Tools and Dielectric Requirements for the Design of Marine Cabling Systems

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***Abstract*—This paper explores various power cable challenges for notional electric ship applications including future technology trends for shipboard power cables. To meet the demands of an "all electric ship," the cabling requirements of the design are not a trivial issue which can result in significant error in estimating final size, weight, and cost at time of construction along with costly failures and early repairs that impact lifecycle cost. This paper provides information on the development of a design tool known as a "Generic Cable Calculator" to estimate parameters such as impedances, weights, and bending radii for ship power cabling. Analysis of actual experience in designing ship cabling suggests improvements in early design tools needed to capture additional requirements in terms of grounding, shielding, and satisfying current standards for cables used in the variable frequency drive train. Also addressed are results specific to future trends of cable insulation and future standards.**

I. Introduction

This document focuses on several different aspects involving ship power cabling for "all electric" ships, defined as future naval ship construction utilizing some form of electric propulsion and an integrated power distribution system. A notional integrated power system (IPS) in a ring bus configuration was used for case studies highlighting three different architectures: MVAC (medium voltage ac), HFAC (high frequency ac), and MVDC (medium voltage dc). The current IEEE standard governing recommended practice for marine cables is 1580-2010 [1]. The design of a ship cabling system is assumed to conform to this standard which allows basic performance requirements to be met using cables with known physical and electrical characteristics as well as address the special circumstances that apply to certain cables, most notably within the propulsion motor drive. For the basic functional properties of the cables we describe a "Generic Cable Calculator" which takes the required amperage and frequency as inputs to calculate outcomes such as impedances, weights, and bending radii.

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Section 5.18.11 of IEEE 1580-2010 introduces additional warnings and requirements for cables used to interconnect variable frequency drives with motors. These additional requirements, which include over insulating the cable as well as providing proper shielding and grounding, are discussed in this document. Current work involving physical experiments with cables especially in regard to their dielectric performance and degradation under conditions approximating those borne by VFD cables is included in this paper.

II. Notional IPS Cable Design

A. Architectures

Three main architectures were analyzed in this study. One architecture was MVAC defined as 4160 V (RMS line-to-line) at 60 Hz power frequency. In this scheme, the power levels for various components ranged from 3–36.5 MW. A second architecture was HFAC defined as 4160 V (RMS line-to-line) at 240 Hz. The power levels for the HFAC system components ranged from 3-50 MW. The third analyzed architecture was MVDC with a main dc distribution voltage of 6 kV with component power levels ranging from 3-50 MW.

A Purdue report in 2011 compared two of the different architectures, MVAC and MVDC, in terms of mass and volume associated with each one [2]. One of the major components in this report dealt with the cables for each case. They noted that there were no commercially available cables with the desired amperage to meet either case, so they developed a model to use existing curves to approximate mass and volume for a particular set of cable data. In their report they noted the need for a common baseline, which was then created by the Electric Ship Research and Development

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Consortium (ESRDC). This baseline will be described in the next section.

B. Cable Layout

To better understand the "all electric" ship design, a notional diagram was developed by the ESRDC Power Systems IPT in June of 2011. This diagram consisted of a ring bus configuration of the power level components.

The ring bus is used for survivability and reconfigurability purposes. Note the redundancy in the system on both starboard and port buses. This particular arrangement is used so that in the event of a component failure, other essential components of the ship will continue to operate from power routed from another part of the ship. The generator ratings, loads, and lengths of the cable were first defined for each notional system. Those values were then used as inputs to the Generic Cable Calculator as described in the next section to determine items such as impedances, weights, and bending radii of the cables.

III. Generic Cable Calculator

A "generic" cable impedance model was developed in MATLAB/Simulink to support naval architects and ship designers to design and evaluate the notional IPS baselines as discussed in Section II. The purpose is to have a simple scalable impedance calculator that can be used to create a library of commercially available cables (where applicable) or an estimate for a cable that is similar to commercial variants. Similarity is defined by the voltage class, the ampacity rating, and the key materials used to make the dielectric and the conductors, including shields and strain protection. This cable estimator is important to support early stage design evaluations of baseline topologies that involve requirements (like high-voltage dc in a marine environment) that are underrepresented in the marketplace. Scaling parameters such as diameter, minimum usable radius of bend, and total weight are computed by the estimator by again referring to cables of a similar class and construction.

