IEEE Open Journal of
Power Electronics

Received 28 December 2020; revised 25 February 2021; accepted 5 March 2021. Date of publication 12 March 2021;
date of current version 21 April 2021. The review of this article was arranged by Associate Editor Mark Johnson.

Digital Object Identifier 10.1109/OJPEL.2021.3065813

Review of Standards on Insulation Coordination for Medium Voltage Power Converters

SABAN OZDEMIR [1] (Senior Member, IEEE), NECMI ALTIN [1] (Senior Member, IEEE), ADEL NASIRI [2] (Senior Member, IEEE), AND ROBERT CUZNER [2] (Senior Member, IEEE)

[1] Department of Electrical-Electronics Engineering, Faculty of Technology, Gazi University, 06560 Ankara, Turkey
[2] Center for Sustainable Electrical Energy Systems, University of Wisconsin-Milwaukee, Milwaukee, WI 53211 USA

CORRESPONDING AUTHOR: ADEL NASIRI (e-mail: nasiri@uwm.edu)

This work was supported in part by the National Science Foundation under Grant 1650470 and in part by Office of Naval Research under Grant N00014-18-1-2622.

ABSTRACT The increasing viability of wide band gap power semiconductors, widespread use of distributed power generations, and rise in power levels of these applications have increased interest and need for medium voltage converters. Understanding the definitions of insulation coordination and their relationship to applications and methodologies used in the test environment allows system engineers to select the correct insulation materials for the design and to calculate the required distances between the conductive surfaces, accessible parts and ground accurately. Although, design guidelines are well established for low voltage systems, there are some deficiencies in understanding and meeting the insulation coordination requirements in medium voltage, medium frequency applications. In this study, an overview on standards for insulation coordination and safety requirements is presented to guide researchers in the development of medium voltage power electronic converters and systems. In addition, an insulation coordination study is performed as a case study for a medium frequency isolated DC/DC converter that provides conversion from a 13.8 kV AC system to a 4.16 kV AC system.

INDEX TERMS Insulation coordination, medium voltage, power converter, standards.

I. INTRODUCTION

Electrical safety standards define the tests and procedures of electrical devices to prevent dangerous situations such as electrical current, electrical arc, ignition, electromagnetic field and static that will endanger human life and health as well as assets. The regulations specified in the standards are constantly evolving as a result of changes and developments in technology and changing needs.

Insulation coordination is the process of definition of insulation levels of the system by considering their voltage levels and determination of dielectric strength of the equipment by considering the service environment and characteristics of the available protection devices. The main purpose of insulation coordination is to protect the system from insulation failure considering practical and economic factors, and to sustain continuity of the system operation. In short, the goal is to provide a system with reliable protection at a minimum cost. While conducting insulation coordination studies, the system voltage stresses need to be analyzed first [1]. In addition, the pollution degree, overvoltage category, grounding type, altitude, type of insulation (or insulation categories) and material type must be considered. A number of studies on insulation coordination have been conducted for various systems including transmission lines [2], substations [3], power transformers [4], ultra-high DC voltage converter stations [5] and transmission systems [6], wind turbines [7], and solid-state transformers [1].

A range of national and international standards has been applied to define the requirements and provide a pathway for conducting insulation coordination studies. These standards provide definitions and methodologies for design and testing at different voltage levels across a range of applications. For example, EN 60601 [8] focuses on the medical electrical equipment connected to grid voltages up to 0.69 kVrms. EN

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

60950-1 [9] describes the safety requirements for systems up to 1 kV; IEC-TC109 [10] and IEC 60664 [11] define the insulation coordination methodologies for equipment within low-voltage systems up to 1 kVrms or 1.5 kVDC. UL508 [12] and UL 840 [13] provide insulation coordination and safety requirements for low voltage systems up to 1.5 kVrms and 1.5 kVDC. UR-E11 [14] and IEC 60092-503 [15] provide requirements for systems operating with voltages above 1 kV up to 15 kV. EN 50124 [16] is the installation coordination standard for railway systems with voltages up to 25 kV. IEC 61800 [17] is a standard for systems up to 35 kV and is most commonly applied to power semiconductor-based power conversion and medium voltage drive systems. EN 60071 [18] explains the insulation coordination for systems with voltages above 1 kV. In addition, some standards for low voltage systems such as EN60601, UL840, IEC60664 and EN60950-1 provide required minimum clearance and creepage distances for higher voltage levels,

It is clear that for any system, one should follow the standards according to the system operation voltage, and most of these standards deal with the low voltage systems. In addition, some of them are proposed for specific applications, such as medical electrical equipment, industrial control systems, information technology equipment, railway applications, luminous signs and discharge lamps, commercial and military marine applications and adjustable speed drives. Requirements for the specific application should also be considered.

In last two decades, applications involving the direct connection of power semiconductors to medium voltage (MV) have grown exponentially. These include adjustable speed drives [19]–[21], Power Electronic Converter (PEC) interfaces to Distributed Energy Resources (DERs) [22]–[28] and solid-state transformers [29]–[32] within specific application environments (i.e., DER interface, shipboard) and as power system components. This trend has been motivated by continued research and increased viability of multi-level power converters and the emergence of Wide Band Gap (WBG) power semiconductors. WGB power semiconductors are an enabling technology for MV applications where present Si devices impose a significant penalty on achievable switching frequency and, as a result, significant cost and size penalty when it comes to meeting power quality requirements at the grid interface and limitations in controllable performance. The increasing commercial availability of Silicon Carbide MOSFET power modules at voltages greater than 1.7 kV, and the potential for commercially viable modules up to 10 kV [33]–[35], will have a substantial impact on the number commercial implementations and applications of MV PEC systems in the future.

Another area of considerable interest is the growth MVDC applications [36]–[38]. Historically, the standards that apply to MV power systems are based upon experience and empirical validations through testing on low frequency power components, such as transformers and switchgear. The MV PEC introduces a mixed frequency electrical environment, from dc to frequencies up to 50kHz on internal parts of the system. These considerations are even more prevalent in MVDC connected systems compensation for such factors as polarization of surface pollutants, dc-triggered surface flashover and line-to-ground voltage transients reduce the reliability of the system [39]–[42]. Significant physics based research in this area has not been translated into standards and it is clear that significant changes to existing standards and the evolution of new standards will follow. In the meantime, it is reasonable to apply the existing standards with well-reasoned adjustments to the nominal system voltage definitions from which creepage and clearance distances are derived. However, this approach may result in conservative approaches that increase the size of the equipment.

To the authors' knowledge, the approaches to MV insulation coordination on emerging power electronic systems have not been fully discussed and covered in the literature. There are only a limited number of studies, which have focused on insulation coordination of specific MV power conversion systems [1], [43], [44].

In this study, a general overview of different standards defining the safety requirements and insulation coordination are provided to gain a better understanding and to guide on methodologies for insulation coordination of MV power electronic systems. Insulation types used in insulation coordination are outlined and definitions related to the environmental conditions are explained. Since they provide general procedures and guidelines, in combination with the MV standards, some low voltage and high voltage standards are also discussed. Furthermore, an insulation coordination study is carried out for an isolated MV medium frequency power electronic system which is supplied from a three-phase 13.8 kV AC grid system with the output voltage of 7.2 kVDC. The procedure and standards that are followed are explained in detail to provide a guideline for future studies.

II. HUMAN SAFETY CONSIDERATIONS

From the standards and the vast number of application notes and white papers addressing the application of these standards to equipment design there are two over-arching requirements of insulation design: (1.) human safety and (2.) equipment operational reliability. Both requirements break down into a host of sub-requirements and underlying considerations and both are equally important. An underlying equipment safety requirement of PECs must be the assurance of autonomous isolation from equipment damage events (faults) through intervening protective equipment external to or separate from the power electronic circuitry. The PEC also has an underlying human safety requirement of assurance of galvanic isolation from electrical energization via manually operated, locked out and tagged out disconnect switches during service and repair. The principal approach to insulation design is to mitigate transient (seconds), short-term (minutes to hours), and long term (days to weeks) insulation failures. If the insulation design focuses on assurance of operational reliability, then threats to

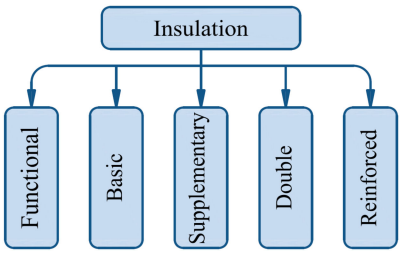


FIGURE 1. Various types of insulation.

