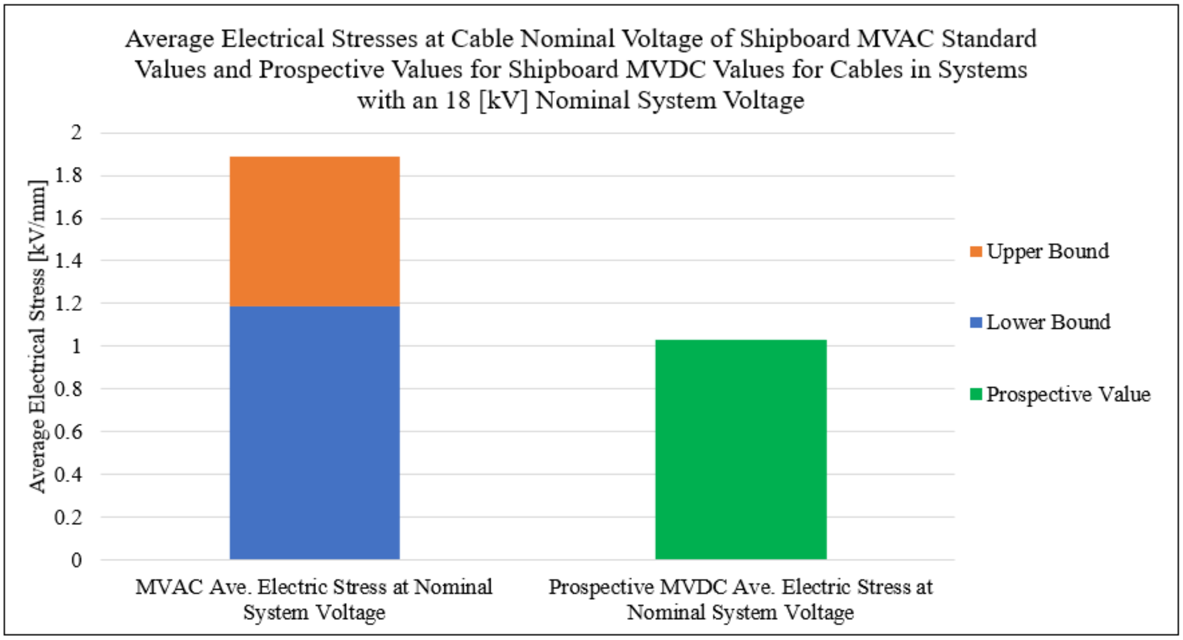
Figure 209: XLPE Insulation Thickness of Shipboard MVAC Standard Values and Prospective Values for Shipboard MVDC Values for Cables in Systems with an 18 [kV] Nominal System Voltage



Note[1]: IEEE Std. 1709 test values shown with IEEE Std. 1580 100% and 133% insulation levels

Note[2]: DC tests voltages and stresses at DC test voltages are shown with non-solid bars

Figure 210: Average Electrical Stresses at Test Voltages of Shipboard MVAC Standard Values and Prospective Values for Shipboard MVDC Values for Cables in Systems with an 18 [kV] Nominal System Voltage



Note: IEEE Std. 1709 does not provide insulation thickness guidance therefore average stresses cannot be calculated.

Figure 211: Average Electrical Stresses at Cable Nominal Voltage of Shipboard MVAC Standard Values and Prospective Values for Shipboard MVDC Values for Cables in Systems with an 18 [kV] Nominal System Voltage

Summary of Shipboard 12 [kV] U_n MVAC Cable Standards Design and Test Values			
Design Parameter	**Units**	**Lower Bound**	**Upper Bound**
XLPE Insulation Thickness	[mm]	4.45[a]	5.46[b]
BIL Test Voltage	[kV]	75[c]	110[c]
AC Acceptance Withstand Test Voltage (U_w)	[kV]	22[d]	44[b]
AC Acceptance Withstand Test Duration	[min]	5[d]	5[b]
DC Acceptance Withstand Test Voltage (U_w)	[kV]	52.8[d]	52.8[d]
DC Acceptance Withstand Test Duration	[min]	1[d]	1[d]

[a] Value from IEEE Std. 1580 100% insulation level [28]
[b] Value from IEEE Std. 1580 133% insulation level [28]
[c] Value from ABS Steel Vessels and IEC Stds. 60092-354/60502-2, note that this is at the transition for ABS Steel Vessels [36] [40] [30]
[d] Value from IEC Std. 60092-350 [31]

Table 48: Summary of Shipboard 12 [kV] Nominal System Voltage MVAC Cable Design Values

Summary of Shipboard 18 [kV] U_n MVAC Cable Standards Design and Test Values			
Design Parameter	**Units**	**Lower Bound**	**Upper Bound**
XLPE Insulation Thickness	[mm]	5.5[a]	8.76[b]
BIL Test Voltage	[kV]	125[a]	125[a]
AC Acceptance Withstand Test Voltage (U_w)	[kV]	42[a]	64[c]
AC Acceptance Withstand Test Duration	[min]	5[a]	5[c]

[a] Value from IEC Stds. 60092-354/60502-2 [40] [30]
[b] Value from IEEE Std. 1580 133% insulation level [28]
[c] Value from IEC Std. 60092-350 [31]

Table 49: Summary of Shipboard 18 [kV] Nominal System Voltage MVAC Cable Design Values

For comparison, the design parameters from IEEE Std. 1709, the sole shipboard MVDC standard, for both 12 and 18 [kV] systems are displayed below in Table 50 and Table 51. Bounds are given in this table for comparison to all other standards, as IEEE Std. 1709 prescribes a BIL and a DC U_w for a cable in a 12 or 18 [kV] U_n systems. However, following the step-like nature of the standards as even a slight increase in U_n would result in the next higher prescribed test value, the "bounds" for IEEE Std. 1709 are the values given in the standard and the value for the next higher given U_n for the lower and upper bounds, respectively.

IEEE Std. 1709 Shipboard 12 [kV] U_n MVDC Cable Test Values			
Design Parameter	**Units**	**Value Given in Standard (Lower Bound)**	**Step-Increase Value for Greater System Voltage (Upper Bound)**
BIL Test Voltage	[kV]	95	110
DC Acceptance Withstand Test Voltage (U_w)	[kV]	35	50
DC Acceptance Withstand Test Duration	[min]	1	1

Table 50: IEEE Std. 1709 Shipboard 12 [kV] Nominal System Voltage MVDC Cable Design Values [2]

IEEE Std. 1709 Shipboard 18 [kV] U_n MVDC Cable Test Values			
Design Parameter	**Units**	**Value Given in Standard (Lower Bound)**	**Step-Increase Value for Greater System Voltage (Upper Bound)**
BIL Test Voltage	[kV]	110	150
DC Acceptance Withstand Test Voltage (U_w)	[kV]	50	70
DC Acceptance Withstand Test Duration	[min]	1	1

Table 51: IEEE Std. 1709 Shipboard 18 [kV] Nominal System Voltage MVDC Cable Design Values [2]

10.1 Impact of Standards on Shipboard MVDC Cables

The size of an MVDC cable system is dependent on three quantities: the Nominal System Voltage (U_n), the conductor diameter, and the expected ground fault clearing time, often expressed as a percent insulation level. Table 52 shows the impact the conductor diameter and percent insulation level have on cable system size for a system with 4-cable (2 pairs of +/- conductor pairs) groups in a shipboard 12 kV DC U_n system with a 75 MW power level. Table 53 shows a similar comparison for a shipboard 18 kV DC U_n system.

