Impact of MV Standards on Shipboard DC Cable System Size

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Abstract There is rising interest in medium-voltage direct current (MVDC) power systems for several reasons, including compatibility with DC loads and avoidance of alternating current (AC) frequency synchronization issues when combining multiple source outputs [1]. However, few MVDC systems are currently in operation, and there is relatively little experience compared to the knowledge available for medium-voltage alternating current (MVAC) systems. Presently, IEEE Std. 1709 is the only standard that provides guidance for MVDC systems [2]. This work's objective is to harmonize the information within MVAC standards to produce prospective design and test values for shipboard MVDC cables and evaluate their impact on cable system sizes. Standards for MVAC cable design and test parameters including Basic Lightning Impulse Insulation Level, Withstand Voltage, and cable insulation thickness are compiled to understand the range of parameter values deemed acceptable for MVAC cables. Based on existing shipboard MVAC standards and IEEE Std. 1709, this study produces prospective design and test values for a shipboard MVDC system with a 12 kV Nominal System Voltage. Additionally, a tradeoff was identified with the thickness of cable insulation where a small reduction in cable system size can be achieved but at the expense of substantially greater electric stresses within the insulation.

***Index Terms*— MVAC Cables, MVDC Cables, MVDC Insulation Thickness, MVDC Test Voltages, Medium Voltage Standards**

I. INTRODUCTION

Naval and commercial applications are developing future ship classes that will have considerably larger electric power requirements than current vessels due to increasing popularity of electric propulsion and high electric load systems. Proposed designs call for systems with a medium-voltage direct current (MVDC) bus, which is currently being researched for both marine and terrestrial applications. MVDC cables are being evaluated based on studies that have found benefits of MVDC systems such as: elimination of alternating current (AC) – direct current (DC) converters for loads requiring DC power, better reliability and survivability of power due to dynamic reconfigurability, compatibility with electronic weaponry, and reduction of magnetic signature [1].

There is extensive knowledge, experience, and standards regarding medium-voltage alternating current (MVAC) systems in contrast to available information for MVDC systems. The only standard found to date for MVDC systems is the IEEE 1709 Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Systems on Ships [2].

The graphs and materials in this paper are largely collected from a detailed study that evaluated existing standards for shipboard and terrestrial MVAC systems and the IEEE standard for shipboard MVDC systems [3]. The bounds of medium-voltage (MV) systems can vary between references; for this study MV is considered to be Nominal System Voltages (U_n) of 1-35 kV. From these standards the prescribed insulation thickness design values, lightning impulse Basic Insulation Level (BIL), and Withstand Voltage (U_w) test values are compared. The objective of this work is to harmonize the information contained in standards to produce prospective design and test values for shipboard MVDC cables. Of note, the sole MVDC standard (IEEE 1709) provides BIL and DC U_w test voltages but does not outline AC U_w tests or insulation thicknesses for MVDC cables [2]. One suggested U_n for a shipboard MVDC is 12 kV [4], and while the full range of MV is evaluated, the 12 kV U_n level is the main focal point of this study. This study produces prospective design and test values for a shipboard MVDC system with a 12 kV Nominal System Voltage.

II. MVAC INSULATION THICKNESS

By convention and as reflected in all evaluated standards, international and local, power cable insulation thicknesses for MVAC systems are fixed at certain specific values. These cable insulation thickness values are determined according to three user-selected quantities: the Nominal System Voltage (U_n), the conductor diameter, and the expected ground fault clearing time. This third quantity by convention corresponds to 3 levels of insulation

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thickness expressed as a percentage: 100%, 133%, and 173%. These apply where ground faults will be cleared within the time limits of 1 min, between 1-60 min, or exceeding 60 min, respectively [5]. Within all evaluated references, insulation thickness for a given U_n and percent insulation level was constant for conductor diameters over the range of 8.25-25.4 mm (AWG 1/0-1000 kcmil). Hence, to reduce user-selected design to 2 quantities, voltage and fault clearing time, conductor diameters within this study are limited to the typical range of 8.25-25.4 mm.

The common material within all evaluated references for the specified insulation thicknesses is extruded cross-linked polyethylene (XLPE), hence XLPE insulation thicknesses are compared in this study. While XLPE is commonly used and is successful with MVAC power cables, with MVDC power cables XLPE can be susceptible to charge accumulation leading to DC breakdown (i.e., insulation failure). This can be overcome by modifying the material with additives, referred to as "filled XLPE" [6]. For this study the insulation will be referred to as XLPE, but a suitably modified XLPE insulation material or equivalent must be considered for application to MVDC cables.

Standard cable insulation thickness values for a given U_n are shown in Fig. 1 [7] [8] [9] [10] [11] [12]. Corresponding references for either land-based or shipboard systems and system current type (AC vs DC) are shown in the legend after the standard name. For example, IEEE Std. 835 (Land, AC), means IEEE Std. 835 is applicable to land-based AC installations. Presently no standards provide insulation thickness guidance for MVDC cables. IEC Std. 60092-354 and IEC Std. 60502-2 contain identical guidance for different location applicability (land vs ship), and so they are shown on the same line with their respective applicability (red in Fig. 1) [11] [12].