An example of the cable impedance estimator is shown in Figure 1. The user modifies the current by using the current slider to input the total cable ampacity of the desired run, which may be satisfied by placing real cables in parallel. The power frequency is changed by modifying the frequency slider, and the cable length is changed with the length slider. Once the user has input the required data and run the simulation, the complex cable impedance in terms of resistance and reactance ($R + jX$) and the magnitude of the impedance are output in ohms.

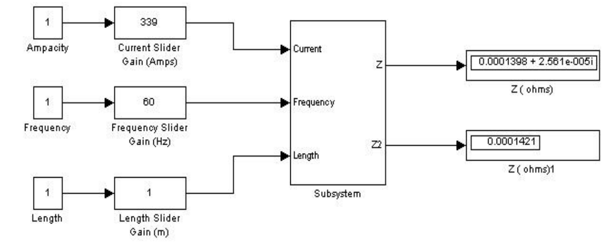

Figure 1. Cable impedance estimator.

A spreadsheet was populated that documented the major cables for the top-level notional system developed by the ESRDC. The spreadsheet utilized information for the power levels and voltage levels of the system. This information was used to calculate required ampacities. The ampacities were then input into the Cable Impedance Estimator to determine the cable impedances for medium voltage ac (MVAC), high frequency ac (HFAC), and medium voltage (MVDC). The spreadsheet then calculated information to obtain the weight, diameter, and bending radii of the required cables. Table I shows a sample of the spreadsheet.

IV. Cable Design Guidelines and Practices

A. Importance of Proper Early Stage Cable Design

At the IEEE Electric Ship Technologies Symposium in April of 2011, Captain Chris Mercer, a participant on the Government Panel session, described improving cable estimates as one of the top lessons learned from the conversion of the USS Makin Island (LDH8) to a hybrid system utilizing gas turbine/electric drive technology. According to Captain Mercer, the actual size, weight, cost, and installation requirements (particularly for bending radius) were not fully understood at the early design stage which resulted in significant problems during the conversion [3].

B. Cable Sizing Requirements

Cable sizing begins with the applicable standard IEEE-1580-2010 (Recommended Practice for Marine Cable for Use on Shipboard and Fixed or Floating Facilities) and the work in progress IEEE-P45 (Recommended Practice for Electrical Installations on Ships). Figure 2, a notional ring-bus one-line

TABLE 1: Sample Cable Spreadsheet

	Electric Load Demand				Cables	Cable Z per Phase		Total Diameter	Total Weight
Voltage (V)	Arch.	P (kW)	PF	Iline (A)	per Phase	R (Ohm)	X(Ohm)	per Phase (mm)	per Phase (kg)
4160	AC - 60Hz	36000	0.8	6245	8	0.001013472	0.00059551	440.8	19922
4160	AC - 240Hz	36000	0.8	6245	8	0.001014615	0.002340892	440.8	19922
6000	DC	36000		6000	7	0.00115956	4.37333E-06	385.7	17432

diagram, will be used to illustrate a common problem facing designers of ships with electric propulsion.

There is special consideration given to VFD (Variable Frequency Drive) cables due to the harmonics, electromagnetic interferences (EMI), common mode currents, and induced voltages in adjacent cables [1] which are problems created by the variable frequency drives themselves. In Figure 2, the VFD cable designation begins on the secondary side of the transformer that converts the 6600 V to the 2000 V needed for the drive itself. Note that on the primary side of the transformer, the cable is rated for 6.6 kV while it is rated 8 kV on the secondary, even though the voltage is stepped down by the transformer. This 8 kV rating results from application of IEEE-1580.5.18.11 which requires that the VFD cable be rated in accordance with VFD manufacturers recommendations.