Since no known MVDC standard provides insulation thicknesses, the 100% and 133% values from IEEE Std. 1580 were used (shipboard standard for MVAC cables) [28]. All other parameters and constraints are equivalent to those shown in §9, including stiffener spacing, cable environment, ampacity, and distance between each cable group.

Conductor Diameter (mm)	Cableway Area (m^2)		% Increase
	100% ins.	133% ins.	
8.25	0.18	-	-
9.27	0.16	0.20	30.53
10.4	0.19	0.22	16.47
11.68	0.18	0.21	15.66
12.7	0.15	0.17	15.04
15.3	0.15	0.16	10.53
16.06	0.14	0.16	9.73
17.96	0.14	0.16	12.60
19.67	0.15	0.17	11.98
21.25	0.15	0.16	11.46
22	0.15	0.17	11.20
22.72	0.16	0.18	10.96
24.1	0.17	0.19	10.56
25.4	0.18	0.16	-11.74

Table 52: Shipboard 75 MW, 12 kV U_n MVDC 4-Cable Group Cableway Cross-Sectional Area Comparison

Note that for a cable system with 25.4 [mm] diameter conductors, the 133% insulation thickness has a smaller cross-sectional area. However, the cable system using 100% insulation thickness fits within a single pair of stiffeners, Region-1. The cable system using 133% requires both Region-1 and Region-2, leave some area within each region that could be utilized for other requirements but may not be ideal.

Conductor Diameter (mm)	Cableway Area (m^2)		% Increase
	100% ins.	133% ins.	
8.25	0.16	0.23	39.63
9.27	0.15	0.20	35.85
10.4	0.16	0.21	34.51
11.68	0.16	0.20	25.95
12.7	0.15	0.19	28.70
15.3	0.13	0.17	26.70
16.06	0.14	0.17	25.81
17.96	0.15	0.19	24.50
19.67	0.17	0.17	0.12
21.25	0.12	0.15	22.39
22	0.13	0.15	21.98
22.72	0.13	0.16	21.63
24.1	0.14	0.17	20.85
25.4	0.15	0.18	20.19

Table 53: Shipboard 75 MW, 18 kV U_n MVDC 4-Cable Group Cableway Cross-Sectional Area Comparison

The average electrical stresses at BIL, DC U_w, and U_o for cables in 12 and 18 kV DC U_n shipboard systems are shown in Table 54 and Table 55, respectively, calculated using Equation 1. The BIL and DC U_w values are from IEEE Std. 1709 [2]. The values on either side of the 12 kV U_n transition point are displayed to highlight the impact of the possible design choices for shipboard MVDC cables. The insulation thicknesses used are the 100% and 133% insulation levels of IEEE std. 1580 [28].

12 kV U_n Cable Insulation Average Electric Stress [kV/mm]				
Voltage		Insulation Level		% Decrease
		100% (4.45 [mm])	133% (5.46 [mm])	
BIL	95 [kV]	21.35	17.40	18.50
	110 [kV]	24.72	20.15	18.49
DC U_w	35 [kV]	7.87	6.41	18.55
	50 [kV]	11.24	9.16	18.51
U_o	6 [kV]	1.35	1.10	18.52

Table 54: Average Electrical Stresses in 12 kV U_n MVDC Cable Insulation

18 kV U_n Cable Insulation Average Electric Stress [kV/mm]				
Voltage		Insulation Level		% Decrease
		100% (6.60 [mm])	133% (8.76 [mm])	
BIL	110 [kV]	16.67	12.56	24.66
	150 [kV]	22.73	17.12	24.66
DC U_w	50 [kV]	7.58	5.71	24.66
	70 [kV]	10.61	7.99	24.66
U_o	9 [kV]	1.36	1.03	24.66

Table 55: Average Electrical Stresses in 18 kV U_n MVDC Cable Insulation

For both the 12 and 18 [kV] U_n, 75 [MW], 133% insulation level systems, the 21.25 [mm] diameter conductor resulted in the lowest cableway cross-sectional area. Note that with a less conservative 100% insulation thickness, the corresponding total cableway cross-sectional areas for the same cable systems would decrease by 10.3% and 18.3% respectively, but the respective average electric stress within the insulation would increase by 22.7% and 32.7%, and hence a substantial penalty in reliability.

10.2 Prospective Shipboard MVDC Design and Test Values

A 2021 study verified that experiments on XLPE insulated MVAC cables can be applied in MVDC systems in case of emergency, however, it is inconclusive as to whether MVAC cables can be used for long term due to problems arising such as conductivity control and space charge [18]. While the space charge issue can be overcome with filled XLPE, further testing and verification will be required to ascertain appropriate and safe design values [61].

Based on the design and test values of the sole existing shipboard MVDC cable standard, and the range of MVAC cable standards design and test values, this study proposes the values shown below in Table 56 and Table 57 for shipboard 12 and 18 [kV] MVDC cable design parameters. Because 12 and 18 [kV] happen to be at a boundary condition for IEEE Std. 1709, and even a slight increase of system voltage would warrant using the next higher test values, the higher values of the transition were selected for BIL and the DC Withstand Test [2]. The XLPE insulation thicknesses are the upper bound of shipboard MVAC standards for the 133% insulation level, both prescribed by IEEE Std. 1580 [28].

Prospective MVDC Cable Design and Test Values at 12 [kV] U_n		
Design Parameter	**Units**	**Value**
XLPE Insulation Thickness	[mm]	5.46
BIL Test Voltage	[kV]	110
DC Acceptance Withstand Test Voltage (U_w)	[kV]	50
DC Acceptance Withstand Test Duration	[min]	1

Table 56: Prospective Shipboard 12 [kV] Nominal System Voltage MVDC Cable Design Values

Prospective U_n MVDC Cable Design and Test Values at 18 [kV]		
Design Parameter	**Units**	**Value**
XLPE Insulation Thickness	[mm]	8.76
BIL Test Voltage	[kV]	150
DC Acceptance Withstand Test Voltage (U_w)	[kV]	70
DC Acceptance Withstand Test Duration	[min]	1

Table 57: Prospective Shipboard 18 [kV] Nominal System Voltage MVDC Cable Design Values

11.0 Conclusions

This study had a goal of evaluating the impact of test voltages, such a BIL levels, on the size of MVDC cable systems, especially for shipboard applications. However, it was found that national and international standards provide guidance for MV cables, which establish a more complex relationships concerning cable size than from the BIL level.