As is stated within some standards, and as is expected in practice, specified values are provided only at several distinct voltage points. Hence, when a desired U_n is above a given specified voltage class the design and test values of the next higher voltage class are to be used. This results in the staircase or step function nature for insulation thickness versus U_n. For example, according to IEEE Std. 1580, cables with system voltage just under 8 kV will require 3.56 mm thickness, while with voltages just above 8 kV cables will be 5.46 mm thick under 133% insulation levels [10].

Note at 12 kV U_n there are no transitions for insulation thickness according to MVAC standards so there is no ambiguity for the thickness value.

III. BIL TEST VOLTAGES

The standards compared in this section provide BIL test values for MV cables for corresponding Nominal System Voltage, U_n. Parameters identified for each BIL test include: (1) the current type of the cable to be tested (either AC or DC), (2) the number of impulses applied, (3) whether the impulse tests are to be applied once at the production facility for a family of cables to demonstrate satisfactory performance characteristics (type test), or to every length of cable produced (acceptance test), (4) the length of cable to

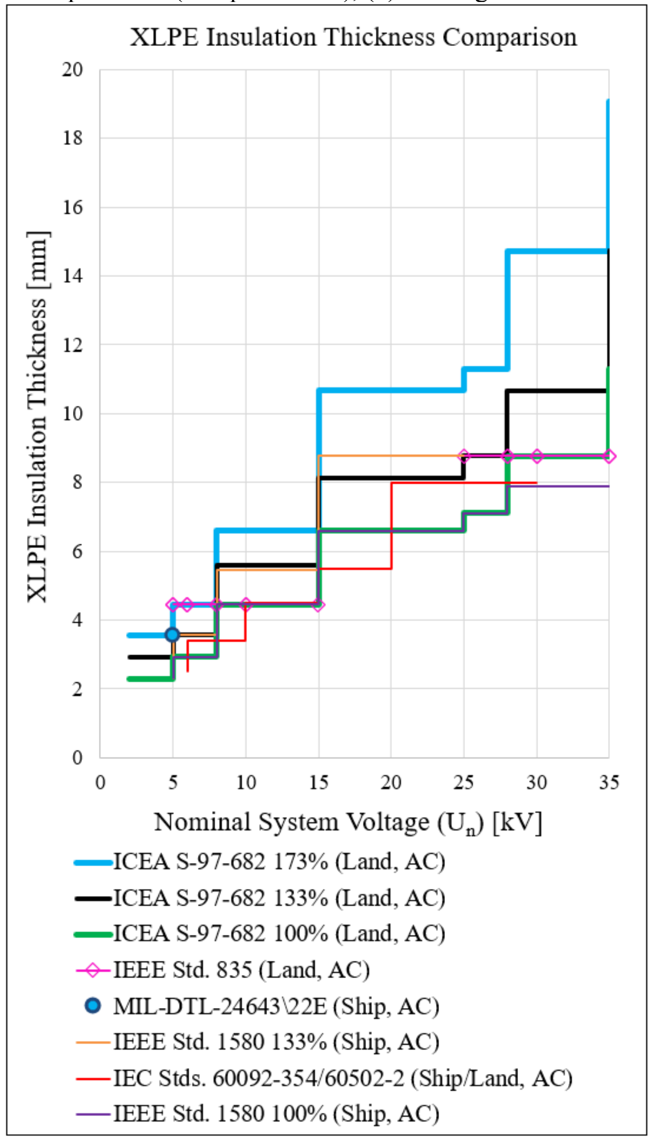


Fig. 1: MVAC Cable XLPE Insulation Thickness vs. Nominal System Voltage

be tested (a sample or the entirety of the cable), and (5) the temperature at which the cable is held before applying the impulses (either ambient or near the maximum rated temperature of the cable). The collected BIL values are shown in Fig. 2, with the legend containing the corresponding reference and key parameters [13] [7] [2] [14] [15] [11] [12] [16]. For example, IEEE Std. 400.1 (Land, AC, 10, Type, Sample, Heated) means IEEE Std. 400.1 is applicable to land based MVAC cables with a 10-impulse type test applied to a sample length of a single cable as a proof of integrity for construction, and the cable is to be heated near the maximum rated temperature when the impulse is applied.

Note, the IEC Std. 60071 series does not specify when the test is to be performed (type or acceptance test), the length of cable to be tested, nor the temperature at which the test is to be performed [14] [15]. Additionally, IEC Std. 60092-350 and IEC Std. 60502-2 contain identical guidance with different applicability, and so they are shown as the same line (red in Fig. 2) with their respective applicability.

No document specifying BIL values for U.S. Navy power cables was found. An interview with a Navy representative indicated that one 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 were used in this evaluation for comparison and are shown in Fig. 2.