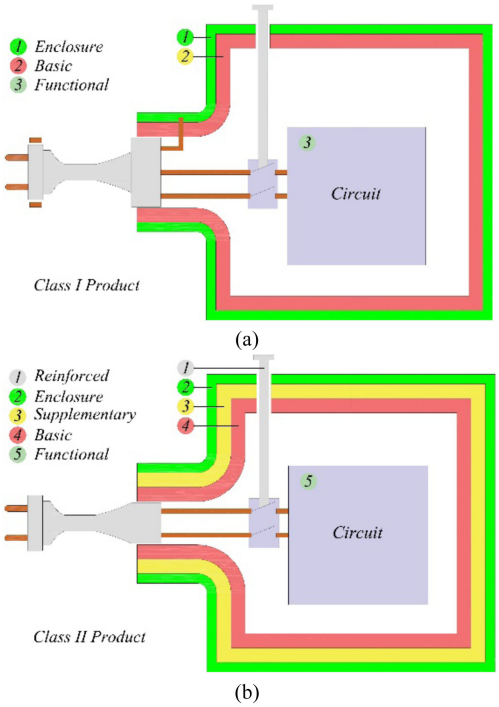


FIGURE 2. Use of these insulation types (a) In Class-I, (b) In Class-II systems.

human safety during catastrophic insulation failures are addressed and appropriate barriers are in place to exposed parts of the system that would otherwise endanger human safety.

III. TYPES OF INSULATION

In general, standards refer to insulation types, which help to break down insulation requirements of the system hierarchically according to sub-system and circuit function, electrical interconnection, and physical placement. The three main classifying categories of insulation types, as depicted in Fig. 1, are functional, insulation, basic insulation and protective separation, which comprises supplementary, double and reinforced insulation [45], [46]. In addition, use of these insulation types in Class-I and Class-II systems is depicted in Fig. 2.

A. FUNCTIONAL INSULATION

Functional insulation applies to the voltage potential differences internal to sub-systems, sub-assemblies, building blocks or components and the assurance that it can live with voltage and associated electric field (E-field) stresses created within its own environment. Its principal purpose is to protect the system against the effects that prevent stable operation of a device such as electric arc, ignition, spike or fire. This assurance is verified through certifiable qualifying and production tests. For example, if the PEC function includes a high frequency isolation transformer, the functional insulation applies to the enamel insulation of its copper wires, primary-to-secondary inter-winding insulation and winding-to-core insulation. When a PEC comprises sub-circuits that are electrically isolated from each other by the high frequency transformer, the transformer is designed to a distinct set of standards (i.e., IEEE C57.12.01) than those that apply to the system and operational reliability is verified through a battery of component-level tests before it is integrated into the system.

Recently, considerable attention has been paid to the packaging of power electronic assemblies into contained Power Electronic Building Blocks (PEBBs) with medium voltage ratings of up to 6 kV. These PEBBs enable modularized system building of PECs capable of handling voltages over the entire MV range. Considerable attention has been paid to the dense packaging of low power control elements in close vicinity with MV rated components and bus bars. Here, an insulation design must occur within the PEBB that follows the same process as insulation coordination at the system level, only heat sinks and chassis frames are floating with respect to the overall system chassis ground. From the system perspective, the end result of internal PEBB insulation system results in a PEBB-level functional insulation. Insulation coordination of the PEBB with rest of the system (which interfaces to the MV grid supply, system chassis and earth ground) requires additional voltage protection of basic insulation and protective separation.

B. BASIC INSULATION

Basic insulation refers to the insulation required to provide a basic protection against electric shocks. Basic insulation is required to separate the MV grid supplied circuitry from exposed grounded parts and is of vital importance to both human safety and equipment functional reliability. For MV systems and, particularly, MV interfacing PECs made up of building blocks, it is the basic requirement that dictates all voltage separation distances within equipment enclosure and at terminal interfaces to the MV grid. It applies to both intentionally energized electrical terminals energized and non-intentional energization of conductive equipment and component surfaces. In the standards, basic insulation requirement dictates the physical separation between windings, solder joints, terminal connections, ungrounded heat sinks, magnetic cores, electrical-assembly enclosures and PEBB enclosures. It also dictates the separation of these energized elements from the equipment chassis ground and grounded enclosures [44]. The definition of basic insulation is consistent across all of the insulation coordination standards, over the range of applications. It establishes the basic insulation level impulse voltage and temporary overvoltage levels from which these

separations are derived. A key purpose of basic insulation is to ensure that a failure in functional insulation does not endanger life due to grounding of exposed parts. Any use of solid or liquid insulators to accomplish the basic insulation requirement must be verified through testing.

C. SUPPLEMENTARY INSULATION

In addition to basic insulation, supplementary insulation is a type of independent second layer of insulation applied to reduce the risk of electric shock in case of insulation failure. The purpose of this layer of insulation is to provide protection from hazardous voltages if there is a failure of the basic insulation. Supplementary insulation is included in addition to basic insulation when a safety ground is not present in a power supply.

D. DOUBLE INSULATION

Double insulation refers to the doubling of the basic insulation solid insulator to increase protective separation. It is principally considered a redundant insulation layer that ensures that if breakdown occurs in one layer, the basic insulation requirement remains intact. If verifiable by test, double insulation can serve the purpose of reinforced insulation—which is the assurance of increased isolation distance for safety purposes. Double insulation implies an additional barrier of safety; however, the standards dictate verification through tests to ensure that no amount of leakage current within the system will result in touch voltages beyond safe levels.

E. REINFORCED INSULATION

Reinforced insulation refers to increase in basic insulation air clearance or insulation thickness of solid or liquid basic insulation implementation. The principal purpose of reinforced insulation is to provide a safe isolation barrier between circuits or circuits that can be touched by the user. The main difference between reinforced insulation and double insulation is that increased insulation over the basic insulation requirement is achieved through the increase in distance (through air or solid insulation) over the basic insulation requirement, as opposed adding another insulation layer to achieve that increase. From a design perspective, it is best to approach the requirement of protective separation through a reinforced insulation approach and the use of air clearances through stand-offs and maintainable separation distances. This approach avoids the uncertainties associated with partial discharge (PD) of solid insulators.

From an equipment reliability of performance perspective, protective separation through reinforced insulation is of extreme importance to power electronic-based systems and PECs. In particular, reinforced insulation relates to the interconnection of low voltage control hardware, sensors and protective monitoring circuitry existing within the same enclosure and in close proximity to MV energized parts of the system. Coupling this proximity with switching frequency and high rates of voltage change (dv/dt) associated with switching power conversion, protective separation also accounts for the assurance of self-immunity to and self-compatibility in the presence of electromagnetic interference (EMI) noise byproducts.

Reinforced insulation also applies to transformer isolated PEC terminals and leads as an additional margin of safety between primary and secondary windings, from windings to core and between conductors and shields. It is important that internal galvanic isolation, afforded by the functional insulation of the transformer, are not compromised at points of exit and entry, as a consequence of electric field non-uniformities at the triple points of interface.

IV. DEFINITIONS OF INSULATION TERMS

In order to fulfill the insulation coordination requirements, the system must meet the values specified in the standards associated with the expressions described below.

A. CLEARANCE

Clearance refers to the shortest distance between two conductive parts. This distance should prevent electric short-circuit made through the air between exposed conductors, and therefore it is determined according to the dielectric constant of the air and the applied peak voltage level. This peak value is expressed in international standards [17] depending on the overvoltage category with a similar classification. In this classification, a ranking is followed depending on how often the equipment is energized.

B. CREEPAGE

Dust and other pollutants accumulate over time and create conductive paths on insulator surfaces between electrical terminals and from electrical terminals to electrically conductive enclosures. This form of insulation breakdown is referred to as tracking. If it is not appropriately mitigated, tracking can result in disastrous electrical failure modes, particularly in MV and high voltage grid-connected systems. In the standards, the creepage distance is derived from the RMS working voltage between conductor terminals or from conductor terminals to chassis enclosure according to material groups that are defined by a Comparative Tracking Index (CTI). The CTI is a property of the insulating material that indicates its ability to resist degradation.

C. SOLID INSULATION

The presence of solid insulation is implied by the functional insulation associated with the cables, transits and subassemblies making up the system. The standards provide guidelines on the use solid insulation in the achievement basic insulation and protective separation. However, any use of solid insulation, in lieu of the air clearance distances derived from the standards, must be verified through testing in order to ensure that the insulation performance has not been compromised by the design or manufacturing process. Solid insulation is a means to achieving equipment operational reliability and reducing the negative impacts on power density. This approach is especially important to PEC based equipment

because the conservative approach of using air clearances to achieve basic and reinforced insulation requirements can also compromise the electromagnetic compatibility of the system, due to the presence of switching frequency harmonics and spectral content of the switching *dv/dt* on buses and bus interconnections.

The most important consideration, when it comes to the use of solid insulation, is the possible presence of voids between the insulating materials and conductors. These voids result in the build-up high electric field concentrations that discharge into the insulating material and form tree-like structures that degrade and eventually irreparably damage the insulator. This behavior is referred to as partial discharge or treeing and is, generally, a long-term breakdown mechanism for insulators.

D. PARTIAL DISCHARGE

PD is one of the most important issues on high voltage applications. Different types of PD events are seen in isolation systems. These are slow or high-rise time spark pulses occurring between nearby conductors, streamer discharges occurring in a very short time due to ionizing radiation at longer distances, the corona event that occurs when a conductive spiky or sharp edge is subjected to high stress, and PDs that occur at surfaces [47]. PD takes place in any high voltage equipment due to the non-linear effect of different physical parameters such as electrical, mechanical, environmental and human error. PD event generates a sudden rise in voltage, current, the flow of charges, non-visible and visible UV light, emission of electromagnetic waves, acoustics wave etc. PD generates tremendous heat which causes chemical changes in the insulating materials. Different on-line, off-line PD measurement and localization techniques have been proposed and successfully applied [48].