An extensive evaluation of standards and recommended practices relevant to MVAC and MVDC systems involved in all 27 different documents. From these documents cable design and test values for lightning impulse Basic Insulation Level (BIL), Withstand Test Voltage (U_w), and insulation thickness were evaluated and compared in terms of magnitude as well as for resultant electric stress within the cable insulation. Both BIL and Withstand test values vary somewhat between standards but are always set according to the Nominal System Voltage U_n value where the cable operates. Furthermore, it was found that the cable insulation thickness is set by standards for MVAC cables, with the thickness value dependent on the Nominal System Voltage (U_n) and on the expected ground fault clearance time, often expressed as a percent insulation level.

All standard test voltage and thickness values are provided as a table or chart with step change increases given at certain specified discrete system voltage U_n values. A cable in a system with a U_n above such a point of change is expected to use the design value corresponding to the next higher step. The standards do not identify the design thickness value to use when a system voltage U_n is at one of the discrete step values. Additionally, there are very limited standards applicable to shipboard MVDC cables, only one was found to date, and the standard identified does not provide insulation thickness values.

The average electric stress within the cable insulation at the Cable Nominal Voltage (U_o) was calculated for all references that provided insulation thickness values. For standards that provided test voltage values, the average electric stress within the cable insulation at these values (BIL, AC U_w and DC U_w) were calculated, when the same standard committee provided cable insulation thicknesses for the same system applicability (e.g. shipboard power cables with the same current type). Since the sole MVDC standard provided test voltage values but not insulation thicknesses, the insulation thickness values from the same standard committee for MVAC cables were used to calculate the average stresses in MVDC cables for comparison. The average values of the average electric stress within cable insulation at BIL, DC U_w, AC U_w, and U_o are approximately 18 [kV/mm], 12 [kV/mm], 7 [kV/mm], and 1.2 [kV/mm] respectively.

Of note, all evaluated references that provide insulation thicknesses do so for cross-linked polyethylene (XLPE) insulation. XLPE insulation is commonly used and is successful with MVAC power cables, however, with a DC voltage XLPE is susceptible to charge accumulation leading to a DC breakdown (i.e. insulation failure). This issue can be overcome by modifying the material with additives, referred to as "filled XLPE" [61]. For this study the insulation material was referred to as XLPE, but a suitably modified XLPE insulation must be considered when designing an MVDC cable.

It was found that MV cable size is set by the insulation thickness and the conductor diameter. The insulation thickness of a given cable is determined according to the U_n system voltage, (and the protection level), however the conductor diameter in the cable depends on a design process for the cable ampacity. The evaluated standards set ampacity values according to conductor size and physical arrangements. Thus, the selection of conductor diameter is evaluated based upon the required power and corresponding voltage and current capability of the designed cable system. Thus, for a 12 [kV] U_n system the insulation can range from 26-52% of the total cable diameter depended upon the cable ampacity. An example MVDC shipboard cable design process is provided for a 75 [MW], 12 [kV] U_n shipboard cable system with average electric stresses similar to shipboard MVAC cables.

Prospective design and test values for 12 and 18 [kV] U_n MVDC shipboard power systems are outlined in §10, along with the resultant average electrical stresses. Design values that would result in a slightly more compact cable system are shown. These alternative designs for the 12 and 18 [kV] U_n systems were 10.3% and 18.3% reduced in cross-sectional area respectively, but with substantial increases to average electrical stresses of 22.7% and 32.7% respectively. The lower stress design is preferred for greater reliability. As more MVDC experience becomes available, it would be appropriate for a standard committee to address MVDC cable systems more completely. Specific needs include clarifications about DC cable insulation thickness, ampacity of DC cable groups, what standard values are appropriate when near or at a step change according to system voltage, and when or if simultaneous operating and transient pulse test voltages are required.

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Appendix A: Cableway Grid Optimization for Minimum Cross-sectional Area or Height, and Mass Calculations