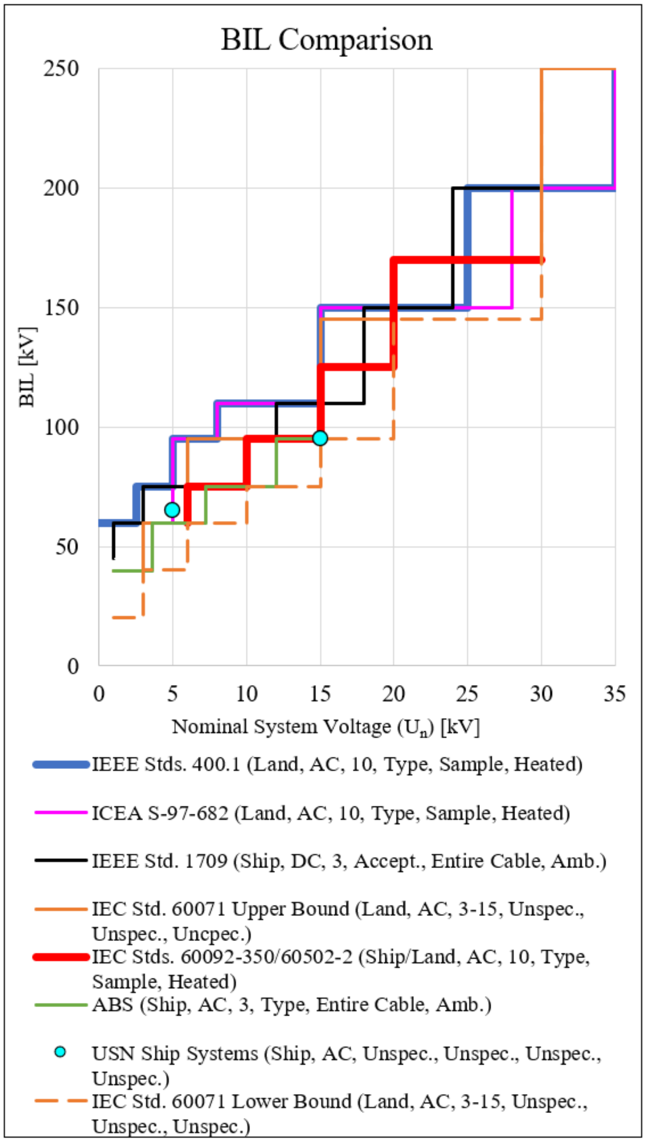


Fig. 2: MV(AC or DC) Cable BIL vs. Nominal System Voltage

Note two standards, IEEE Std. 1709 and ABS Steel Vessels, define a BIL step increase exactly at a 12 kV system voltage [2] [16]. By convention the next higher BIL levels of 110 kV and 95 kV respectively could be considered appropriate for a 12 kV system, whereas these BIL levels become 95 kV and 75 kV respectively for system voltages just under 12 kV.

IV. ACCEPTANCE AC AND DC WITHSTAND TESTS

The parameters within the evaluated standards for Withstand Tests for MV cables include: (1) the corresponding Nominal System Voltage, (2) the Withstand Test category (type or acceptance), (3) the Withstand Voltage (U_w) level, (4) the test duration, (5) the expected ground fault clearing time (often expressed as an insulation percentage), and (6) the frequency for the applied U_w (if U_w is AC). All evaluated references provide test values for acceptance tests (factory post-production tests), and AC frequencies within the range of 48-62 Hz.

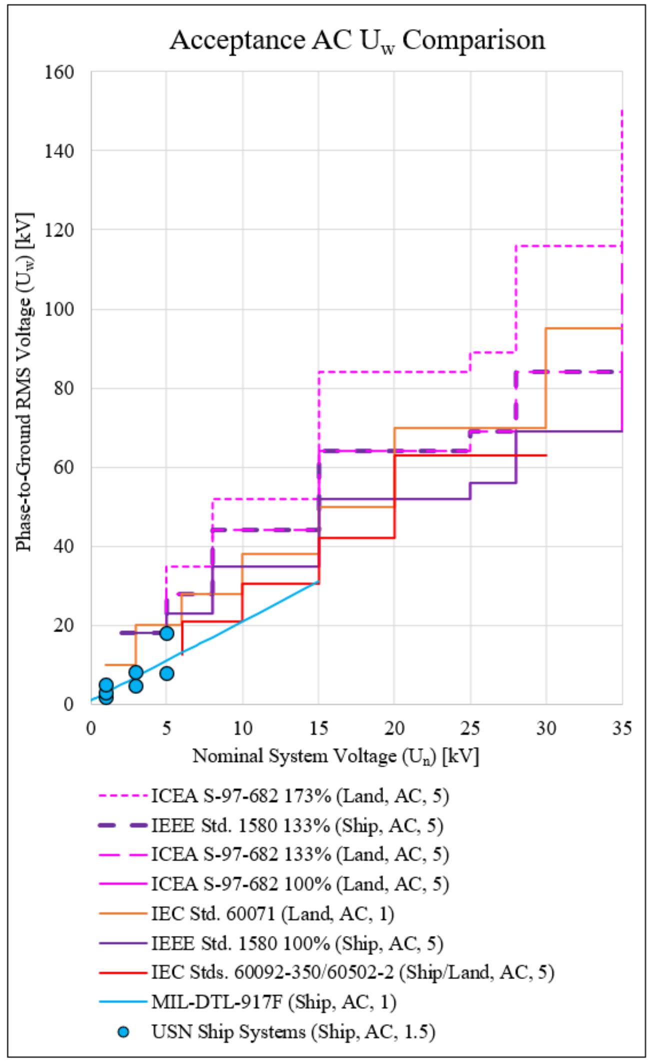


Fig. 3: Acceptance AC Withstand Voltage vs. Nominal System Voltage for MVAC Cables