PD tests can be applied to cables, transformers, rotating machines, switchgear, capacitors etc. Online test systems are also available. The main idea is to test the equipment whether it is below the permissible level. Depending on the application, the partial permitted discharge levels may differ. For instance, IEEE Std. C57.124 [49] defines the partial discharge limits for resin-encapsulated transformers as 50pC, it defines solid cast windings as 10pC. A laboratory test setup for PD testing is given in Fig. 3(a) [48]. The test procedure for dry type transformer defined in IEEE Std. C57.124 and IEC 60076-11 is given Fig. 3(b). For different equipment, different period of time and different voltage levels are defined by the standards such as IEC60270 and IEC 61287-1. Here, the voltage is increased to the 1.8 times of the rated voltage level for at least 30 seconds, then it is adjusted to 1.3 times of the rated voltage level for 180 seconds, and the discharge level is observed whether it exceeds the limit during this period. PD testing results for different types of equipment are presented in past studies [48], [50]–[52].

V. EFFECT OF THE ENVIRONMENTAL CONDITION

In this section, effects of peripheral components and ambient variables such as material group, temperature, humidity and atmospheric pressure will be explained.

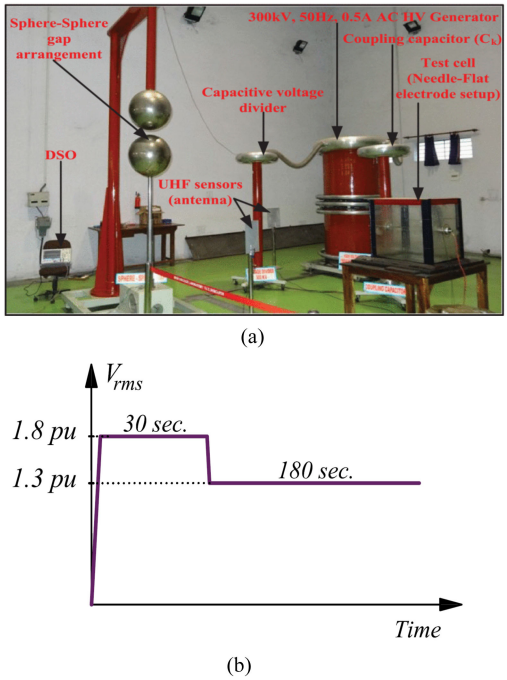


FIGURE 3. (a) Partial discharge test setup, (b) Partial discharge test procedure according to IEEE Std. C57.124 and IEC 60076-11.

A. INSULATING MATERIALS GROUP

High voltage has effects on the materials and may create a conductive path on the surface that starts a current flow gradually which results in an electrical failure. CTI is an expression of the deterioration effect of the high voltage in materials. In order to avoid malfunctions, the creepage distance is defined by using CTI which has a certain value for each material. Materials with high CTI level, which is graded as 0, I, II, IIIa and IIIb, provide better insulation. While there is no surface insulation deterioration in materials in the 0th group such as glass, ceramic and inorganic material, effects are significant for the highest level in group IIIb. However, while determining the creepage distance, CTI index starts from Group-I.

B. POLLUTION DEGREE

Pollution Degree (PLD) refers to the ambient conditions of the device subject to electrical isolation that dramatically affects device lifetime. It is the rating made to define the environmental conditions in which the safe operation can be ensured for the device. These conditions are defined such as “no”, “only dry”, “non-conductive”, “temporary”, “conductive pollution” etc., and it is highly effective in determining the clearance and creepage distances. Pollution degree is graded as PLD-1 to PLD-4, from no pollution to environmental conditions that can produce permanent conductivity such as conductive dust and rain etc.

C. THERMAL EFFECTS

There are two cases of thermal impact. The first case; one off the circuit components can be ignited by exposure to heat.

This situation can only be eliminated by selecting the circuit components appropriately. IEC 60695-11-10 has rated the flammability classifications of materials that emphasize the class should be equal or greater than V-1 [53]. According to IEC-61800-5-1, when the device is tested at its rated condition, the temperature should be lower than rated class which is given in a table as Class A to Class N.

Another issue regarding temperature is the dependency of the insulation level of materials to the temperature. Therefore, it is necessary to choose the insulation materials by considering the ambient temperature ranges. These events can even lead to a breakdown of the insulation. For example, the reason for the breakdown event specified in the section in CTI can be said as the heating of the insulation material due to surface currents and the further weakening of the heated insulation material, resulting in more leakage current continuing gradually and as a result insulation break down.

D. ALTITUDE EFFECTS

According to the Paschen's Law electrical discharge related to the air pressure [54]. When the altitude changes, there are two cases of insulation. The first is the weakening of the insulation system as a result of the change in the dielectric properties of the materials. Other one is deterioration of the cooling capacity due to the low air density. Unless a vacuum environment can be achieved, the clearance distance should be increased inversely proportional to the air pressure. The altitude correction factor is given in relevant standards.

VI. DESCRIPTION OF STANDARDS FOR MV

Although it may not apply for all over the world, UL, EN and IEC standards are most prominent MV standards. They are explained below for insulation coordination and safety.

A. UL STANDARDS

Underwriters Laboratories (UL) standards differ from international and European standards. Therefore, compliance with UL standards does generally remove the need for tests with IEC and EN standards. Functional and basic insulation are used as basic in many UL standards, resulting in greater distance requirements. Therefore, it can be concluded that UL standards are more conservative in some cases.

UL 508, STANDARD FOR SAFETY FOR INDUSTRIAL CONTROL EQUIPMENT:

These requirements cover industrial control devices and devices accessories for starting, stopping, regulating, controlling, or protecting electric motors. These requirements also cover industrial control devices or systems that store or process information and are provided with an output motor control function(s). The clearance and creepage distances are defined for less than 1000 Vrms or 1500 VDC. These requirements cover devices rated 1500 V or less. It is also mentioned in the standard that clearances and creepage distances may be evaluated in accordance with the requirements in UL 840, the Standard for Insulation Coordination Including Clearance and Creepage Distances for Electrical Equipment. In addition, the requirements defined in this standard are intended for use in an ambient temperature of 0 – 40 °C (32 – 104°F) unless specifically indicated for use in other conditions [12].

UL 840, STANDARD INSULATION COORDINATION INCLUDING CLEARANCE AND CREEPAGE DISTANCES FOR ELECTRICAL EQUIPMENT:

This standard covers an alternate approach defining the clearance and creepage distances for electrical equipment by using insulation coordination principles. Since this standard may be used as an alternate to end-product standards defining the required minimum clearance distances of end-products, there are two conditions, the over voltages are controlled or uncontrolled. If the overvoltage is uncontrolled, this case is called equivalency. For this case, for a given clearance distances, the corresponding test voltage level is given in the standard. Then, one can determine the test voltage value for an end-product standard specified minimum clearance distance and five different altitudes (0 m, 200 m, 500 m, 1000 m and 2000 m). Interpolation is also permitted to determine the test voltage for specified minimum clearance. If the overvoltage is controlled, the required minimum clearance distances depending on four different overvoltage categories and four different pollution degrees are defined up to 1.5 kVrms (or up to 1.5 kVDC). The required minimum creepage distance is defined up to 10 kVrms (or up to 10 kVDC) for four different pollution degrees and four material groups. For printed wire boards, the minimum required clearance distances are also given for up to 1 kVrms (or up to 1 kVDC) operating voltage, while the creepage distance is given depending on the maximum recurring peak voltage up to 2.2 kVrms (or 2.2 kVDC). Material groups, pollution degree groups and overvoltage categories are all defined. Besides, the minimum width of the grove is defined according to the pollution degree.

B. EUROPEAN STANDARDS

IEC 60601-1, MEDICAL ELECTRICAL EQUIPMENT –PART 1: GENERAL REQUIREMENTS FOR BASIC SAFETY AND ESSENTIAL PERFORMANCE:

It is developed based on IEC/TR 60513, Basic Aspects of The Safety Philosophy for Electrical Equipment Used in Medical Practice [8]. This standard defines the basic insulation requirements for medical systems operating with up to 690Vrms mains voltage. However, since it is released for the medical system, it gives requirements up to 42 KVDC (or 30 kVrms) for clearance, and 14.14 kVDC (or 10 kVrms) for creepage distances to provide patient protection. In addition, this standard defines the clearance and creepage distances depending on the overvoltage category. It provides the overvoltage categories according to IEC 60664-1 [11] and the nominal mains voltage. Besides, it also defines the pollution degree levels and uses this pollution degree in determination of the required clearance and creepage distances. The distances determined in the standard are valid for the equipment operating at an

altitude $\leq$2000 m. If the equipment is rated to be operated over this altitude (e.g., in aircrafts), a multiplication factor is defined to be used in determination of the clearance distances. The multiplication factor is not needed to be applied for creepage distances, but the creepage distance shall always be at least as large as the resulting value for clearance.