The following MatLab script was used to calculate the minimum cable way dimensions for both area and height of the cable way:

```
% Joshua Malone
% 28 January 2022
% Cableway calculations for fixed dimensions and variable conductor size

%% Required User Inputs
% User must modify the below 2 default design parameters to their desired system
% levels
Un = 12; % kV, Nominal System Voltage ****MUST BE EITHER 12 OR 18***, if another
voltage is desired, t_ins in the given section must be appropriately modified
P = 75; % MW, Total System Power

%% Givens and assumptions
% Required cable construction components from MIL-DTL-24643/86, with
% component thickness sources outlined in section 9.9 of this thesis.

cable_length = 200; %m, outlined in section 9.6

cond_d_awg = [10,20,30,40,250,350,400,500,600,700,750,800,900,1000]; %AWG sizes, 10-
40 corresponding to 1/0-4/0, remaining sizes are kcmil

cond_d =
[8.25,9.27,10.4,11.68,12.7,15.03,16.06,17.96,19.67,21.25,22,22.72,24.1,25.4]; % mm,
conductor diameters corresponding to AWG sizes

cond_amp = [187,211,223,260,288,360,395,453,486,550,576,609,636,654]; %amp, single
condcutor ampacity, shown in Table 26 in section 9.5

if Un == 12 % if statement to set insulation thickness based on nominal system
voltage, this must be modified if any Un outside of 12 or 18 is desired
    t_ins = 4.98; % mm, insulation thickness for a 12 kV system from section 9.3
elseif Un == 18
    t_ins = 7.13; % mm, insulation thickness for a 18 kV system from section 9.12
else
    msg = 'Nominal System Voltage (Un) must be either 12 or 18'; % Error message to
ensure user knows the options for Un
    error(msg)
end

t_st = 0.127; %mm, individual cable and cable group semi conducting tape thickness
assumed to be 5 [mils], outlined in section 9.9

t_ft = 2.032; %mm, individual cable silicone or fiberglass tape thickness assumed to
be 0.08 [in], outlined in section 9.9

t_clst = 0.254; %mm, cross-lapped semi conducting tapes thickness assumed to be 0.01
[in], outlined in section 9.9

t_sheild = 0.4064; % mm, cable group shielding thickness, assumed to be 16 [mils]
thick outlined in section 9.9
```

```
t_pt = 0.127; %mm, cable group polyester tape thickness assumed to be 5 [mils], outlined in section 9.9

t_j = 2.286; %mm, cross-linked polyolefin jacket, with a thickness of 0.09 [in], outlined in section 9.9

stiffener_spacing = 570; %mm, assumed set point for this example.

stiffener_web = 100; %mm, assumed set point for this example.

t_web = 5; % mm, assumed thickness of web

rho_cu = 0.00896; % g/mm^3 assumed density of copper conductor, outlined in section 9.12

rho_xlpe = 0.000965; % g/mm^3 assumed density of XLPE, outlined in section 9.12

rho_st = 0.000425; % g/mm^3 assumed density of semi-conducting tape, outlined in section 9.12

rho_ft = 0.00114;% g/mm^3 assumed density of fiberglass tape, outlined in section 9.12

rho_pt = 0.00075;% g/mm^3 assumed density of polyester tape, outlined in section 9.12

%% Calculated Values
P_4cg = 1000*Un.*cond_amp.*2./1000000; % MW, Power of a 4-cable group, Equation 10 from section 9.5

N_rcg = ceil(P./P_4cg); %Number of required cable groups for each conductor size, rounded up

cable_d = cond_d+2*(t_st+t_ins+t_ft+t_clst); % mm, single cable diameter including all components outlined in section 9.9

cg_d = (cable_d+sqrt(2.*cable_d.^2))+2*(t_st+t_sheild+t_pt+t_j); %mm, cable group diameter found from diameter of 4 cables, wrapped in concentric tape, shielding, tape, and jacket as outlined in section 9.9

cg_spacing = 2.15.*cable_d; %mm, minimum spacing between adjacent cable groups outlined in section 9.4

surf_spacing = 1.075.*cable_d;  %mm, minimum spacing between cable groups and a surface outlined in section 9.4

max_cg_columns = floor((stiffener_spacing-2.*surf_spacing+cg_spacing)./(cg_d+cg_spacing)); % maximum number of cable groups columns that can fit between stiffeners, spacing between cable groups and cable way (surface) accounted for

N_rr = ceil(N_rcg./max_cg_columns); % determining the number of required rows of cables.
%% Minimum required volume
% This section calculates the minimum volume required for each conductor
```

```
% size at the give Nominal System Voltage and System power

cables_1st_row = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %# placeholder for grid
dimensions, 99 to be overwritten unless conductor diameter is infeasible
cables_2nd_row = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %# placeholder for grid
dimensions, 99 to be overwritten unless conductor diameter is infeasible
cables_3rd_row = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %# placeholder for grid
dimensions, 1st row of 2nd space inbetween stiffeners, 99 to be overwritten unless
conductor diameter is infeasible
cables_4th_row = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %# placeholder for grid
dimensions, 2nd row of 2nd space inbetween stiffeners, 99 to be overwritten unless
conductor diameter is infeasible
cableway_height_area1 = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %m placeholder
for grid dimensions, first area is the between only 2 stiffeners, 99 to be
overwritten unless conductor diameter is infeasible
cableway_width_area1 = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %m placeholder
for grid dimensions, 99 to be overwritten unless conductor diameter is infeasible
cableway_height_area2 = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %m placeholder
for grid dimensions, second area is the adjacent area between the 3rd stiffener, 99
to be overwritten unless conductor diameter is infeasible
cableway_width_area2 = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %m placeholder
for grid dimensions, 99 to be overwritten unless conductor diameter is infeasible
cableway_area = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %m^2 placeholder for
grid dimensions, 99 to be overwritten unless conductor diameter is infeasible
cableway_volume = [99,99,99,99,99,99,99,99,99,99,99,99,99,99]; %m^3 placeholder for
grid dimensions, 99 to be overwritten unless conductor diameter is infeasible

%repeating all above holders to save the data for a single row of
%conductors, if a minimum height of cableway is preferred over a minimum
%area. Only 1 value is needed as the smalled conductor size that can fit
%into a single row will yield the smallest height (or two, considering both areas
inbetween stiffeners)
% , the desired parameter to
%minimize.
sr_cables_1st_row = 99; %# placeholder for grid dimensions, 99 to be overwritten
unless conductor diameter is infeasible
sr_cables_3rd_row = 99; %# placeholder for grid dimensions, 99 to be overwritten
unless conductor diameter is infeasible
sr_cableway_height = 99; %m placeholder for grid dimensions, 99 to be overwritten
unless conductor diameter is infeasible
sr_cableway_width = 99; %m placeholder for grid dimensions, 99 to be overwritten