The Withstand Voltages versus Nominal System Voltage are shown in Fig. 3 and Fig. 4 for AC and DC, respectively [7] [10] [14] [15] [11] [12] [17] [18] [19] [20] [21] [22] [9] [23] [24] [25]. The remaining test parameters and reference applicability are shown in the legends of the figures. For example, IEEE Std. 1580 100% (Ship, AC, 5) means the given thickness values are from IEEE Std. 1580 applicable to a shipboard AC power system with a 100% insulation level and the Withstand Test has a 5-minute duration. IEC Std. 60092-350 and IEC Std. 60502-2 contain identical guidance with different applicability, and so they are shown as the same line with their respective applicability (red in Fig. 3) [18] [12].

Note, while the identified withstand voltage values for AC systems have no step amount transitions for a 12 kV system voltage, for DC systems the IEEE Std. 1709 shipboard standard does identify a transition at 12 kV [2]. Hence a DC system just above 12 kV requires a U_w of 50 kV, whereas for a U_n just below 12 kV a U_w of 35 kV is required.

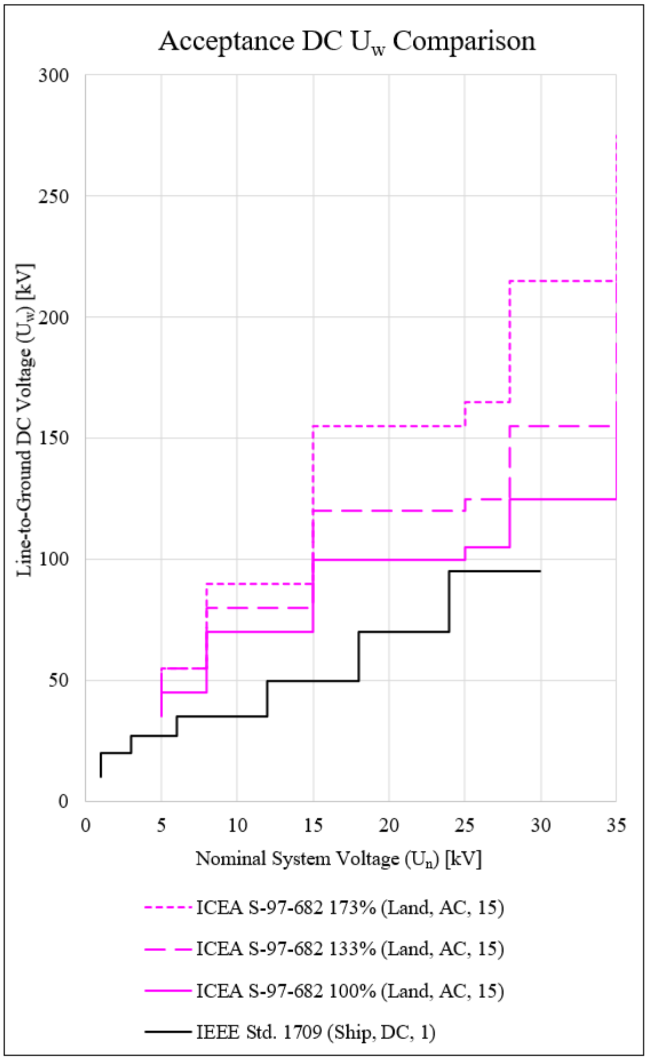


Fig. 4: Acceptance DC Withstand Voltage vs. Nominal System Voltage, MV(AC or DC) Cable

V. CABLE INSULATION ELECTRIC STRESS AT OPERATIONAL AND TEST VOLTAGES

The average electric stress within the insulation of a cable was calculated with Equation 1. E_{ave} is the average electric stress within the insulation, V is the voltage applied to the cable, and t_{ins} is the insulation thickness.

$$E_{ave} = \frac{V}{t_{ins}} \qquad (1)$$

The average electrical stress at operational voltage was calculated for all references that provide insulation thicknesses for MVAC cable, using the phase-to-ground root mean square (RMS) Cable Nominal Voltage (U_o). The average electrical stress at test voltages was calculated for all references that provide both insulation thickness values and test voltage values from the same standard committee with the same applicability (i.e. standards from the IEC applicable to shipboard MVAC systems). Test values are provided within the sole MVDC standard, IEEE Std. 1709 applicable to shipboard MVDC cables, however no insulation thicknesses are provided [2]. For this evaluation, the thicknesses for MVAC shipboard cables, IEEE Std. 1580, were used to calculate the electric stresses at corresponding U_n values [10].