IEC 61800, ADJUSTABLE SPEED ELECTRICAL POWER DRIVE SYSTEMS:

This standard defines the requirements for the adjustable speed drives. Its part 5, IEC 61800-5, is on safety requirements and specifies requirements for adjustable speed power drive systems, or their elements, with respect to electrical, thermal and energy safety considerations. It is applicable to adjustable speed electric drive systems which include the power conversion, drive control, and motor or motors. The traction applications and electrical vehicle drives are not covered by this standard. This standard is applicable for drive systems whose converter input and output voltages are up to 35 kV. It is one of the rare standards dealing with MV power electronic conversion systems.

In this standard, the adjustable drive system is divided into different parts, such as power drive system, complete drive module, basic drive module, basic drive module and etc. and it defines the required insulation type among these parts as basic insulation, functional insulation or protective separation. Similar to IEC 60601-1, this standard also defines four pollution degrees depending on the occurring pollution level and four overvoltage categories (based on IEC 60364-4-44 and IEC 60664-1). It covers the impulse voltage test, performed with a voltage having a 1.2/50 μs waveform (based on IEC 60060-1) and is intended to simulate over voltages of atmospheric origin. IEC 61800 defines the impulse test voltage level according to the operating voltage up to 36 kVrms. This impulse test voltage level is used to determine the clearance distance required to provide functional, basic, or supplementary insulation. IEC 61800 also defines the required creepage distance up to 32 kVrms operating voltage. These defined minimum clearance distances are applicable for up to 2000 m altitude. IEC 61800 also defines a correction factor to determine the required minimum clearance distances up to 20000 m based on IEC 60664-1.

IEC 60664-1, INSULATION COORDINATION FOR EQUIPMENT WITHIN LOW-VOLTAGE SYSTEMS:

This standard is applicable to the electrical equipment for up to 1 kVrms with rated frequencies up to 30kHz and up to 1.5 kVDC operating below 2000 m altitude. It defines the requirements for clearance distances, creepage distances and solid insulation for equipment based upon their performance criteria. The minimum clearances specified in this standard do not apply where ionized gases occur. Four pollution degree groups are defined to evaluate the creepage and clearance distances. Besides, four different material groups are defined based on the CTI values (tested based on IEC 60112) [55].

Dimensioning of clearances of basic, supplementary and reinforced insulation are defined. One can determine the rated impulse test voltages depending on the nominal voltage of the system which is up to 1 kV. For the reinforced insulation, impulse withstand voltage shall be dimensioned to be 160% of the required for basic insulation. Then, the required minimum clearance distance can be determined by using this impulse voltage for different pollution degrees and homogeneous and inhomogeneous field conditions. The required minimum creepage distance up to 63 kVrms voltage is defined in the standard depending on the pollution degree and the material group. This voltage is operating voltage for functional insulation. For basic and supplementary insulation, the voltage level should be rationalized as described. Creepage distances for reinforced insulation shall be twice the creepage distance for the basic insulation. However, the required creepage distances equal to or larger than 8 mm under pollution degree 3, may be reduced by the use of a rib. The rib shall have a minimum width of 20% and a minimum height of 25% of the required creepage distance. The dimensions defined in the standard are valid for altitudes up to 2000 m above sea level, and the altitude correction factors are specified for clearances for altitudes above 2000 m. The partial distance test is also defined.

IEC 60071, INSULATION COORDINATION:

IEC 60071 is applicable to three-phase AC systems above 1 kV. It defines the procedure for the selection of the rated withstand voltages for the phase-to-earth, phase-to-phase and longitudinal insulation of the equipment and the installations of these systems. It also provides a procedure for the selection of the rated withstand voltages for the equipment. This standard defines the standard rated lightning impulse withstand voltage for 1 kV $< u <$ 245 kV and 245 kV $< u <$ 1200 kV. Then, the required minimum clearance distance according to the standard rated lightning impulse withstand voltage can be obtained for rod-structure and conductor-structure. This standard does not cover the creepage distance.

VII. SPECIFICS OF STANDARDS FOR COORDINATION

There are a limited number of standards for MV applications as they were described in the last section. Some of the current standards used in insulation coordination studies are summarized in Fig. 4 in order to specify the process [55]. In Table 1, an overview of standards for insulation coordination and safety requirements is presented. These are given in the table according to their voltage levels, standard type (basic standard-BS, product standard-PS, and product group standard-PGS) and defined creepage and clearance voltage levels. Although there is no basic standard for direct MV converter, some standards are taken into consideration for creepage, clearance distances and partial discharge evaluation. In addition to these standards, the MV adjustable motor drive product standards can help on the MV converter design in terms of insulation coordination. In this section, UL 840, EN

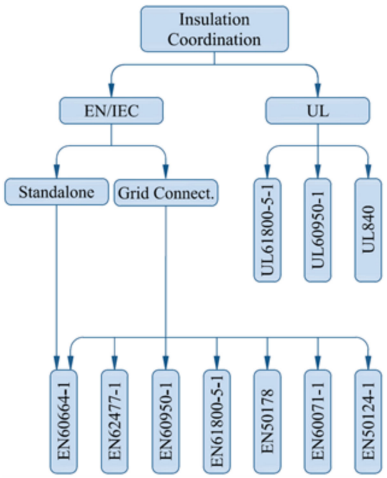


FIGURE 4. Insulation coordination process.

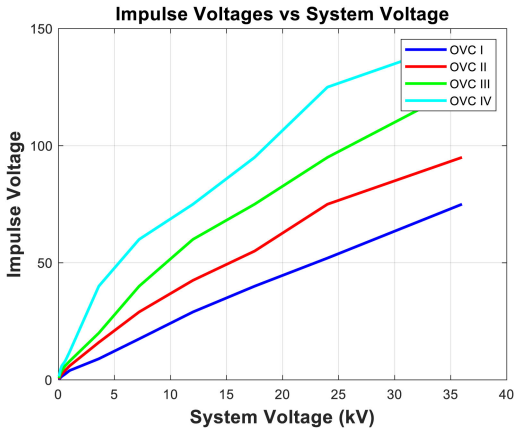


FIGURE 5. Impulse voltages according to system voltage for OVC I to OVC IV.

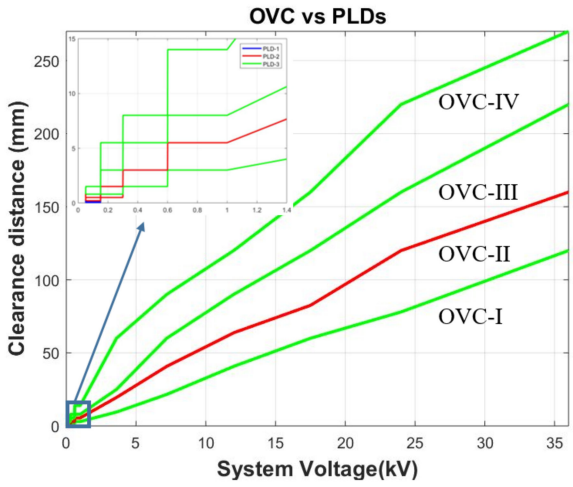


FIGURE 6. Clearance distance according to the pollution degree and impulse voltage.

TABLE 1 Standards for Insulation Coordination and Safety Requirements

Standard	Operating Voltage	Clearance	Creepage	Standard Type		
				BS	PS	PGS
UL 508	< 1.5kVrms or 1.5kVDC	<=1kVrms or 1.5kVDC	<=1kVrms or 1.5kVDC		X	
EN 60601	<= 0.69kVrms	<=42kVDC or 30kVrms	<=14.14kVDC or 10kVrms	X		
EN 60950-1	< 1kV	< =42kV	<= 63kV		X	
IEC-TC 109	< 1kVrms or 1.5kVDC	<2kVrms and 3kVDC	<2kVrms and 3kVDC			
IEC 60664	< 1kVrms or 1.5kVDC	<=1kV	<=63kV	X		
UL 840	<=1.5kVrms and 1.5kVDC	<=1.5kVrms and 1.5kVDC	<=10kVrms and 10kVDC	X		
UR-E11	1kVrms < u < 15kVrms	1kVrms < u < 15kVrms	1kVrms < u < 15kVrms			
EN 50124	=< 25kVrms or 25kVDC	=< 25kVrms or 25kVDC	=< 25kVrms or 25kVDC		X	
IEC 61800	< 35kVrms	<=36kVrms	<= 32kVrms		X	
IEC 60092-503	1kVrms < u < 15kVrms	1kVrms < u < 15kVrms	1kVrms < u < 15kVrms		X	
IEC 60071	1kVrms < u <1200kVrms	1kVrms< u <1200kVrms	-	X		
EN 50178	< 1kVrms or 1.5kVDC, <10kVrms	<10kVrms	<32kVrms			X
EN 62477-1	< 1kVrms or 1.5kVDC					X

60664, EN 60071 basic standards (BS) and UL 61800, EN 61800, EN 60950 and UL 950 product standards (PS) will be used in the insulation coordination design of MV power electronic converters.