unless conductor diameter is infeasible
sr_cableway_area = 99; %m^2 placeholder for grid dimensions, 99 to be overwritten
unless conductor diameter is infeasible
sr_cableway_volume = 99; %m^3 placeholder for grid dimensions, 99 to be overwritten
unless conductor diameter is infeasible
sr_possible = 0; % placeholder if a single row is possible or not, 1 = yes 0 = no

for k=1:length(cond_d) %for loop to fit in all the conductor sizes, checking to see
if they are feasible and saving their lowest area (with priorities, if it all can fit
in region-1 then that will be saved)
    if N_rr(k) == 1 % if it can fit in 1 row
        cables_1st_row(k) = N_rcg(k); % saving the number of required cables in the
1st row
        cables_2nd_row(k) = 0;% saving the number of required cables
```

```
        cables_3rd_row(k) = 0;% saving the number of required cables
        cables_4th_row(k) = 0;% saving the number of required cables
        cableway_height_area2(k) = 0; %not used for this conductor size for this
iteration
        cableway_width_area2(k) = 0; %not used for this conductor size for this
iteration
        cableway_height_area1(k) = (cg_d(k)+surf_spacing(k))/1000; %m setting the
height of cable way for a single conductor size plus spacing from the top surface
        %area1 indicates the area within the first 2 stiffeners
        cableway_width_area1(k) = (N_rcg(k)*cg_d(k)+(N_rcg(k)-
1)*cg_spacing(k)+2*surf_spacing(k))/1000; %m setting the width of cable way for a
single conductor size plus spacing from both webs
        cableway_area(k) = cableway_height_area1(k)*cableway_width_area1(k); %m^2,
the area of the smallest possible cableway with the current conductor size
        cableway_volume(k) = cableway_area(k)*cable_length; %m^2, the volume of the
smallest possible cableway with the current conductor size
    elseif N_rr(k) == 2 % If 2 rows of cable groups are needed, the double-banked
solution within 2 adjacent stiffeners, only 1 area needed between 2 stiffeners for
this case
        c1r = max_cg_columns(k); %variable for the initial number of cables in each
row
        c2r = N_rcg(k) - max_cg_columns(k); % initial number of cables in the second
row
        cableway_height_area2(k) = 0; %not used for this conductor size for this
iteration
        cableway_width_area2(k) = 0; %not used for this conductor size for this
iteration
        cables_3rd_row(k) = 0;% saving the number of required cables
        cables_4th_row(k) = 0;% saving the number of required cables
        while c2r <= c1r    %checking volumes for each geometry moving one cable to
the 2nd row each iteration until it is rectangular (or as close as possible)
            it_area = (c1r*cg_d(k)+(c1r-
1)*cg_spacing(k)+2*surf_spacing(k))*(2*cg_d(k)+cg_spacing(k)+surf_spacing(k))/(100000
0); %m2 cross-sectional area of a rectangular box 2 cable groups and spacing tall and
c1r cables and spacing wide
            if it_area < cableway_area(k) % Checking to see if this iteration is
smaller than any previously calculated, or originally stored 99 (overwriting if so)
                cables_1st_row(k) = c1r; % Resetting value with ideal configuration
                cables_2nd_row(k) = c2r; % Resetting value with ideal configuration
                cableway_height_area1(k) =
(2*cg_d(k)+cg_spacing(k)+surf_spacing(k))/1000; %m setting the height of cable way
for a single conductor size
                cableway_width_area1(k) = (c1r*cg_d(k)+(c1r-
1)*cg_spacing(k)+2*surf_spacing(k))/1000; %m setting the width of cable way for a
single conductor size
                cableway_area(k) = cableway_height_area1(k)*cableway_width_area1(k);
%m^2, the area of the smallest possible cableway with the current conductor size
                cableway_volume(k) = cableway_area(k)*cable_length; %m^2, the volume
of the smallest possible cableway with the current conductor size
            end
            c2r = c2r + 1; % taking 1 cable from the first row and adding it to the
second
            c1r = c1r - 1;
        end
```

```
    elseif N_rr(k) == 3 % If 3 rows of cable groups are needed, double banked in
region-1 and single banked in region-2
            c1r = max_cg_columns(k); %variable for the initial number of cables in
each row
            c2r = max_cg_columns(k); %variable for the initial number of cables in
each row
            c3r = N_rcg(k) - 2*max_cg_columns(k); % initial number of cables in the
second row
            cables_1st_row(k) = c1r; % Resetting value with ideal configuration
            cables_2nd_row(k) = c2r; % Resetting value with ideal configuration
            cables_3rd_row(k) = c3r;% saving the number of required cables
            cables_4th_row(k) = 0;% saving the number of required cables
            cableway_height_area1(k) =
(2*cg_d(k)+cg_spacing(k)+surf_spacing(k))/1000; %m setting the height of cable way
for a single conductor size
            %area1 indicates the area within the first 2 stiffeners
            cableway_height_area2(k) = (cg_d(k)+surf_spacing(k))/1000; %m setting the
height of cable way for a single conductor size
            %area2 indicates the area within the second and third stiffeners
            cableway_width_area1(k) = (c1r*cg_d(k)+(c1r-
1)*cg_spacing(k)+2*surf_spacing(k))/1000; %m setting the width of cable way for a
single conductor size
            cableway_width_area2(k) =  (2*surf_spacing(k)+c3r*cg_d(k)+(c3r-
1)*cg_spacing(k))/1000;
            area_1st_space = cableway_height_area1(k)*cableway_width_area1(k); %m2
cross-sectional area of a rectangular box 2 cable groups and spacing tall and c1r
cables and spacing wide
            area_2nd_space = cableway_height_area2(k)*cableway_width_area2(k); %m2
cross-sectional area of rectangular box of 1 cable group and spacing tall and c3r
groups and spacing wide
            cableway_area(k) = area_1st_space+area_2nd_space; %m^2, the area of the
smallest possible cableway with the current conductor size
            cableway_volume(k) = cableway_area(k)*cable_length; %m^2, the volume of
the smallest possible cableway with the current conductor size
    elseif N_rr(k) == 4 % If 4 rows of cable groups are needed, double banked in the
first area between stiffeners and double banked between the adjacent space
           c1r = max_cg_columns(k); %variable for the initial number of cables in
each row
           c2r = max_cg_columns(k); %variable for the initial number of cables in
each row
           c3r = max_cg_columns(k); %variable for the initial number of cables in
each row
           c4r = N_rcg(k) - 3*max_cg_columns(k); % initial number of cables in the
second row
           cableway_height_area1(k) = (2*cg_d(k)+cg_spacing(k)+surf_spacing(k))/1000;
%m setting the height of cable way for a single conductor size
           cableway_width_area1(k) = (c1r*cg_d(k)+(c1r-