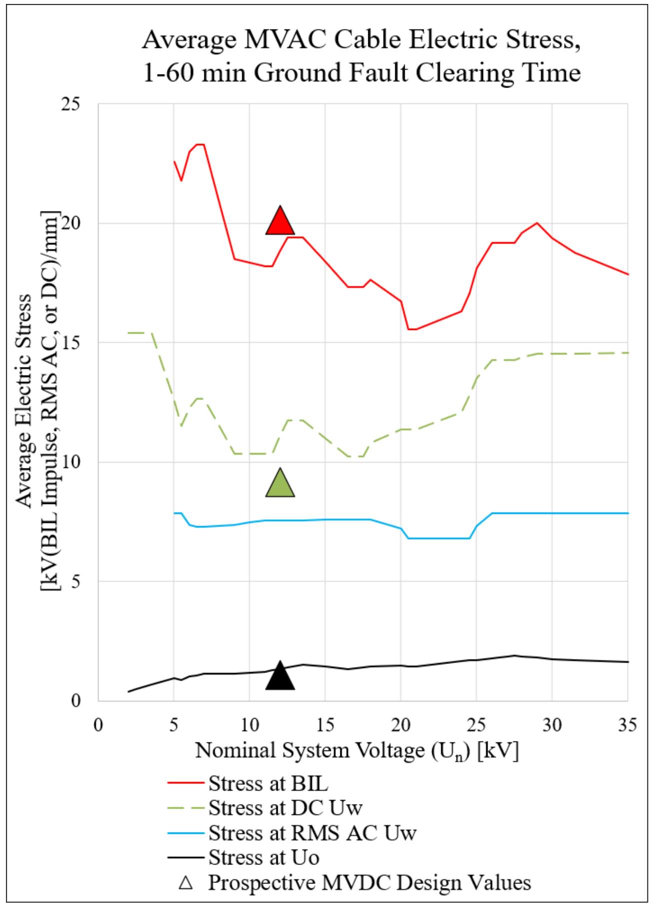
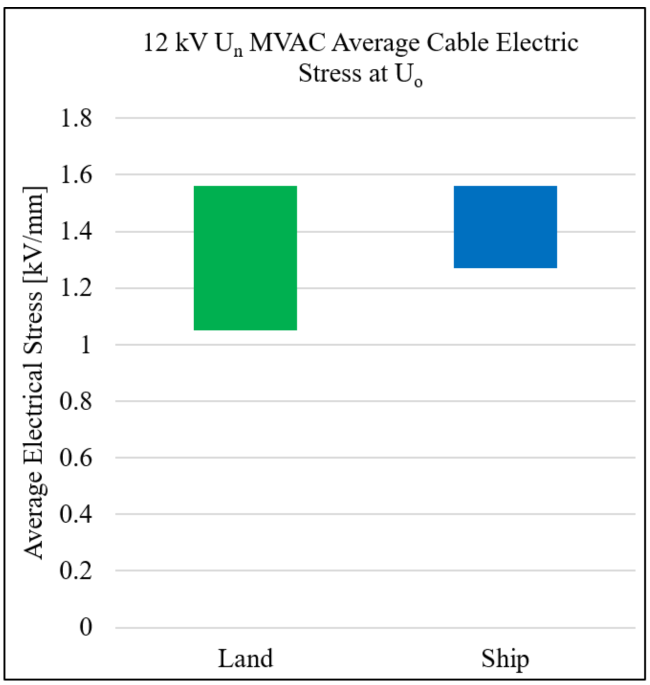


Fig. 5: Average Electric Stress within Cable Insulation at Operational and Test Voltages for MVAC Cables, Triangles are MVDC Design Values

The average electrical stresses for each category of ground fault clearing times were averaged to highlight typical values. The details behind these averages are presented in "The Impact of Electrical Standards on MVDC Shipboard Power Cable Size" [3]. Assuming shipboard ground fault clearing times have the potential to exceed 1 min but under 1 hour, the design and test electrical stress values for a 133% insulation level (with clearance time of 1-60 min) are shown in Fig. 5. Prospective MVDC design values at 12 kV U_n, discussed later in this paper, are also shown in Fig. 5 as triangles to highlight that the resultant proposed cable stresses are compatible with typical values identified by the standards.

VI. INSULATION ELECTRIC STRESS FOR MVAC CABLES IN A SYSTEM WITH A 12 KV NOMINAL SYSTEM VOLTAGE

The resultant average line-to-ground electrical stresses within the MVAC cable insulation at the Cable Nominal Voltage, U_o, were calculated for references that provide insulation thicknesses for cables in a 12 kV U_n system using Equation 1. U_o for an AC system is considered to be the phase-to-ground RMS voltage experienced by the cable during normal operation, and the line-to-ground voltage (1/2 U_n) for DC cables. Fig. 6 displays the range of average electrical stresses at the 12 kV operational voltage for MVAC cables for all given percent insulation levels (ground fault clearing times), separated for land based and shipboard references. The highlighted regions in Fig. 6 depict the range of permmited values. The refereces for each category are shown below the figure. If the reference provides multiple insulation levels, they are listed following the reference.