Apart from the above, there are a few standards for specific areas such as ships, railways, military applications (such as MIL-DTL-32483, Mil-E-917, UR E11, IEC 60092-503, EN50124). These standards generally refer to the standards summarized in Table 1. These standards are for low and medium voltages but they generally refer to EN60071-1 and EN60664-1 for defining the required minimum creepage and clearance distances. Therefore, they require similar levels of creepage clearance, except for some exceptions.

IEC-61800-5-1 (Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy) standard is defined for adjustable speed drives but it can be the basis for MV converter applications. It is used as the basic work for insulation coordination studies. Therefore, clearance and creepage distances versus system voltage or impulse test voltage for different pollution degrees and insulation material groups are depicted in Fig. 5–Fig. 7. In Fig. 5, the impulse voltage versus the system voltage is given for different overvoltage categories (OVCs) according to IEC-61800-5. The clearance distance depends on this impulse voltage level. The OVC depends on whether the device is exposed to transient voltage and the type of device installation. More precisely, OVC I indicates that the equipment has transient

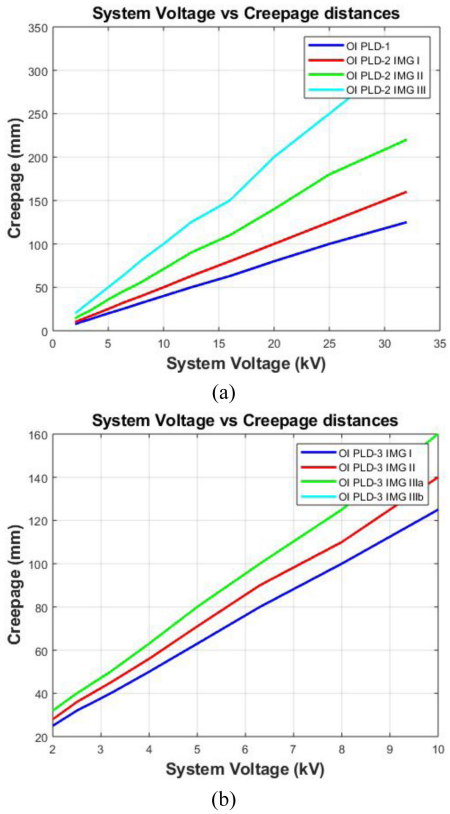


FIGURE 7. Creepage distance according to the insulation material group and pollution degree.

voltage protection, OVC II indicates that equipment does not have fixed installation, OVC III indicates that the equipment has fixed installation, and finally OVC IV indicates that the equipment is connected to the origin of installation supply mains [45]. According to this installation types and transient over voltage impulse voltages, the clearance distances can be defined.

In Fig. 6(a) and Fig. 6(b), the impulse voltage and clearance distance relationship is given according to the IEC 61800-5-1 for OVC I to OVC IV, respectively. Although PLD and impulse voltage are both effective when defining clearance distances, IEC 61800-5-1 does not consider the PLD classes and defines only one clearance distance for any PLD class above 1.5 kV impulse voltage. Thus, in these figures, all pollution degrees give the same clearance above the 1.5 kV.

As described in Section IV-A, insulation CTI is another factor for insulation coordination. While the clearance distance relates to flashover, the creepage distance relates to tracking. So, material group and pollution degree become important for the creepage distance. In Fig. 7(a) and Fig. 7(b), the creepage distance is given with these parameters according to the IEC 61800-5-1. In this figure, OI refers to the other insulator, PLD is the pollution degree and IMG is the insulation material group. While the pollution degree 3 material defined up to 10 kV, PLD-1 and PLD-2 defined up to 32 kV system voltage level.

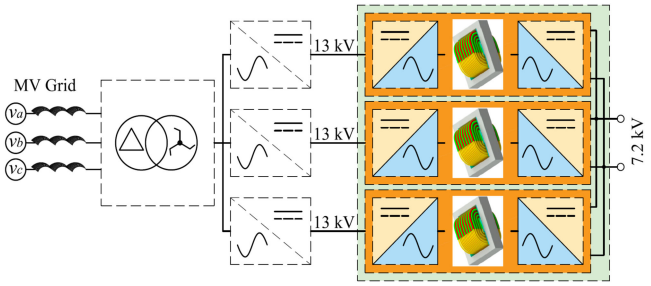


FIGURE 8. Converter structure for the case study.

VIII. CASE STUDY

In this study, an insulation coordination study is carried out for a medium frequency three-level DC/DC converter structure that includes three isolated DC/DC converter modules. The input voltage of each DC/DC converter is supplied by a single-phase AC/DC active-front-end converter which is connected to the three-phase 13.8 kVAC grid system. These single-phase active-front-end rectifiers generate 13 kVDC voltage level at the input of the DC/DC converter modules, and each DC/DC converter generates 7.2 kVDC output voltage. Three DC/DC converter modules are connected in parallel to provide the required voltage level for three-phase 4.16 kVAC voltage level inverters. The converter structure is given in Fig. 8. Minimum clearance and creepage distances vary with the operating frequency. In this study, switching frequency is considered to under 30kHz when determining the creepage and clearance distances. For higher frequencies IEC-61800-5-1 Annex E should be followed.

As discussed in the previous sections, there are a limited number of standards above the 1.5 kV. Although, MV adjustable motor drivers were the most common MV power electronic applications, today increasing number of distributed generation applications and increasing interest on solid state transformers are changing this status, especially after the high frequency MV wide-bandgap devices became readily available in the market. It would be useful to establish new standards directly describing MV converters. However, existing standards must be adapted for such applications until appropriate standards are approved. Therefore, in this study, the case study is performed using IEC-61800-5-1. The idea behind IEC 618500-5-1 is building up the entire system and using the Basic Insulation and Reinforced Insulation rules to convert lower rated building blocks into to system compatible building blocks. Initially, some characterization is required for defining the required minimum creepage and clearance distances.

The first parameter that is needed to be determined is the OVC that defines impulse voltage level required to determine the clearance distance. IEC-61800-5-1 states that it is sufficient for some converters to have OVC I due to no direct connection [43]. However, in the same standard, section "*Insulation to the Surroundings*", the OVC definitions are classified from OVC II to OVC IV depending on parameters

such as whether the device is directly connected to the supply mains or connected directly to the origin of the installation supply mains and the connection type. The converters which are subject of this study are supplied by another converter and not suitable for plug connection due to power level. Therefore, definitions in *"Basic insulation evaluation for circuits connected directly to the supply mains*" in the section *"Insulation to the Surroundings"* of the IEC-61800-5-1 are considered. For circuits and parts (in this case inverter part such as SiC devices, capacitors etc.), affected by external voltage transient, should be categorized as OVC II for functional insulation. Although this standard states that OVC III can be applied as OVC II and OVC II as OVC I in a reduced type when measures to reduce transient over voltages are provided, OVC II is selected for circuit and parts, and OVC III is selected for accessible parts. If OVC I would be selected, the clearance distances would be smaller.

The second required parameter is the material group that depends on the CTI, which is defined in the previous section. Since the creepage distance changes dramatically with this index, using a material such as plastic, melamine with CTI index of over 600 (class I) will provide an optimum design. The last parameter is the pollution degree. The pollution degree can be selected as PLD-1 with an assumption that there is no pollution or only dry and non-conductive pollution. However, this assumption may not be realistic in most situations, so pollution is changed to PLD-2. While material group is important only in determining creepage distance, the PLD impacts the clearance distance for systems with impulse voltage up to 1.5 kV. Therefore, both of these parameters are relevant only in determination of the creepage distance for the given system.

The pollution degree, CTI and OVC definitions are measures of which category to be evaluated in determination of the clearance and creepage distances. However, these parameters do not determine which type of insulation will be made such as functional, basic etc. IEC-61800-5-1 is marked as class D for Decisive Voltage Classification (DVC) above the 1.5 kVDC. This classification requires protection against direct contact. While the basic insulation is required for earthed parts, accessible unearthed conductive parts need protective separation. Between the adjacent circuits, the basic insulation level is needed. On the other hand, IEC/UL-950 grades insulation levels. Combining these standards can help define insulation grades that are shown in Fig. 9, indicating insulation classifications required for control circuits of converters, other modules, input power supply and accessible parts. In this figure *F*, *B* and *R* refer to the functional, basic and reinforced insulation, respectively.

A structure representing each of the three-levels of the case study converter is given in Fig. 10. For convenience, tags are assigned to the connection point of each element of the converter [45]. In addition, the cold plate and transformer core are also tagged. The voltages levels at each point were calculated according to the given input and output voltage levels and possible switching signals. These voltage levels are given in Table 2.