1)*cg_spacing(k)+2*surf_spacing(k))/1000; %m setting the width of cable way for
conductor size and geometry
           area_1st_space = cableway_height_area1(k)*cableway_width_area1(k); %m2
cross-sectional area of a rectangular box 2 cable groups and spacing tall and c1r
cables and spacing wide
           cables_1st_row(k) = c1r; % Setting the required value
           cables_2nd_row(k) = c2r; % Setting the required value
```

```
            while c4r <= c3r    %checking volumes for each geometry moving one cable
to the 2nd row each iteration until it is rectangular (or as close as possible)
                area2 = (c3r*cg_d(k)+(c3r-
1)*cg_spacing(k)+2*surf_spacing(k))*(2*cg_d(k)+cg_spacing(k)+surf_spacing(k))/(100000
0); %m2 cross-sectional area of a rectangular box 2 cable groups and spacing tall and
c1r cables and spacing wide
                it_area = area_1st_space+area2; %Total area for the 2 spaces between
adjacent stiffeners
                if it_area < cableway_area(k) % Checking to see if this iteration is
smaller than any previously calculated
                    cables_3rd_row(k) = c3r; %re-setting value with ideal
configuration
                    cables_4th_row(k) = c4r; %re-setting value with ideal
configuration
                    cableway_height_area2(k) =
(2*cg_d(k)+cg_spacing(k)+surf_spacing(k))/1000; %m setting the height of cable way
for a single conductor size
                    cableway_width_area2(k) = (2*surf_spacing(k)+c3r*cg_d(k)+(c3r-
1)*cg_spacing(k))/1000;%m setting the width of cable way for conductor size and
geometry
                    area_2nd_space = cableway_height_area2(k)*cableway_width_area2(k);
%m2 cross-sectional area of rectangular box of 1 cable group and spacing tall and c3r
groups and spacing wide
                    cableway_area(k) = area_1st_space+area_2nd_space; %m^2, the area
of the smallest possible cableway with the current conductor size
                    cableway_volume(k) = cableway_area(k)*cable_length; %m^2, the
volume of the smallest possible cableway with the current conductor size
                end
                c4r = c4r + 1; % taking 1 cable from the third row and adding it to
the fourth
                c3r = c3r - 1;
            end
    end

    %checking the case where the minimum height is preferred over minimum area
    if N_rr(k) <= 2 && sr_possible == 0 % if 1 or 2 cable rows are needed
        sr_possible = 1; % ensuring this loop is only entered once, for the smallest
conductor size (as this will result in the minimum height)
        sr_N_rcg = N_rcg(k); % saving the value of number of required cable groups
for the given conductor size
        sr_cond_d_awg = cond_d_awg(k); % Saving the conductor diameter
        sr_cond_d = cond_d(k);% Saving the conductor diameter
        sr_cable_d = cable_d(k); % Saving the cable diameter
        sr_cableway_height = (cg_d(k)+surf_spacing(k))/1000; %m setting the height of
cable way for a single conductor size, plus surface spacing
        if N_rr(k) == 2 % if the other space between stiffeners has to be used
            sr_cableway_width = (sr_N_rcg*cg_d(k)+(sr_N_rcg-
1)*cg_spacing(k)+4*surf_spacing(k))/1000; %m setting the width of cable way for a
single conductor size
            %adds the cable group widths of the 1st row to the cable group
            %spacing, the cable group width and spacing of
            %the 3rd row (the 2st in the 2nd area) and finally the spacing for
            %the cable groups from a surface (4x)
            sr_cables_1st_row = max_cg_columns(k); % setting the number of cables in
the area between the 1st and 2nd stiffeners
```

```
            sr_cables_3rd_row = sr_N_rcg - sr_cables_1st_row; % setting the number of
cables in the area between the 2nd and 3rd stiffeners
            sr_cableway_area = sr_cableway_height*sr_cableway_width; %m^2, the area
of the smallest possible cableway with the current conductor size
            sr_cableway_volume = sr_cableway_area*cable_length; %m^2, the volume of
the smallest possible cableway with the current conductor size
        else
            % only other option is if it all fits in 1 row
            sr_cableway_width = (sr_N_rcg*cg_d(k)+(sr_N_rcg-
1)*cg_spacing+2*surf_spacing(k))/1000; % m, required cable group diameters and
spacing between cables, puls 2x spacing between surface
            sr_cableway_area = sr_cableway_height*sr_cableway_width; %m^2, the area
of the smallest possible cableway with the current conductor size
            sr_cableway_volume = sr_cableway_area*cable_length; %m^2, the volume of
the smallest possible cableway with the current conductor size
        end
    end
end

%Now create a loop to check for the lowest area, prioritizing if it can all
%fit in area1
Area = 99; % placeholder variable for the lowest area
Vol = 99; % placeholder variable for the lowest volume
ind = 99; % placeholder variable for the lowest conductor size indicator

if sr_possible == 1 % checked for in previous loop, true if any conductor has 1 or 2
rows required
    for j=1:length(cond_d) % checking through all conductor diameters
        if N_rr(j) <=2 % if the current conductor size requires 2 or less rows
            if cableway_area(j) < Area %Checking to see if the current iteration is
the smallest area
                Area = cableway_area(j); % Setting the area equal to the current
conductor area
                Vol = cableway_volume(j); % Setting the area equal to the current
conductor area
                ind = j; %Setting an indicato variable for later use
            end
        end
    end
else % 1 or 2 rows isnt possible, checking all possible solutions
    for j=1:length(cond_d) % checking through all conductor diameters
        if cableway_area(j) < Area %Checking to see if the current iteration is the
smallest area
            Area = cableway_area(j); % Setting the area equal to the current
conductor area
            Vol = cableway_volume(j); % Setting the area equal to the current
conductor area
            ind = j; %Setting an indicato variable for later use
        end
    end
end

if Vol == 99 %sending an error message if no possible solutions exist
    msg = 'Unable to meet power requirement within spatial constraints'; % Error
message to ensure user knows the options for Un
```

```
    error(msg)
end

%% Mass Calculations
%first will find the kg/m^2 area density of a single cable cross-section,
%then multiply by the number of cables and the length of the cables to get
%a full cable system mass
cond_r = cond_d./2; %mm creating an array of conductor radii

%the following area densities work cumulatively by adding the area density
%of each consecutive layer of the cable and cable group outlined in section
%9.9

ad_sc = rho_cu*pi*(cond_r(ind)^2); %kg/m area density of a single conductor, 1 to 1
unit conversion from g/mm