IEEE-1580.5.18.11.2.1 indicates that compliance may require cables overrated by up to three times the nominal voltage in response to transient electrical stresses associated with, for example, pulse width modulation in the VFD [1]. Therefore, if, as in this example, the nominal voltage is 2 kV, a cable rated as high as 8 kV could be selected from among standard cables rated in families at 1, 2, 5, and 8 kV. Early cable failure could result from not adequately overrating the cable insulation. Anticipating the special ratings requirements for cables interconnecting the largest loads on the ship (propulsion) is required at the early design stage to avoid serious underestimates that may not be addressed until construction begins, where it would be costly to rectify.

C. *Future Design Tools*

As described in the previous section, the proper sizing of power cables and their associated grounding and shielding are vital to the design of an “all electric” ship. To address the electrical stresses caused by variable frequency drives, overrating of the VFD-qualified cables is necessary. However, the amount of overrating is a topic for further research. Full-bandwidth models of the propulsion drives are required for this type of detail but are hampered by lack of effective high-performance computing simulations tools to make practical for early stage design. The creation of state-space-averaged models, while computationally attractive for other power system studies (e.g., protection and stability), eliminate the detail needed to properly address the true electrical stresses that can be expected on real-world cables used in VFDs.

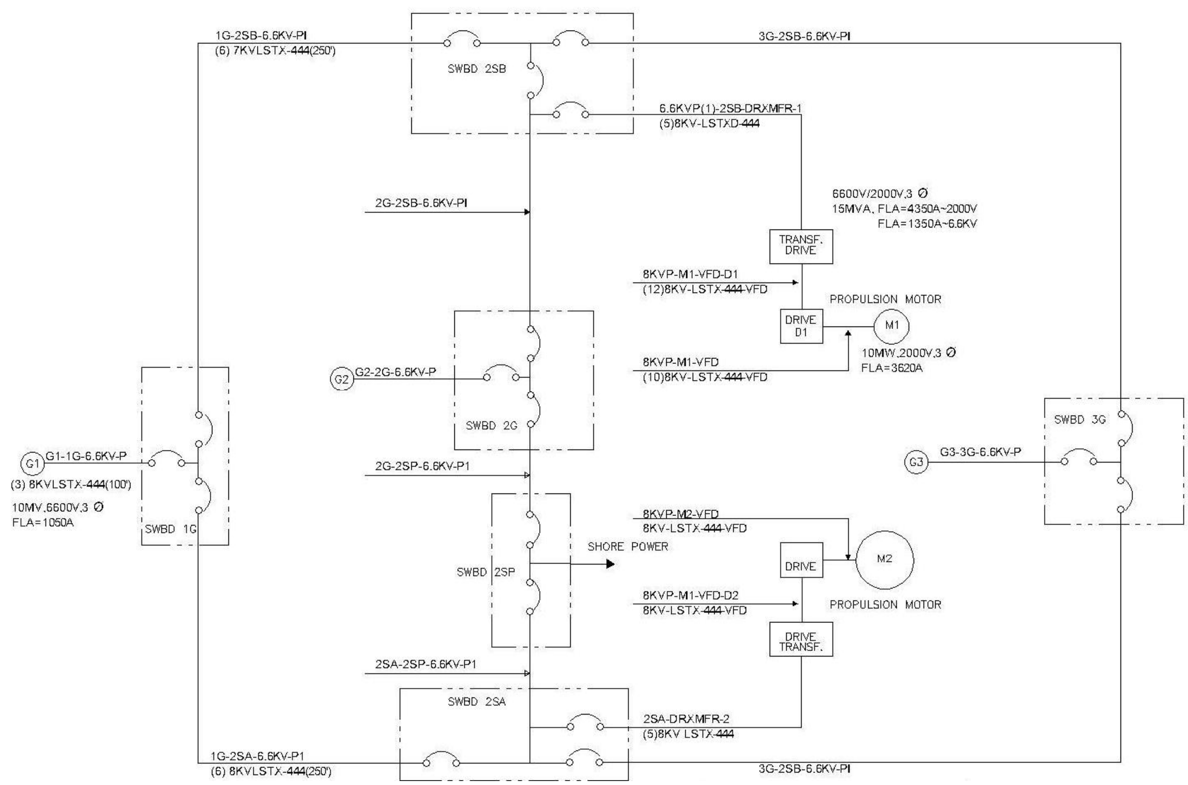

Figure 2. A notional ring bus configuration for a generic ship.