Land Based: [7] 100, 133, and 173% Ins. Levels, [8], [12]
Shipboard: [10] 100 and 133% Ins. Levels, [11]

Fig. 6: MVAC Cable Insulation Electrical Stress at Cable Nominal Voltage

The average electrical stresses at each test voltage were calculated for references that provide both test voltage guidance and insulation thickness. Fig. 7 shows these two stresses of BIL and AC U_w seperated for land and shipboard applications for all given percent insulation levels (ground fault clearing times). Table 1 provides the corresponding references covered within each category of Fig. 7, citing the reference for the test voltage and insulation thickness, if they are different references but have the same applicability and are from the same organization. The highlighted regions in Fig. 7 depict the range of stresses, if a category has a single data point the stress is indicated by a line.

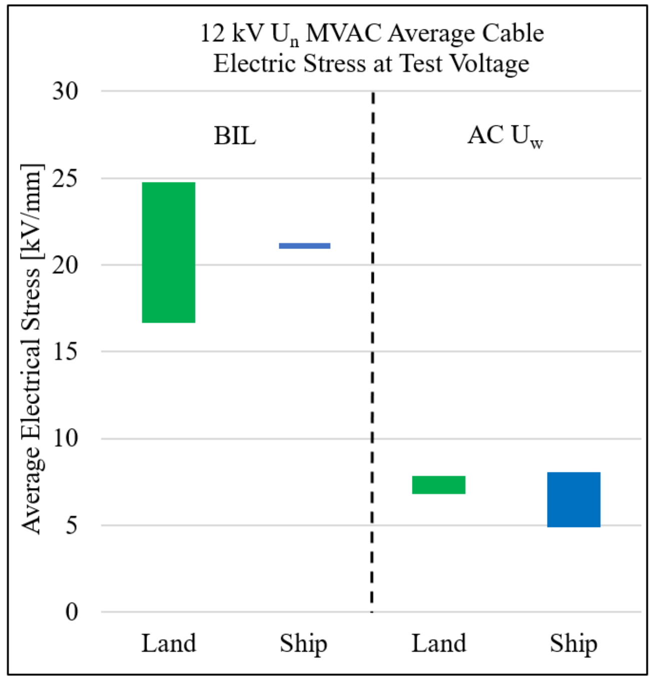


Fig. 7: MVAC Cable Insulation Electrical Stress at Test Voltages

Category	Applicable Standards	
	Test Voltage	**Insulation Thickness**
Land Based at BIL	[7] 100, 133, and 173% Ins. Levels	[7]
	[12]	[12]
	[26]	[8]
	[14] Upper and Lower Bounds	[12]
Shipboard at BIL	[18]	[11]
Land-Based at AC U_w	[12]	[12]
	[7] 100, 133, and 173% Ins. Levels	[7]
Shipboard at AC U_w	[18]	[11]
	[10] 100 and 133% Ins. Levels	[10]

Table 1: References for MVAC Cable Insulation Electrical Stress at Test Voltages

VII. IMPACT OF STANDARDS ON SHIPBOARD MVDC CABLE SYSTEMS

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, which is often expressed as a percent insulation level. Table 2 shows the impact the conductor diameter and percent insulation level have on cable system area for a system with 4-conductor (2 pairs of +/- conductor pairs) cables in a shipboard 12 kV DC U_n system with a 75 MW power level

[3]. 4-conductor cables were selected to reduce the magnetic signature of the power cables [4].

Since no known MVDC standard provides insulation thicknesses, the 100% and 133% values from IEEE Std. 1580 are used for this example (shipboard standard for MVAC cables) [10]. The arrangement of the cables for this example was constrained within a notional ship, with the cables within the overhead stiffeners of an internal deck [3]. The ampacity of MVDC cables must be considered to determine the required number of conductors for a given power system. Presently, no existing standard provides ampacities for MVDC cables. Since cable ampacities are determined by the allowed heat flux per unit length of the cable, one method of approximating 4-conductor (2 pairs of +/- conductor pairs) MVDC cable group ampacities is to use standard ampacities for 3-conductor MVAC cables for guidance [4]. For this evaluation, the ampacity of 4-conductor MVDC cables were calculated by setting the heat produced per unit length for 3-conductor MVAC cables, with the ampacities found in Table 6 of IEEE Std. 45.8, equal to that of 4-conductor MVDC cables with the same conductor size [5]. The heat produced per unit length of a 3-conductor AC cable group was found using Equation 2. $HeatProduced_{AC3Cond}$ is the heat produced per unit length of a 3-conductor group with AC current, $I_{ACSingleCond}$ is the ampacity of a single conductor in the 3-conductor AC group, and R_{AC} is the conductor resistance to AC current.