r_tsc = cond_r(ind)+t_st; %mm radius of single taped conductor
ad_tsc = ad_sc+rho_st*pi*(((r_tsc)^2)-(cond_r(ind)^2)); %kg/m area density of a
single taped conductor

r_tisc = r_tsc+t_ins; %mm radius of single taped and insulated conductor
ad_tisc = ad_tsc+rho_xlpe*pi*((r_tisc^2)-(r_tsc^2)); %kg/m area density of a single
taped and insulated conductor

r_titsc = r_tisc+t_ft; %mm radius of single taped-insulated-taped conductor
ad_titsc = ad_tisc+rho_ft*pi*((r_titsc^2)-(r_tisc^2)); %kg/m area density of a single
taped-insulated-taped conductor

r_titxsc = r_titsc+t_clst;  %mm radius of single taped-insulated-taped-crosslapped
taped conductor
ad_titxsc = ad_titsc+rho_st*pi*((r_titxsc^2)-(r_titsc^2)); %kg/m area density of a
single taped-insulated-taped-crosslapped taped conductor

%from here transitioning to the group of cables from the single cables,
%cg_d is previously defined as the radius of a 4-cable group

cg_r = (cable_d+sqrt(2.*cable_d.^2))/2;  %mm creating an array of cable group radii

ad_cg = 4*ad_titxsc; %kg/m, 4 times a single cable's area density

r_tcg = cg_r(ind)+t_st; %mm, radius of taped 4-cable group
ad_tcg = ad_cg+rho_st*pi*((r_tcg^2)-(cg_r(ind)^2)); %kg/m, area density of taped 4-
cable group, conservatively assuming tape is a perfect cylinder around the radius of
the cable group

r_tscg = r_tcg+t_sheild;  %mm, radius of taped-shielded 4-cable group
ad_tscg = ad_tcg+rho_cu*pi*((r_tscg^2)-(r_tcg^2)); %kg/m, area density of taped-
shielded 4-cable group

r_tstcg = r_tscg+t_pt; %mm, radius of taped-shielded-taped 4-cable group
ad_tstcg = ad_tscg+rho_pt*pi*((r_tstcg^2)-(r_tscg^2));  %kg/m, area density of taped-
sheleded-taped 4-cable group

r_tstjcg = r_tstcg+t_j; %mm, radius of taped-shielded-taped-jacketed 4-cable group
```

```
ad_tstjcg = ad_tstcg+rho_xlpe*pi*((r_tstjcg^2)-(r_tstcg^2));  %kg/m, area density of taped-shielded-taped-jacketed 4-cable group

Cable_Group_Mass = cable_length*ad_tstjcg/1000; %MT Mass of a single cable group

Total_System_Mass = N_rcg(ind)*Cable_Group_Mass; %MT Mass of entire system

if sr_possible == 1 % Calculating the mass of a single row of cables, if it is possible within given parameters
    sr_ad_sc = rho_cu*pi*((sr_cond_d/2)^2); %kg/m area density of a single conductor, 1 to 1 unit conversion from g/mm

    sr_r_tsc = (sr_cond_d/2)+t_st; %mm radius of single taped conductor
    sr_ad_tsc = sr_ad_sc+rho_st*pi*(((sr_r_tsc)^2)-((sr_cond_d/2)^2)); %kg/m area density of a single taped conductor

    sr_r_tisc = sr_r_tsc+t_ins; %mm radius of single taped and insulated conductor
    sr_ad_tisc = sr_ad_tsc+rho_xlpe*pi*((sr_r_tisc^2)-(sr_r_tsc^2)); %kg/m area density of a single taped and insulated conductor

    sr_r_titsc = sr_r_tisc+t_ft; %mm radius of single taped-insulated-taped conductor
    sr_ad_titsc = sr_ad_tisc+rho_ft*pi*((sr_r_titsc^2)-(sr_r_tisc^2)); %kg/m area density of a single taped-insulated-taped conductor

    sr_r_titxsc = sr_r_titsc+t_clst;  %mm radius of single taped-insulated-taped-crosslapped taped conductor
    sr_ad_titxsc = sr_ad_titsc+rho_st*pi*((sr_r_titxsc^2)-(sr_r_titsc^2)); %kg/m area density of a single taped-insulated-taped-crosslapped taped conductor

    %from here transitioning to the group of cables from the single cables,
    %cg_d is previously defined as the radius of a 4-cable group

    sr_cg_r = (sr_cable_d+sqrt(2*sr_cable_d^2))/2;  %mm creating cable group radius

    sr_ad_cg = 4*sr_ad_titxsc; %kg/m, 4 times a single cable's area density

    sr_r_tcg = sr_cg_r+t_st; %mm, radius of taped 4-cable group
    sr_ad_tcg = sr_ad_cg+rho_st*pi*((sr_r_tcg^2)-(sr_cg_r^2)); %kg/m, area density of taped 4-cable group, conservatively assuming tape is a perfect cylinder around the radius of the cable group

    sr_r_tscg = sr_r_tcg+t_sheild;  %mm, radius of taped-shielded 4-cable group
    sr_ad_tscg = sr_ad_tcg+rho_cu*pi*((sr_r_tscg^2)-(sr_r_tcg^2)); %kg/m, area density of taped-shielded 4-cable group

    sr_r_tstcg = sr_r_tscg+t_pt; %mm, radius of taped-shielded-taped 4-cable group
    sr_ad_tstcg = sr_ad_tscg+rho_pt*pi*((sr_r_tstcg^2)-(sr_r_tscg^2));  %kg/m, area density of taped-shielded-taped 4-cable group

    sr_r_tstjcg = sr_r_tstcg+t_j; %mm, radius of taped-shielded-taped-jacketed 4-cable group
    sr_ad_tstjcg = sr_ad_tstcg+rho_xlpe*pi*((sr_r_tstjcg^2)-(sr_r_tstcg^2));  %kg/m, area density of taped-shielded-taped-jacketed 4-cable group
```

```
    sr_Cable_Group_Mass = cable_length*sr_ad_tstjcg/1000; %MT Mass of a single cable
group

    sr_Total_System_Mass = sr_N_rcg*sr_Cable_Group_Mass; %MT Mass of entire system
end



%% Results
msg = 'The smallest cableway volume with the given constraints (prioritizing double-
banking the first space between stiffeners over single-banking both spaces between
stiffeners) is (m^3):';
msg
Vol
msg = 'With a corresponding cableway cross-sectional area of (m^2):';
msg
Area
msg = 'Resulting from the respective cableway height and width (m):';
msg
cableway_height_area1(ind)
cableway_width_area1(ind)
msg = 'The mass of this system is (MT):';
msg
Total_System_Mass
msg = 'The cableway grid consists of:';
msg
N_rcg(ind)
msg = 'Cables, with conductor size:';
msg
cond_d_awg(ind)
msg = 'Reminder, 10-40 corresonds to AWG sizes 1/0-4/0, all other sizes are kcmils.';
msg
msg = 'This corresponds to a conductor diameter of (mm):';
msg
cond_d(ind)
msg = 'The cables are oriented with the following grid dimensions (number of cables
in the 1st x 2nd 3rd x and 4th rows, with the 3rd and 4th rows being in the adjacent
stiffener space):';
msg
cables_1st_row(ind)
cables_2nd_row(ind)
cables_3rd_row(ind)
cables_4th_row(ind)

if sr_possible == 1 %if it is possible to have the cables in a single row with any
conductor size (possibly desired if minimum height is more important than minimum
area)
    msg = 'A single row of cable groups is possible if a minimum height is preferred
instead of prioritizing double-banking the first space between stiffeners over
single-banking both spaces between stiffeners, with the following specifications:';
    msg
    msg = 'The smallest cableway volume of a single-row grid is (m^3):';
    msg
    sr_cableway_volume
    msg = 'With a corresponding cableway cross-sectional area of (m^2):';
```

```
    msg
    sr_cableway_area
    msg = 'Resulting from the respective cableway height and width (m):';
    msg
    sr_cableway_height
    sr_cableway_width
    msg = 'The mass of this system is (MT):';
    msg
    sr_Total_System_Mass
    msg = 'The cableway grid consists of:';
    msg
    sr_N_rcg
    msg = 'Cables, with conductor size:';
    msg
    sr_cond_d_awg
    msg = 'Reminder, 10-40 corresponds to AWG sizes 1/0-4/0, all other sizes are
kcmils.';
    msg
    msg = 'This corresponds to a conductor diameter of (mm):';
    msg
    sr_cond_d
else
    msg = 'A single row of cable groups is not possible within the given
constraints';
    msg
end
```