The Generic Cable Calculator was developed to address the cable information based upon nominal rated voltages and does not account for overrating. It also does not include grounding and shielding requirements which obviously impact size, weight, and cost of the system. Future improvements to the generic cable calculator will capture these requirements to create more realistic early ship design tools.

V. Physical Experiments on Cable Insulation

In order to further improve early stage design tools, component technology should also be addressed. Shipboard power systems of future generations of all electric ships will potentially be based on MVDC. Most distribution cables for terrestrial power systems are designed for ac operation. It is expected that degradation of cables in MVDC power systems is different compared to that in terrestrial ac distribution systems and therefore require special investigation. In this paper, two distinct studies are made. The first is a study of transient effects on cables with insulation based on cross-linked polyethylene (XLPE) because of its widespread application in terrestrial power systems. This study applies transient waveforms applicable to the conditions expected in VFD cables. The second is a lifetime study on cables with insulation based on both XLPE and ethylene propylene rubber (EPR) using combined electrical and thermal stress. Due to its high dielectric strength, resistance to water treeing, and thermal stability, EPR material is an excellent alternative to XLPE for polymeric power cable insulation. The influence of electrical and thermal stress on both the power distribution and the VFD cables in the ship can be inferred from the accelerated aging statistics deduced.

A. *XLPE Insulation under Transient Stress*

The most reasonable choice of cables for an MVDC system would be specialized dc cables, dedicated to handle the requirements in dc power systems. While such cable is available for high voltage dc (HVDC) transmission lines, there is no such product for the intended voltage range of about 5 kV to 20 kV for shipboard power systems. Hence, the question is whether ac cable designed for terrestrial distribution systems could be used for application in all-electric ships.

One of the key parameters of any dielectric system is the dielectric strength of the material chosen. When considering dc applications, it can be noted that the theoretical dielectrical strength typically decreases with increasing frequency (Figure 3; [4]). Cross-linked polyethylene (XLPE) cable and tree-retardant XLPE (TRXLPE) cable are likely candidates for shipboard cabling since they are widely used for modern terrestrial power systems in the medium- and high-voltage range [5]. Figure 3 shows that XLPE exhibits an approximately three times higher withstand capability to dc electric fields compared to ac fields (240 kV/mm in dc fields vs. 80 kV/mm at 60 Hz). However, shipboard power systems of all-electric ships are expected to feature power electronic loads, resulting in high-frequency switching harmonics superimposed on dc or low-frequency ac; an extreme example of which is the propulsion motor VFD. Such harmonics potentially also include a ripple voltage from rectifying the ac voltage of generators, voltage transients caused by large pulse loads, as well as voltage transients caused by rare (ground) faults or abrupt load shedding. All these higher frequency harmonics need to be taken into account for selection of suitable cables.

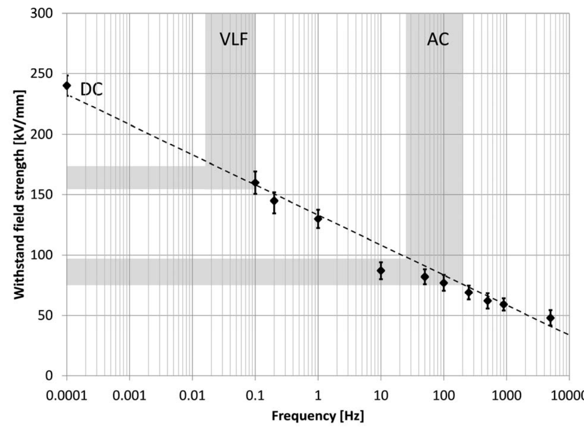

Figure 3. Withstand field strength E_m in XLPE as a function of frequency. Highlighted are the zones showing typical operating frequencies for power systems (AC) and very low frequency testing (VLF).