$$HeatProduced_{AC3Cond} = 3 * I^2_{AC_{SingleCond}} * R_{AC} \quad (2)$$

The heat produced per unit length of a 4-conductor DC cable group was found using Equation 3. $HeatProduced_{DC4Cond}$ is the heat produced per unit length of a 4-conductor group with DC current, $I_{DCSingleCond}$ is the ampacity of a single conductor in the 4-conductor DC group, and R_{DC} is the conductor resistance to DC current.

$$HeatProduced_{DC4Cond} = 4 * I^2_{DC_{SingleCond}} * R_{DC} \quad (3)$$

Setting the heat produced per unit length for each respective cable group and solving for $I_{DCSingleCond}$ results in Equation 4.

$$I_{DC_{SingleCond}} = \sqrt{\frac{3 * R_{AC}}{R_{DC}} * \frac{I_{AC_{SingleCond}}}{2}} \quad (4)$$

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 [4]. 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 [27]. Using this method, for conductors with diameters in the range of 8.25–25.4 mm and a 60 Hz frequency, the AC resistance is equivalent to the DC resistance. This equivalency applied to Equation 4 results in Equation 5, which was used to calculate DC ampacities for this study.

$$I_{DC_{SingleCond}} = \frac{\sqrt{3}}{2} * I_{AC_{SingleCond}} \quad (5)$$

The distance between each cable group was calculated using IEEE MVAC cable spacing guidance, with the spacing between a cable group and a surface set to half the required spacing between cable groups [5] [3].

Conductor Diameter (mm)	**Cableway Area (m^2)**		**% Incr.**
	100% ins.	**133% ins.**	
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

Table 2: Shipboard 75 MW, 12 kV U_n MVDC 4-Conductor Cableway Cross-Sectional Area Increase Due to Insulation Level

The average electrical stresses at BIL, DC U_w, and U_o for cables in a 12 kV DC U_n shipboard system are shown in Table 3, as 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 [10]. The use of the 133% insulation level causes an 18.5% reduction in average electric stress for all tests.

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 3: Average Electrical Stresses in 12 kV U_n MVDC Cable Insulation

VIII. PROSPECTIVE VALUE FOR SHIPBOARD MVDC CABLES

Based on the design and test values of the sole existing shipboard MVDC cable standard and the range of MVAC cable standard design and test values, prospective design and test values are shown in Table 4 for shipboard MVDC systems with a 12 kV Nominal System Voltage.

Prospective MVDC Cable Design and Test Values at 12 kV Nominal System Voltage		
Design Parameter	**Units**	**Value**
XLPE Insulation Thickness	mm	5.46
BIL Test Voltage	kV	110
DC Acceptance U_w	kV	50
DC Accept. Withstand Test Duration	min	1

Table 4: Prospective Shipboard Cable Design and Test Values at 12 kV U_n

Because 12 kV U_n happens to be at a boundary condition for IEEE Std. 1709 and any slight increase in actual U_n would require meeting the next higher level of test values, it appears viable to select the higher test values for a 12 kV U_n system [2]. The BIL and DC U_w values in Table 4 correspond to the values given by IEEE Std. 1709 for a system with a U_n between 12-18 kV [2]. The XLPE insulation thickness is the value of the IEEE shipboard MVAC 133% insulation level (1-60 min ground fault clearing time).

The average electrical stresses for the design and test values of the prospective MVDC cable design are shown in Table 5 and in Fig. 5. The prospective average stresses are compared to the shipboard MVAC average stresses for all given percent insulation levels (ground fault clearing times) in Fig. 8 and Fig. 9. The range of stresses in these figures are represented by the highlighted regions, if a category has a single data point the stress is indicated by a line.

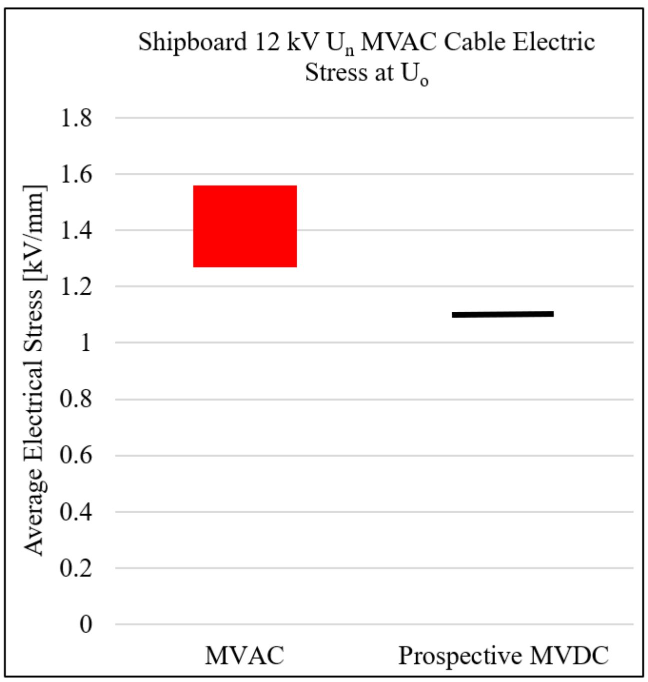


Fig. 8: Shipboard MV Cable Insulation Average Electrical Stress at Cable Nominal Voltage

Note, while the DC U_w in Fig. 9 appears larger than that for AC, it is less than the DC U_w tests of AC cables, see Fig. 5.