Appendix B: Cable Way Dimensions

System Power Level	Nominal System Voltage (U_n)	Conductor Diameter	Height Region-1	Width Region-1	Height Region-2	Width Region-2	Total Cable-way Area	Total Cable System Volume
[MW]	[kV]	[mm]	[m]	[m]	[m]	[m]	[m^2]	[m^3]
75	12	8.25	0.1973	0.5552	0.1973	0.4441	0.197162	39.43238
75	12	9.27	0.2055	0.4628	0.2055	0.4628	0.190211	38.04216
75	12	10.4	0.2146	0.4834	0.2146	0.4834	0.207475	41.49506
75	12	11.68	0.2249	0.5068	0.2249	0.3801	0.199464	39.89276
75	12	12.7	0.2331	0.5254	0.1018	0.3940	0.16258	32.51599
75	12	15.03	0.2519	0.5679	0.1099	0.1420	0.15866	31.73196
75	12	16.06	0.2602	0.4400	0.1135	0.2934	0.147789	29.55778
75	12	17.96	0.2755	0.4661	0.1202	0.1554	0.147090	29.41793
75	12	19.67	0.2893	0.4895	0.1261	0.1632	0.162192	32.43837
75	12	21.25	0.3020	0.5111	N/A	N/A	0.154352	30.87044
75	12	22	0.3080	0.5214	N/A	N/A	0.160591	32.11824
75	12	22.72	0.3138	0.5312	N/A	N/A	0.166691	33.33811
75	12	24.1	0.3250	0.5501	N/A	N/A	0.178783	35.7565
75	12	25.4	0.3354	0.5679	N/A	N/A	0.190474	38.09473
100	12	8.25	N/A	N/A	N/A	N/A	N/A	N/A
100	12	9.27	N/A	N/A	N/A	N/A	N/A	N/A
100	12	10.4	N/A	N/A	N/A	N/A	N/A	N/A
100	12	11.68	N/A	N/A	N/A	N/A	N/A	N/A
100	12	12.7	0.2331	0.5254	0.2331	0.5254	0.244941	48.9883
100	12	15.03	0.2519	0.5679	0.1099	0.5679	0.205466	41.09324
100	12	16.06	0.2602	0.4400	0.2602	0.4400	0.228976	45.7952
100	12	17.96	0.2755	0.4661	0.2755	0.3107	0.214008	42.80168
100	12	19.67	0.2893	0.4895	0.1261	0.4895	0.203338	40.66766
100	12	21.25	0.3020	0.5111	0.1316	0.3407	0.199188	39.83766
100	12	22	0.308	0.5214	0.1342	0.3476	0.207239	41.44782
100	12	22.72	0.3138	0.5312	0.1368	0.1771	0.190918	38.18357
100	12	24.1	0.3250	0.5501	0.1416	0.1834	0.204752	40.95039
100	12	25.4	0.3354	0.5679	0.1461	0.1893	0.218130	43.62608
125	12	8.25	N/A	N/A	N/A	N/A	N/A	N/A
125	12	9.27	N/A	N/A	N/A	N/A	N/A	N/A
125	12	10.4	N/A	N/A	N/A	N/A	N/A	N/A
125	12	11.68	N/A	N/A	N/A	N/A	N/A	N/A
125	12	12.7	N/A	N/A	N/A	N/A	N/A	N/A
125	12	15.03	0.2519	0.5679	0.2519	0.5679	0.286108	57.2216
125	12	16.06	N/A	N/A	N/A	N/A	N/A	N/A

System Power Level	Nominal System Voltage (U_n)	Conductor Diameter	Height Region-1	Width Region-1	Height Region-2	Width Region-2	Total Cable-way Area	Total Cable System Volume
[MW]	[kV]	[mm]	[m]	[m]	[m]	[m]	[m^2]	[m^3]
125	12	17.96	0.2755	0.4661	0.2755	0.4661	0.256821	51.36422
125	12	19.67	0.2893	0.4895	0.2893	0.4895	0.283225	56.64494
125	12	21.25	0.3020	0.5111	0.30200	0.3407	0.257244	51.44872
125	12	22	0.3080	0.5214	0.308	0.3476	0.267652	53.5304
125	12	22.72	0.3138	0.5312	0.1368	0.5312	0.239359	47.87174
125	12	24.1	0.3250	0.5501	0.1416	0.5501	0.256677	51.33533
125	12	25.4	0.3354	0.5679	0.1461	0.3786	0.245787	49.15742
75	18	8.25	0.2319	0.5226	0.1013	0.5226	0.174130	34.82606
75	18	9.27	0.2401	0.5413	0.1048	0.2706	0.158325	31.665
75	18	10.4	0.2492	0.5619	0.1088	0.2809	0.170587	34.11748
75	18	11.68	0.2596	0.4389	0.1132	0.4389	0.163622	32.72438
75	18	12.7	0.2678	0.4529	0.1168	0.3019	0.156549	31.30971
75	18	15.03	0.2865	0.4848	N/A	N/A	0.138895	27.77904
75	18	16.06	0.2948	0.4989	N/A	N/A	0.147076	29.41514
75	18	17.96	0.3101	0.5249	N/A	N/A	0.162771	32.5543
75	18	19.67	0.3239	0.5484	N/A	N/A	0.177627	35.52535
75	18	21.25	0.3366	0.3800	N/A	N/A	0.127908	25.5816
75	18	22	0.3427	0.3868	N/A	N/A	0.132556	26.51127
75	18	22.72	0.3485	0.3934	N/A	N/A	0.137100	27.41998
75	18	24.1	0.3596	0.4060	N/A	N/A	0.145998	29.19952
75	18	25.4	0.3701	0.4179	N/A	N/A	0.154665	30.93296
100	18	8.25	0.2319	0.5226	0.2319	0.5226	0.242382	48.47638
100	18	9.27	0.2401	0.5413	0.2401	0.4059	0.227423	45.48454
100	18	10.4	0.2492	0.5619	0.2492	0.4214	0.245038	49.00767
100	18	11.68	0.2596	0.4389	0.2596	0.4389	0.227877	45.57538
100	18	12.7	0.2678	0.4529	0.2678	0.3019	0.202135	40.42709
100	18	15.03	0.2865	0.4848	0.1249	0.3232	0.179263	35.85258
100	18	16.06	0.2948	0.4989	0.1285	0.3326	0.189815	37.96296
100	18	17.96	0.3101	0.5249	0.1352	0.1750	0.186431	37.2863
100	18	19.67	0.3239	0.5484	N/A	N/A	0.177627	35.52535
100	18	21.25	0.3366	0.5700	N/A	N/A	0.191862	38.3724
100	18	22	0.3427	0.3868	0.1493	0.1934	0.161431	32.2862
100	18	22.72	0.3485	0.3949	0.1518	0.1967	0.167482	33.49634
100	18	24.1	0.3596	0.4060	0.1566	0.203	0.177787	35.55748
100	18	25.4	0.3701	0.4179	0.1611	0.2089	0.188319	37.66372
125	18	8.25	N/A	N/A	N/A	N/A	N/A	N/A
125	18	9.27	N/A	N/A	N/A	N/A	N/A	N/A

System Power Level	Nominal System Voltage (U_n)	Conductor Diameter	Height Region-1	Width Region-1	Height Region-2	Width Region-2	Total Cable-way Area	Total Cable System Volume
[MW]	[kV]	[mm]	[m]	[m]	[m]	[m]	[m^2]	[m^3]
125	18	10.4	0.2492	0.5619	0.2492	0.5619	0.280051	56.01019
125	18	11.68	N/A	N/A	N/A	N/A	N/A	N/A
125	18	12.7	N/A	N/A	N/A	N/A	N/A	N/A
125	18	15.03	0.2865	0.4848	0.2865	0.3232	0.231492	46.2984
125	18	16.06	0.2948	0.4989	0.1285	0.4989	0.211184	42.23687
125	18	17.96	0.3101	0.5249	0.1352	0.35	0.210091	42.0183
125	18	19.67	0.3239	0.5484	0.1411	0.3656	0.229213	45.84258
125	18	21.25	0.3366	0.5700	0.1466	0.17	0.216784	43.3568
125	18	22	0.3427	0.3868	0.3427	0.3868	0.265113	53.02254
125	18	22.72	0.3485	0.3934	0.1518	0.3934	0.196818	39.3636
125	18	24.1	0.3596	0.406	0.1566	0.406	0.209577	41.91544
125	18	25.4	0.3701	0.4179	0.1611	0.4179	0.221988	44.3977