It is known from HVDC cables that XLPE can potentially accumulate space charge with adverse effects to life expectancy in the presence of frequent voltage transients [6]. If a steady dc field is applied to a low-loss dielectric material such as XLPE, charge can migrate into the material. This space charge can remain for up to several hours after de-energizing. The rate of recombination depends mainly on material properties and temperature. Such charge creates its own electric field, interacting with the field applied by the external voltage. A problem can arise during fast transients. The residual background field due to space charge gets superimposed on the transient field due to the fault, possibly creating local field stresses, which exceed the maximum withstand level. This can lead to the formation of electrical trees and eventually to breakdown of the insulator. It is therefore recommended to operate the cable at a voltage below the threshold where substantial quantities of space charge could migrate into the insulator.

An XLPE distribution cable rated for 5 kV rms was tested in the high voltage laboratory of the Center for Advanced Power Systems at Florida State University. The chosen test method was developed by Ildstad et al. [7]. The basic principle of this test was to short circuit a cable, which was energized with a certain dc voltage resulting in a high frequency transient. This voltage was typically substantially higher than nominal operating voltage of the cable. Figure 4 shows the test circuit. Variable autotransformer Tr1 allowed adjustment of the test voltage. The high voltage transformer Tr2, protected by fuse F1, provided a maximum output voltage of 100 kV RMS. Diode D1 rectified the ac voltage. The polarity was changed by rotating D1 (represented by switch S1). Resistor R1 limited the current in the diode and the transformers. R1 also decoupled the charging circuit from the resonant circuit. Capacitor C1 filtered the dc voltage and was part of the resonant circuit. The XLPE sample cable of 1 m length was connected to capacitor C1 and to the grounding switch S2. The sheath of the cable was grounded on both ends. Grounding switch S2 was used to initiate the high frequency oscillation in the resonant circuit.

Figure 5 shows the transient voltage during a test at negative polarity (S1 in position B). The charging voltage was −62 kV. The short circuit at one end of the cable produced an oscillation, which increased the voltage at the open end of the cable momentarily to a positive value of +26 kV. The oscillation frequency was approximately 2.9 MHz, resulting in a maximum rate of change of voltage of 0.4 kV/ns. After the test, the grounding switch was opened and the cable energized again. The plan was to repeat this process until the cable failed. The number of short circuits necessary to break the cable would be counted.

At this time, only one cable sample was tested. After more than 40 fast transients at various voltage levels and both polarities, no breakdown could be triggered. This was not sufficient to yield a definitive conclusion whether space charge was present and if it had a detrimental effect. However, discussions with manufacturers of XLPE cables revealed that the thickness of the insulation of cables rated up to approximately 10 kV are determined mainly by requirements for mechanical robustness; therefore, such cables are usually over dimensioned for the dielectric stress during normal operation. Further investigation and potentially additional high voltage testing might be required to reach a definitive conclusion.

B. XLPE and EPR Cable under Electrical Stress

The cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) are the most commonly used materials for polymeric power cable insulation [8-9].

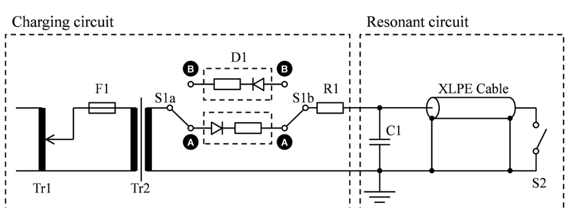

Figure 4. Circuit diagram of the experiment for dc breakdown tests based on test method [7]. For positive dc voltage, switch S1a/S1b was in position A, for negative voltage it was in position B.

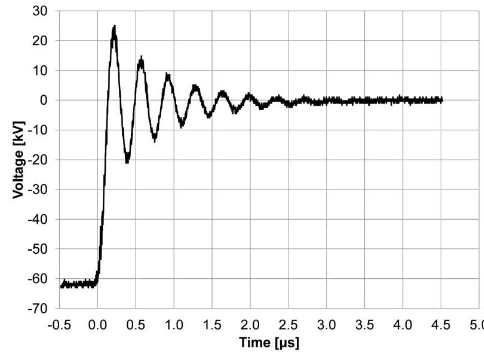

Figure 5. Transient voltage measured across C1 while S2 was closed.

Compared with the traditional paper oil-insulated cables, the main advantages of the polymeric power cables lie in the better electric properties, lower vapor transmission, higher moisture resistance, higher thermal limits, and higher resistant to chemicals and solvents.