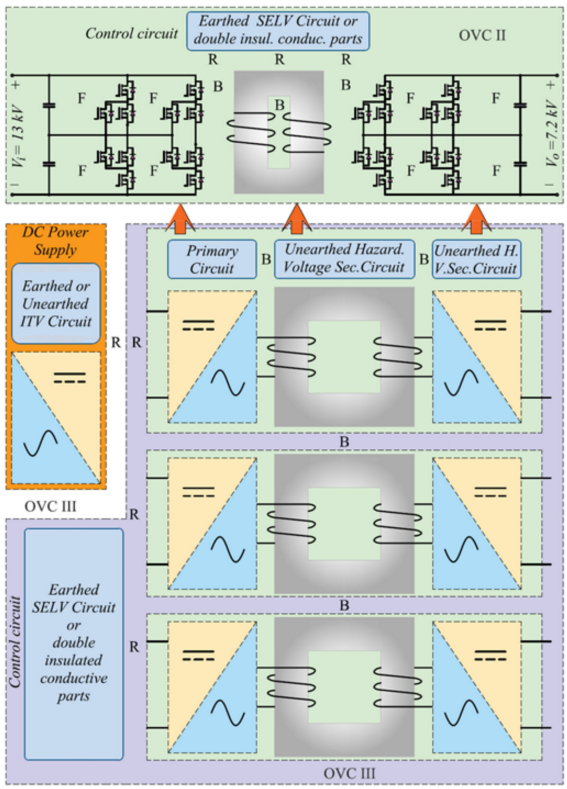


FIGURE 9. Required insulation and OCV levels for the case study converter.

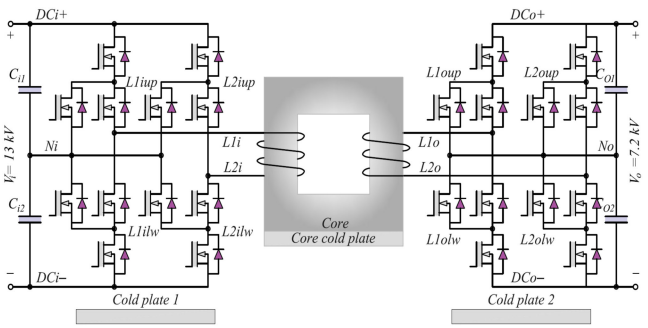


FIGURE 10. A single stage of the converter for the case study.

It is worth noting that the transformer insulation system is not discussed here. The transformer is considered as an equipment of the system and it is assumed that it is properly designed and required insulation system is implemented. Since insulation requirements of the transformer may result with higher leakage inductances and capacitances, which limits the power transfer capacity and may cause some other additional problems, in MV high power isolated converter design generally galvanic isolation is distributed over a number of transformers. This may increase the size and volume, however smaller transformers in this topology enables higher frequency values and balance some part of this disadvantage.

For the high frequency transformer insulation requirements IEC 60076-11: Power transformers - Part 11: Dry-Type Transformers can be applied. IEC 60076-11 covers dry-type power

TABLE 2 **Working Voltage and Clearance and Creepage Distances for the Case Study Converter**

Clearance/Creepage distance (mm)	Working Voltage Level (kV)																				
	(	DCi+	DCi-	Ni	L1iup	L2iup	L1ilw	L2ilw	L1i	L2i	Core	Cold P1	Cold P2	L2o	L1o	L2olw	L1olw	L2oup	L1oup	No	DCo-	DCo+
	DCi+		13	6.5	6.5	6.5	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
	DCi-	67.2/65.5		6.5	13	13	6.5	6.5	13	13	13	13	13	13	13	13	13	13	13	13	13	13
	Ni	36.4/33	36.4/33		6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	13	13	13	13	13	13	13	13	13
	L1iup	36.4/33	67.2/65.5	36.4/33		6.5	6.5	13	6.5	13	13	13	13	13	13	13	13	13	13	13	13	13
	L2iup	36.4/33	67.2/65.5	36.4/33	36.4/33		6.5	6.5	13	6.5	13	13	13	13	13	13	13	13	13	13	13	13
	L1ilw	67.2/65.5	36.4/33	36.4/33	36.4/33	36.4/33		6.5	6.5	13	13	13	13	13	13	13	13	13	13	13	13	13
	L2ilw	67.2/65.5	36.4/33	36.4/33	67.2/65.5	36.4/33	36.4/33		13	6.5	13	13	13	13	13	13	13	13	13	13	13	13
	L1i	67.2/65.5	67.2/65.5	36.4/33	67.2/65.5	67.2/65.5	36.4/33	67.2/65.5		13	13	13	13	13	13	13	13	13	13	13	13	13
	L2i	67.2/65.5	67.2/65.5	36.4/33	67.2/65.5	19.5/18	67.2/65.5	36.4/33	67.2/65.5		13	13	13	13	13	13	13	13	13	13	13	13
	Core	67.2/65.5	67.2/65.5	36.4/33	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5		13	13	13	13	13	13	13	13	13	13	13
	Cold P1	67.2/65.5	67.2/65.5	36.4/33	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5		13	13	13	13	13	13	13	13	13	13
	Cold P2	67.2/65.5	67.2/65.5	36.4/33	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5		7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	L2o	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3		7.2	3.6	7.2	3.6	7.2	3.6	7.2	7.2
	L1o	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	40.8/36.3		7.2	3.6	7.2	3.6	3.6	7.2	7.2
	L2olw	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	19.5/18	40.8/36.3		3.6	3.6	7.2	3.6	3.6	7.2
	L1olw	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	40.8/36.3	19.5/18	19.5/18		7.2	3.6	3.6	3.6	7.2
	L2oup	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	19.5/18	40.8/36.3	19.5/18	40.8/36.3		3.6	3.6	7.2	3.6
	L1oup	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	40.8/36.3	19.5/18	40.8/36.3	19.5/18	19.5/18		3.6	7.2	3.6
	No	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	19.5/18	19.5/18	19.5/18	19.5/18	19.5/18	19.5/18		3.6	3.6
	DCo-	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	40.8/36.3	40.8/36.3	19.5/18	19.5/18	40.8/36.3	40.8/36.3	19.5/18		7.2
	DCo+	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	67.2/65.5	40.8/36.3	40.8/36.3	40.8/36.3	40.8/36.3	40.8/36.3	19.5/18	19.5/18	19.5/18	40.8/36.3	

transformers (including auto-transformers) having values of highest voltage for equipment up to and including 36 kV and at least one winding operating at greater than 1.1 kV [56]. In this standard, insulation voltage levels based on European practice and North American practice are given in Table 3 and Table 4, respectively by refereeing IEC60071. While IEC-61800-5-1 is referring IEC60664-1 for low voltage levels, for high voltage levels it is referring IEC-62103 for OVC-I and OVC-II, and IEC-60071 (same with IEC 60076-11) the for OVC-III and OVC-IV. If the Table 3 of IEC 60076-11 and Table 8 of IEC-61800-5-1 are checked and compared, it can be easily seen that the voltage levels given for OVC-III and OVC-IV in IEC-61800-5-1 are the same with values in IEC 60076-11 except 36 kV system voltage. There is a difference at this voltage level. In addition, IEC 60076-3: Power Transformers-Part 3: Insulation Levels, Dielectric Tests and External Clearances in Air provides applicable dielectric tests and minimum dielectric test levels [57]. Table 2 in IEC 60076-3 provides level of standard test voltages up to 420 kV, identified by highest voltage for equipment U_m of a winding by referring IEC60071-1. Different from IEC60071-1, Chopped Wave Lightning Impulse voltage are given in Table 2 of IEC 60076-3. In addition, while the switching impulse voltage is given 300 kV and above in IEC60071-1, this value is provided for 100 kV and above voltage levels in IEC 60076-3.

According to the selection procedure described earlier, the impulse voltage levels for each point of OVC II is defined via the insulation voltage for high voltage circuits table in IEC-61800-5-1. Then the required clearance distance is determined from the clearance distance table according to the defined impulse voltage level. This table is valid for functional, basic, or supplementary insulation. In order to determine the creepage

distances, the material group, pollution degree and system voltage parameters are evaluated from the creepage distance table. As in the clearance selection procedure, the creepage distance, in case of the functional, basic, or supplementary insulation can be found directly.

The clearance and creepage distances obtained from both tables given in Table 2 in the form of clearance/creepage according to the voltage level.

According to the IEC-61800-5-1, in case of reinforced insulation, the clearance and the creepage distances determined as explained above cannot be directly used. For the reinforced insulation, the determined impulse test voltage level should be selected 1.6 times of the regular case. Similarly, the creepage distances determined as described above need to be doubled for the reinforced insulation. According to these explanations, 13 kV impulse voltage can be found via interpolating the table given in IEC 61800-5-1 for OVC II and OVC III, respectively. While OVC II can be used for basic insulation, OVC III should be used for reinforced insulation due to the basic insulation evaluation for circuits connected directly to the supply mains section in given standard. So, it is concluded that the clearance and creepage distances marked with the letter *B* in Fig. 9 should be 67.2 mm and 65.5mm, respectively.

The impulse voltage, which needs to be defined for determining the clearance distance for 13 kV, is highly affected by both the increase of the OVC from OVC II to OVC III and the requirement to select this impulse voltage 1.6 larger than other calculations for reinforced insulation. So, this distance is defined as 170.73 mm considering all these effects. For the creepage distance, the determined values should be doubled, and it gives 131mm.