Average Electrical Stresses of Prospective MVDC Cable Design at Operation and Test Voltages	
Voltage (Operational or Test)	**kV/mm**
BIL Test Voltage	20.15
DC Accept. Withstand Test Voltage (U_w)	9.16
Cable Nominal Voltage (1/2 U_n)	1.10

Table 5: Average Electrical Stresses of Prospective MVDC Cable Design

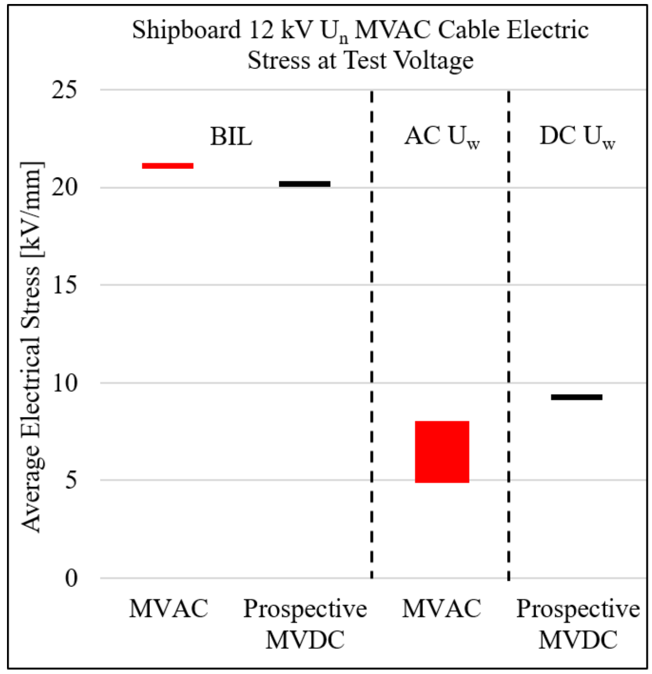


Fig. 9: Shipboard MV Cable Insulation Average Electrical Stress at Test Voltages

Using the prospective insulation thickness design for shipboard MVDC cables, an example shipboard cableway was dimensioned. Furthermore, the design values have been optimized for a minimal cross-sectional area [3]. The cableway shown in Fig. 10 is a shipboard MVDC system with 75 MW overall power, a 12 kV Nominal System Voltage, and 21.25 mm diameter conductors. The constraints outlined in section VII were used for spacing, cable geometry, and cable ampacity.

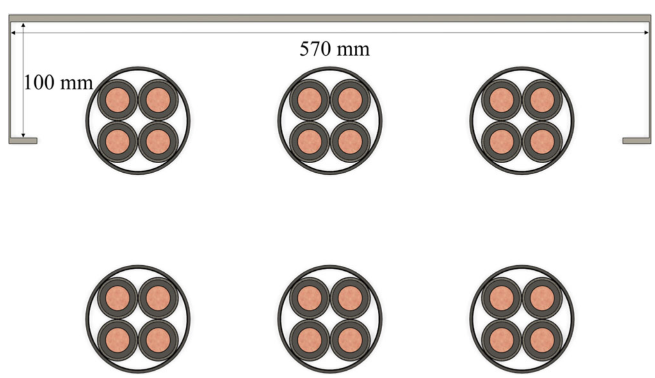


Fig. 10: Example MVDC Cableway: 75 MW, 12 kV Nominal System Voltage, 21.25 mm Conductors

Note for a less conservative 100% insulation thickness, the corresponding total cableway cross-sectional area for the same 12 kV DC, 75 MW, 21.25 mm conductor cable system would decrease by 10.3%, but the average electric stress within the insulation would increase by 22.7%, and hence a substantial penalty in reliability.

IX. CONCLUSIONS

A comparison of standard design and test values of MVAC land-based and shipboard standards to the sole MVDC shipboard standard was conducted. These references show a wide range of acceptable design and test values for cables used in MV systems. The design choices made in accordance with standards have an impact on the cable system size and electrical stresses. Selecting the insulation level and conductor diameter directly impacts the cable system size. The test values and resultant stresses within standards leave some ambiguity at transition values, as the test value just above or below a transition point could be selected, thereby impacting the electrical stresses within the cable insulation. Clarity or additional guidance within the standards may be appropriate as to what values are to be employed if the selected U_n is at or near a transitional value.

This study provides a prospective shipboard MVDC cable design with corresponding cable insulation thickness and test voltages. An alternate design could reduce the required cableway area by 10.3%, but at the substantial expense of a 22.7% increase to electric stress. As more experience and knowledge of MVDC systems becomes available, future standards committees could address MVDC cable systems more generally.

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