The power cables need to endure the threats from electrical, mechanical, and thermal stress [10-12]. All of these stresses will initiate the change of properties of cable insulation materials, resulting in the deterioration of cable insulation [13-14]. Among all of these stresses, the switching surges are treated as one of the most hazardous sources. Yet the detailed information regarding the aging mechanism caused by switching impulses is not fully understood, especially those regarding the long term behaviors of the polymeric cables [15-17].

1) Details of the Tested Cable Samples: The Mississippi State University High Voltage Laboratory studied the aging of polymeric cables. The samples were made from commercially available 15 kV XLPE and EPR cables.

2) Aging Conditions: In the experiments, the switching impulses were generated by a 400 kV, 8 kJ impulse generator. The applied switching impulses were 100 kV in magnitude, with front/tail time of 250/2500 µs. The switching impulses were applied at the rate of 2 impulses per minute. Ambient temperature during the experiment was maintained at 20˚C. In the experiment, the cable samples were aged by the specific number of impulses [8-12].

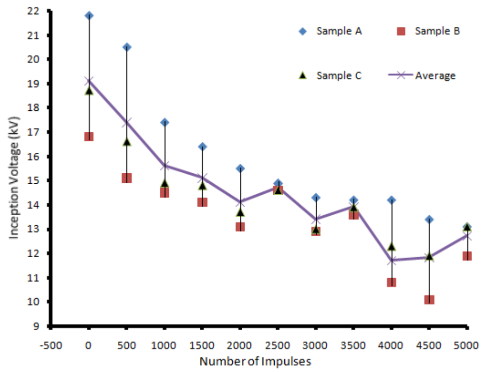

Figure 6. Inception voltage of XLPE cable samples aged by 5000 switching impulses [10].

3) Partial Discharge (PD) on Cables aged by Switching Impulses: The measurements of PD parameters were taken after certain numbers of switching impulses were applied to the samples. Figure 6 shows one example of aging the XLPE cable. Similar studies were made using more switching impulses (10,000) as well as EPR cables.

Once the studies were complete, the PD inception voltages of the cable samples were compared. Although the absolute values of the inception voltages for each tested samples were different, similar variation of the PD inception voltages could be observed for all the samples at the early stages of the aging, especially for those aged by fewer switching impulses. At the completion of 10,000 switching impulses, the tested XLPE samples showed 55.2% of the original PD inception voltages while the inception voltages for the EPR cable samples was 60.9% of the original value. It indicated that the EPR cable samples were less prone to the electrical aging caused by the switching impulses.

4) AC Breakdown Voltage of Cables Aged by Switching Impulses: The ac breakdown voltages of all XLPE and EPR cable samples were determined after the application of the switching impulses. The ac breakdown voltages measurement could serve as an evaluation tool to reveal the status of the cable samples after aging. Table II presents the measurement results for all EPR cable samples [8-9]. A similar process was performed for all XLPE cable samples.

TABLE II: AC BREAKDOWN VOLTAGE OF EPR CABLE SAMPLES (KV)

Number of Impulses	Sample #1	Sample #2	Sample #3	Average
0	160.8	156.6	151.0	156.1
100	140.7	116.4	119.1	125.4
500	162.9	119.1	147.2	143.0
1000	124.8	129.1	174.2	142.7
5000	121.7	124.8	90.4	112.3
10000	98.8	105.1	111.4	105.1

The dielectric degradation of the 15 kV XLPE and EPR power cables caused by the switching impulses was obvious. Both cables showed signs of degradation in the tests. The partial discharge inception voltages provided the most evident proof that deterioration of the cable insulation has occurred. The ac breakdown voltages of the EPR cables reduced significantly after the application of the switching impulses.