In MV power converter applications, depending on the converter topology, DC link voltage or part of the DC link voltage is applied to the gate driver board. Therefore, gate drivers used in these applications also need careful insulation design and clearance and creepage distances. Different gate driver options including voltage based gate driver, current loop gate driver and wireless gate driver can be considered. By using IEC-61800-5-1 and related DVC, and OVC classes and CTI of the PCB material, required clearance and creepage distances can be calculated [44]. Once these distances are calculated, V grooves, air gaps and insulated barriers are used to meet the creepage and/or clearance distance requirements.

IX. CONCLUSION

Since, most of the existing insulation coordination and safety standards are recommended for low voltage systems, MV converter designers have difficulties in understanding definitions of insulation coordination and safety design. There are a limited number of studies for MV medium frequency converter applications and they are generally for specific product standards. In this study, definitions of the insulation coordination were explained and main standards for insulation coordination were overviewed. Then an inference is made for MV power electronic applications. An insulation coordination study carried out as an example for a medium frequency three-level isolated DC/DC converter structure. The structure is suitable for a 13.8 kVAC to 4.16 kVAC step-down solid state transformer system that includes three three-level DC/DC converter groups. The input and output voltage of each DC/DC converter are 13 kVDC and 7.2 kVDC respectively. The required minimum Clearance and creepage distances and type of insulation have been given for system and determined parts.

ACKNOWLEDGMENT

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation and Office of Naval Research.

REFERENCES

[1] X. Rong, G. G. Karady, D. Zhang, and G. T. Heydt, "Insulation coordination of FREEDM solid state transformer," in *Proc. CIGRÉ Grid Future Conf.*, Philadelphia, PA, 2016.

[2] R. R. Nunes and W. d. C. Boaventura, "Insulation coordination considering the switching overvoltage waveshape—Part I: Methodology," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2434–2440, Oct. 2009.

[3] S. Bedoui, and A. Bayadi, "Insulation coordination study of 400 kV high voltage substation," in *Proc. Algerian Large Elect. Netw. Conf.*, Algiers, Algeria, pp. 1–6, 2019.

[4] G. Ueta, T. Tsuboi, J. Takami, and S. Okabe, "Insulation characteristics of oil-immersed power transformer under lightning impulse and AC superimposed voltage," *IEEE Trans. Dielectrics Elect. Insul.*, vol. 21, no. 3, pp. 1384–1392, Jun. 2014.

[5] W. Pan, X. Liu, and D. Nie, "Development and application of insulation coordination program for UHVDC converter stations," in *Proc. 3rd Int. Conf. Electric Utility Deregulation Restructuring Power Technol.*, Nanjing, China, 2008, pp. 2262–2266.

[6] Z. Cuixia and Z. Liuchun, "Insulation coordination optimization study for ±800kV UHVDC project with increased transmission capacity," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Vancouver, BC, Canada, 2013, pp. 1–5.

[7] S. Sekioka, J. Takami, and S. Okabe, "Insulation coordination of a wind turbine and a power distribution line," in *Proc. Int. Symp. Lightning Protection*, Fortaleza, 2011, pp. 235–240.

[8] *IEC Medical Electrical Equipment –Part 1: General Requirements for Basic Safety and Essential Performance*, IEC Standard 60601-1:2005, 2005.

[9] *EN Information Technology Equipment - Safety Part 1: General Requirements*, EN Standard 60950-1, 2006.

[10] *Insulation Co-Ordination for Low-Voltage Equipment*, IEC-TC Standard 109, 2019.

[11] *IEC Insulation Coordination for Equipment Within Low-Voltage Supply Systems - Part 1: Principles, Requirements and Tests*, IEC Standard 60664, 2007.

[12] *UL Standard for Safety for Industrial Control Equipment*, UL Standard 508, 1999.

[13] *UL Standard for Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment*, UL Standard 840, 2005.

[14] *Unified Requirements for Systems With Voltages Above 1 kV up to 15 kV*, UR Standard E11, 2018.

[15] *IEC Electrical Installations in Ships - Part 503: Special Features - AC Supply Systems With Voltages in the Range of Above 1 kV up to and Including 15 kV*, IEC Standard 60092-503:2007, 2007.

[16] *EN Railway Applications - Insulation Coordination - Part 1: Basic Requirements - Clearances and Creepage Distances for All Electrical and Electronic Equipment*, EN Standard 50124-1, 2017.

[17] *EN Adjustable Speed Electrical Power Drive Systems - Part 5-1: Safety Requirements - Electrical, Thermal and Energy*, EN Standard, 61800-5-1, 2007.

[18] *EN Insulation Co-Ordination - Part 1: Definitions, Principles and Rules*, EN Standard 60071-1, 2006.

[19] Y. Shakweh, "Evaluation of MV power stack topologies," in *IEE Seminar PWM Medium Voltage Drives*. Birmingham, U. K., pp. 8/1–8/6, 2000.

[20] E. Cengelci, P. N. Enjeti, and J. W. Gray, "A new modular motor-modular inverter concept for medium-voltage adjustable-speed-drive systems," *IEEE Trans. Ind. Appl.*, vol. 36, no. 3, pp. 786–796, May/Jun. 2000.
[21] M. Verma, N. Bhatia, S. D. Holdridge, and T. O'Neal, "Isolation techniques for medium-voltage adjustable speed drives: Drive topologies for maintaining line-side performance," *IEEE Ind. Appl. Mag.*, vol. 25, no. 6, pp. 92–100, Nov./Dec. 2019.
[22] G. Jean-Pierre, N. Altin, A. E. Shafei., and A. Nasiri, "A control scheme based on lyapunov function for cascaded H-Bridge multilevel active rectifiers," *IEEE Appl. Power Electron. Conf. Expo.*, New Orleans, LA, USA, doi: 10.1109/APEC39645.2020.9124234, 2020.
[23] E. de Jong, E. de Meulemeester, and P. Heskes, "Design and realisation of a unique MV converter implemented in a new power electronic equipment test laboratory for emerging MV applications," *IEEE Power Energy Soc. Gen. Meet. - Convers. Del. Elect. Energy 21st Century*, Pittsburgh, PA, USA, 2008, pp. 1–4.
[24] N. Altin, S. Ozdemir, and A. Nasiri, "A novel solar PV inverter topology based on an LLC resonant converter," in *Proc. IEEE Energy Convers. Congr. Expo.)*, Baltimore, MD, USA, 2019, pp. 6734–6740.
[25] C. Zhao *et al.*, "Power electronic transformer (PET) converter: Design of a 1.2MW demonstrator for traction applications," in *Proc. Int. Symp. Power Electron. Power Electron., Elect. Drives, Automat. Motion*, Sorrento, Italy, 2012, pp. 855–860.
[26] S. Ozdemir, S. Balci, N. Altin, and I. Sefa, "Design and performance analysis of the three-level isolated DC-DC converter with the nanocyrstalline core transformer," *Int. J. Hydrogen Energy*, vol. 42, no. 28, pp. 17801–17812, 2017.
[27] S. Sayed, M. Elmenshawy, M. Elmenshawy, L. Ben-Brahim, and A. Massoud, "Design and analysis of high-gain medium-voltage DC-DC converters for high-power PV applications," in *Proc. IEEE 12th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG 2018)*, Doha, Qatar, 2018, pp. 1–5.
[28] M. Narimani, B. Wu, and N. R. Zargari, "A novel seven-level voltage source converter for medium-voltage (MV) applications," in *Proc. IEEE Energy Convers. Congr. Expo.*, Montreal, QC, Canada, 2015, pp. 4277–4282.
[29] A. El Shafei, S. Ozdemir, N. Altin, G. Jean-Pierre, and A. Nasiri, "Design and implementation of a medium voltage, high power, high frequency four-port transformer," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, New Orleans, LA, USA, 2020, pp. 2352–2357.
[30] M. Rashidi *et al.*, "Design and implementation of a LLC resonant solid-state transformer," *IEEE Trans. Ind. Appl.*, vol. 56, no. 4, pp. 3855–3864, Jul./Aug. 2020.
[31] S. Madhusoodhanan *et al.*, "Solid-State transformer and MV grid tie applications enabled by 15 kV SiC IGBTs and 10 kV SiC MOSFETs based multilevel converters," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3343–3360, Jul./Aug. 2015.
[32] M. Rashidi, N. N. Altin, S. S. Ozdemir, A. Bani-Ahmed, and A. Nasiri, "Design and development of a high-frequency multiport solid-state transformer with decoupled control scheme," *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 7515–7526, Nov./Dec. 2019.
[33] J. B. Casady *et al.*, "New generation 10kV SiC power MOSFET and diodes for industrial applications," in *Proc. PCIM Europe 2015*;in *Int. Exhib. Conf. for Power Electron., Intell. Motion, Renewable Energy Energy Manage.*, 2015, pp. 1–8. VDE.
[34] K. Shenai, M. Dudley, and R. F. Davis, "Current status and emerging trends in wide bandgap (WBG) semiconductor power switching devices," *ECS J. Solid State Sci. Technol.*, vol. 2, no. 8, pp. N3055–N3063, 2013.
[35] C. DiMarino *et al.*, "Fabrication and characterization of a high-power-density, planar 10 kV SiC MOSFET power module," in *Proc. CIPS ; 10th Int. Conf. Integr. Power Electron. Syst.*, 2018, pp. 1–6. VDE.
[36] G. F. Reed *et al.*, "Advancements in medium voltage DC architecture development with applications for powering electric vehicle charging stations," in *Proc. IEEE Energytech*, 2012, pp. 1–8. IEEE.
[37] M. Stieneker, and R. W. De Doncker, "Medium-voltage DC distribution grids in urban areas," in *Proc. IEEE 7th Int. Symp. Power Electron. for Distrib. Gener. Syst.*, 2016, pp. 1–7.
[38] D. Bosich, A. Vicenzutti, R. Pelaschiar, R. Menis, and G. Sulligoi, "Toward the future: The MVDC large ship research program," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, 2015, pp. 1–6. IEEE.
[39] A. Cavallini, D. Fabiani, and G. C. Montanari, "Power electronics and electrical insulation systems-part 1: Phenomenology overview," *IEEE Elect. Insul. Magn.*, vol. 26, no. 3, pp. 7–15, 2010.
[40] A. Cavallini, D. Fabiani, and G. C. Montanari, "Power electronics and electrical insulation systems-part 2: Life modeling for insulation design," *IEEE Elect. Insul. Mag.*, vol. 26, no. 4, pp. 33–39, Jul./Aug. 2010.
[41] C. Li, J. Hu, C. Lin, and J. He, "The potentially neglected culprit of DC surface flashover: Electron migration under temperature gradients," *Sci. Rep.*, vol. 7, no. 1, pp. 1–11, 2017.
[42] G. C. Montanari, P. Seri, and H. Naderiallaf, "A contribution to everlasting electrical insulation for DC voltage: PD-Phobic materials," *IEEE Access*, vol. 8, pp. 41882–41888, 2020.
[43] A. Christe, E. Coulinge, and D. Dujic, "Insulation coordination for a modular multilevel converter prototype," in *Proc. 18th Eur. Conf. Power Electron. Appl. (EPE'16 ECCE Europe)*, 2016, pp. 1–9.
[44] T. Batra, G. Gohil, A. Kumar Sesham, N. Rodriguez, and S. Bhattacharya, "Isolation design considerations for power supply of medium voltage silicon carbide gate drivers." in *Proc. IEEE Energy Convers. Congr. Expo.*, 2017, pp. 2552–2559.
[45] Semikron Application Note, AN1405, R:03, Iss.: 2017-12-07. P. by: Rainer Weiss, A. by: Ulrich Nicolai.
[46] A. S. Kamath Isolation in AC Motor Drives: Understanding the IEC 61800-5-1 Safety Standard Texas Instruments White Paper, 2015.
[47] R. Hemmati, F. Wu, and A. El-Refaie, "Survey of insulation systems in electrical machines," *IEEE Int. Electric Machines Drives Conf.*, 2019, pp. 2069–2076.
[48] B. Anitha, D. K. Mishra, and C. Koley, "Localisation of partial discharge source through delay calculation using UHF sensors," in *Proc. IEEE Int. WIE Conf. Elect. Comput. Eng. (WIECON-ECE)*, Dehradun, U. K. India, 2017, pp. 172–175.
[49] *IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers*, IEEE Standard C57.124, 1991.
[50] S. M. Hoek, S. Coenen, M. Bornowski, and S. Tenbohlen, "Fundamental differences of the PD measurement according to IEC 60270 and in UHF range," in *Proc. Int. Conf. Condition Monit. Diagnosis*, Beijing, China, 2008, pp. 79–81.
[51] J. Wu, A. R. Mor, and J. J. Smit, "The effects of superimposed impulse transients on partial discharge in XLPE cable joint," *Int. J. Elect. Power Energy Syst.*, vol. 110, pp. 497–509, Sep. 2019.
[52] -P. Mraz, S. A. Madhar, P. Treyer, and U. Hammer, "Guidelines for PD measurement according to IEC 60270," in *Proc. 21st Int. Symp. High Voltage Eng.*, Budapest, Hungary, 2019.
[53] *IEC Fire Hazard Testing - Part 11-10: Test Flames - 50 W Horizontal and Vertical Flame Test Methods*, IEC Standard 60695-11-10, 2013.
[54] G. Galli *et al.*, "Paschen's law in extreme pressure and temperature conditions," *IEEE Trans. Plasma Sci., Inst. Elect. Electron. Engineers*, vol. 47, no. 3, pp. 1641–1647, Mar. 2017.
[55] *IEC Method for the Determination of the Proof and the Comparative Tracking Indices of Solid Insulating Materials*, IEC Standard 60112, 2013.
[56] *IEC Power Transformers - Part 11: Dry-Type Transformers can be Applied. IEC 60076-11 Covers Dry-Type Power Transformers (Including Auto-Transformers) Having Values of Highest Voltage for Equipment up to and Including 36 kV and at Least One Winding Operating at Greater Than 1,1 kV*, IEC Standard 60076-11, 2018.
[57] *IEC Power Transformers-Part 3: Insulation Levels, Dielectric Tests and External Clearances in Air*, IEC Standard 60076-3, 2013.



SABAN OZDEMIR (Senior Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical education from Gazi University, Ankara, Turkey, in 2004, 2007, and 2013, respectively. From 2008 to 2009, he was with Baskent University, Ankara, Turkey. In 2009, he joined Gazi University. He is currently an Associate Professor with the Department of Electrical and Electronics Engineering, Faculty of Technology, Gazi University. From 2017 to 2018, he was a Visiting Scholar and from 2018 to 2019, he was a Research Associate with the University of Wisconsin-Milwaukee, Milwaukee, WI, USA. He has coauthored a book and a book chapter. He has also authored or coauthored more than 60 journal and conference papers in his areas of interests, which include power electronics, uninterruptible power supplies, grid interactive inverters, solid-state transformers, and resonant converters.

He is currently an Associate Editor for the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS for Renewable and Sustainable Energy Conversion Systems Committee.



NECMI ALTIN (Senior Member, IEEE) received the B.Sc., M.Sc. and Ph.D. degrees from Gazi University, Ankara, Turkey, in 2000, 2003, and 2009, respectively. In 2010, he joined the Department of Electrical and Electronics Engineering, Faculty of Technology, Gazi University, as an Assistant Professor and in 2014, he was promoted to an Associate Professor and in 2020, a Full Professor positions. From 2017 to 2019, he was a Visiting Scholar with the University of Wisconsin-Milwaukee, Milwaukee, WI, USA. He has authored or coauthored more than 150 journal and conference papers, and a book chapter. His current research interests include power electronics, application of power electronics in renewable energy systems, high power factor rectifiers, grid interactive inverters, solid state transformers, and control systems.

He is currently an Associate Editor for the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS for Renewable and Sustainable Energy Conversion Systems Committee.



ADEL NASIRI (Senior Member, IEEE) received the B.S. and M.S. degrees in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 1996 and 1998, respectively, and the Ph.D. degree in electrical engineering from the Illinois Institute of Technology, Chicago, IL, USA, in 2004.

From 1998 to 2001, he was with Moshanir Power Engineering Company, Tehran. From 2004 to 2005, he was also with ForHealth Technologies, Inc., Daytona Beach, FL, USA. He is currently Richard Grigg, Jr. Professor and the Director of the Center for Sustainable Electrical Energy Systems, College of Engineering and Applied Sciences, University of Wisconsin–Milwaukee, Milwaukee, WI, USA. He is also the Site Director for the NSF Center on Grid-connected Advanced Power Electronic Systems. He was a Primary Investigator on many federal and industry sponsored projects. He has holds seven patents and coauthored two books. He has also authored or coauthored numerous technical journal and conference papers in his areas of research, which include high power energy conversion, energy storage, and microgrids.

He is currently the Chair of the IEEE Industry Applications Society Committee on renewable and sustainable energy conversion. He is also the Editor of the Power Components and Systems, and an Associate Editor for the *International Journal of Power Electronics*. From 2013 to 2019, he was the Editor of the IEEE TRANSACTIONS ON SMART GRID and from 2018 to 2019, the Paper Review Chair for IAS. He was the General Chair of 2012 IEEE Symposium on Sensorless Electric Drives, 2014 International Conference on Renewable Energy Research and Applications (ICRERA 2014), and 2014 IEEE Power Electronics and Machines for Wind and Water Applications (PEMWA 2014).



ROBERT CUZNER (Senior Member, IEEE) received the B.S. degree in electrical and computer engineering from Brigham Young University, Provo, UT, USA, in 1988, and the M.S. and PhD. degrees in electrical and computer engineering from the University of Wisconsin-Madison, Milwaukee, WI, USA, in 1990 and 2013, respectively. In 2014, he joined the Department of Electrical Engineering and Computer Sciences, University of Wisconsin-Milwaukee. Prior to that, he was with industry for 24 years developing systems for power generation, power conversion and variable speed motor drives for both Navy and industrial applications. He has authored more than 60 journal and conference publications, two book chapters and five patents. His research interests include vessel electrification through MVdc and LVdc power distribution systems, integration of wide band gap power semiconductor based systems, electromagnetic compatibility, dc protection, and resiliency of islanded microgrids and remote grids.