C. EPR Insulation under Electrical and Thermal Stress

Since EPR insulation has a higher dissipation factor, its use as power cable insulation is limited to distribution cables. For most of the thick-wall medium voltage EPR cables, the operational electrical stress does not exceed 4 kV/mm. Moreover, past studies [8] revealed that perfectly manufactured EPR material would not have significant aging under the ac electrical field stress that was less than 20 kV/mm. Under some extreme conditions, such as lightning surges and switching transient conditions in power systems, the local electric field stress could be over ten times the operational field stress [15-17]. The majority of the commercially available EPR cables have a maximum working temperature of 105°C. The occasional overload of the cables can exert extra thermal stress on cable insulation that will accelerate the aging. Due to a deficiency of information regarding the aging phenomenon of EPR cable insulation, it was necessary to carry out the aging experiments on the EPR cable insulation under the condition of combined high electrical and thermal stress.

In this experiment conducted in the High Voltage Laboratory at Mississippi State University, the tested EPR material was sliced from commercial 15 kV EPR power cables. The sample had a size of 15 mm × 15 mm and was 90 µm in thickness. Each sample's thickness was maintained within ± 5 µm to reduce or eliminate the impact on the experimental data of thickness variations. Ac voltage with constant value was applied to the cable samples while the test temperature was kept at 70°C, 105°C, and 140°C accordingly. The data for time-to-breakdown was collected to extrapolate the life-time model of the tested EPR cable insulation material. The calculated life-time characteristics can be compared to the data collected from the aging test on full-scale EPR cable samples.

At each temperature, the time-to-failure data was determined according to the two-parameter Weibull distribution. Based on the Weibull plots parameters calculation, the time-to-failure data of all the EPR insulation samples for 63.2% probability was obtained. The data for the EPR insulation samples aged under different conditions is summarized in Table III.

TABLE III. CALCULATED TIME-TO-FAILURE DATA OF THE EPR CABLE INSULATION SAMPLES (SEC.)

Temp. (°C)	70 kV/mm	75kV/mm	80 kV/mm
70 °C	*	1519	84
105 °C	5949	664	27
140 °C	4601	30	†

Notes:
*Time to failure exceeded duration of test.
† Leakage current exceeded limit at beginning of test.

Further studies on the aging of polymeric cables caused by lightning and switching impulses are needed.

VI. CONCLUSIONS

The study reports the development of an early stage design tool for estimating the electrical, thermal, and mechanical properties of an integrated power cable system design and its initial application in a trade study of MVAC, HFAC, and MVDC notional ship architectures. Reference to the relevant IEEE standards revealed additional improvements needed to make early stage estimates realistic, which include (1) studying the technical factors behind recommended practice to overrate the cables used in the variable frequency drive; and (2) capturing the complexity of the ship's ground and bonding system in the cable system design estimator.

Pursuant to item (1), initial results of a study on the impact of electrical stresses on XLPE insulated medium voltage cables commonly used in ac distribution was reported. The goal of the study was to identify failure mechanisms for commercial ac cables with XLPE insulation if used in a MVDC distribution system with power-electronic-based transient stresses. The study could lead to a procedure for qualifying or specifying the use of medium-voltage commercial ac cables in a dc distribution system and/or to satisfy the requirements for cables interconnecting variable frequency drives to propulsion motors. Finally, two experiments to study the accelerated aging are reported. The first studied XLPE and EPR cable insulation materials under combined ac and switching impulse voltage stress and the second studied EPR cable insulation under combined high electrical and thermal stress. The life-time data of the tested EPR samples were recorded and the time-to-failure data was analyzed. At one corner of the test matrix (70 kV/mm and 70°C) the life-time was longer than the practical duration of the test. At the opposite corner of the test matrix (80 kV/mm and 140°C) failure was recorded at the beginning of the experiment. Weibull distributions were estimated between these two extremes giving confidence in the accelerated aging parameters thus estimated.

REFERENCES

[1] IEEE Std 1580-2010, Recommended Practice for Marine Cable for Use on Shipboard and Fixed or Floating Facilities,.

[2] S. Pekarek, Nir Vaks, "Baseline Architectures: Comparing Mass/Volume of MVAC and MVDC Architectures", unpublished report for the Electric Ship Research and Development Consortium (ESRDC) by Purdue University, 2011.

[3] Captain Chris Mercer, "Presentation on USS Makin Island LDH8" during Government Panel Session of IEEE Electric Ship Technologies Symposium, Alexandria, Virginia, 10-13 June 2011.

[4] M. Fenger, "Partial Discharge in Cables – Lowering the Risk of Unforeseen Cable Insulation Failures", short course as part of the *International Symposium on Electrical Insulation ISEI*, San Diego, CA, 6-9 June 2010.

[5] I.A. Metwally, "The Evolution of Medium Voltage Power Cables", IEEE Potentials, p. 20-25, May/June 2012.

[6] D. Fabiani, G.C. Montanari, C. Laurent, G. Teyssedre, P.H.F. Morshuis, R. Bodega, L.A. Dissado, A. Campus, U.H. Nilsson, "Polymeric HVDC Cable Design and Space Charge Accumulation. Part 1: Insulation/Semicon Interface", IEEE Electrical Insulation Magazine, Vol 23, p. 11-19, Issue 6, 2007.

[7] E. Ildstad, M. Seljord, F. Mauseth, R. Hegerberg, B. Sanden, M. Jeroense, J.E. Larsen, "Breakdown Caused by Abrupt DC-Voltage Grounding of XLPE Cable Insulation", *Jicable conference*, Paris-Versailles, France, 24-28 June 2007.

[8] P. Shrestha, "Study of the Dielectric Degradation of XLPE and EPR Power Cables by Switching Impulses", Master Thesis, Mississippi State University, December, 2008.

[9] L. Cao, "Study of Accelerated Aging of 15 kV XLPE and EPR Cable Insulation by Switching Impulses and Elevated ac Voltage", Master Thesis, Mississippi State University, May, 2010.

[10] S. Grzybowski, P. Shrestha, L. Cao, "Electrical Degradation of High Voltage Cable Insulation Energized by Switching Impulses", *Proceedings of the IEEE 2008 Annual Report Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2008)*, Quebec City, Quebec, Canada, 2008, CD-ROM, pp. 25-28.

[11] S. Grzybowski, P. Shrestha, L. Cao, "Electrical Aging Phenomena of XLPE and EPR Cable Insulation Energized by Switching Impulses", *Proceedings of 2008 International Conference on High Voltage Engineering and Application (2008 ICHVE),* Chongqing, China, 2008, pp. 422-425.

[12] Grzybowski, S., Cao, L. Shrestha, P., "Electrical Degradation of 15 kV XLPE and EPR Cable Energized by Switching Impulses," *Proceedings of the 16th International Symposium on High Voltage Engineering (ISH 2009)*, Cape Town, South Africa, 2009, CD-ROM, Paper # A-18.

[13] S. Grzybowski, L. Cao, B. Pushpanathan, "Electrical Accelerated Aging of EPR Cable Insulation Energized by ac Voltage and Switching Impulses", *Proceedings of 2009 Conference of Electrical Insulation and Dielectric Phenomena (CEIDP 2009),*Virginia Beach, Virginia, USA, CD-ROM, 2009, Paper #52.

[14] L. Cao, A. Zanwar, B. Pushpanathan, S. Grzybowski, "Electrical Aging of 15 kV EPR cable Energized by ac Voltage with Switching Impulses Superimposed:, *Proceedings of 2010 High Voltage Engineering and Application (ICHVE 2010),* New Orleans, LA, USA, 2010, CD-ROM, pp. 148-151.

[15] L. Cao, A. Zanwar, S. Grzybowski, "Electrical Aging Phenomena of Medium Voltage EPR Cable Energized by ac Voltage with Switching Impulses Superimposed", *Proceedings of IEEE Electrical Ship Technologies Symposium (ESTS 2011)*, Alexandra, Virginia, USA, 2011, CD-ROM, pp. 353-356.

[16] S. Grzybowski, L. Cao, A. Zanwar, "Accelerated Aging Phenomena of 15 kV EPR Cable Energized by Elevated ac Voltage with Switching Impulses Superimposed", XVII International Symposium on High Voltage Engineering, Hannover, Germany, August 22-26, 2011, CD ROM, Paper E-015.

[17] L. Cao, A. Zanwar, S. Grzybowski, "Electrical aging phenomena of power cables aged by switching impulses", Journal on High Voltage Engineering (in English), China, 2012, in printing.