Lappeenranta-Lahti University of Technology LUT
School of Energy Systems
Degree Program in Electrical Engineering

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ELECTRICAL SAFETY AND INSULATION COORDINATION OF A POWER ELECTRONIC DEVICE. CASE: VISEDO POWERMASTER

Examiners: Professor Pertti Silventoinen
M.Sc. Matti Iskanius

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ABSTRACT

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Master's Thesis

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Keywords: insulation coordination, Low Voltage Directive, adjustable speed drive

The focus of this thesis is on the electrical safety requirements regarding power conversion equipment. It is done as a case study on Visedo PowerMASTER converter. Main source of information used is literary review. A new version of the converter is planned for higher rated voltage and the electrical safety requirements imposed on the converter have to be determined. European Commission requires electrical equipment sold on European Economic Area to conform to safety requirements set in Low Voltage Directive. The main point of the Directive is that electrical equipment has to be designed and manufactured in such manner that its intended use doesn't endanger the health and safety of persons, domestic animals or property. Other changes unrelated to safety requirements but necessary for proper functionality of the device are also determined.

TIIVISTELMÄ

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Tässä opinnäytetyössä keskitytään tehoelektroniikkalaitteille asetettuihin sähköturvallisuusvaatimuksiin. Esimerkkitapauksena käytetään Visedo Oy:n PowerMASTER-konvertteria. Pääasiallinen työssä käytetty tiedonhankintamenetelmä on kirjallisuustutkimus. Tavoitteena on suunnitella uusi versio korkeamman käyttöjännitteen järjestelmiin olemassa olevan konvertterin pohjalta. Tämä edellyttää konvertterille asetettujen sähköturvallisuusvaatimusten määrittelyä. Euroopan talousalueella myytävien pienjännitelaitteiden sähköturvallisuusvaatimukset määritellään pienjännitedirektiivissä. Sen lähtökohtana on, että sähkölaite on suunniteltu ja valmistettu siten, ettei sen tarkoituksenmukaisesta käytöstä aiheudu vaaraa ihmisille, kotieläimille tai omaisuudelle. Myös turvallisuusvaatimuksista erilliset, laitteen toiminnan kannalta vaadittavat muutokset ovat määritelty.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
AFE	Active front end
CAD	Computer aided design
CTI	Comparative tracking index
DC	Direct current
DVC	Decisive voltage class
EC	European Commission
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EU	European Union
FEP	Fluorinated ethylene propylene
I	Current
IC	Integrated circuit
IGBT	Insulated gate bipolar transistor
IP	Ingress protection
LVD	Low Voltage Directive
MOSFET	Metal-oxide-semiconductor field-effect-transistor
RMS	Root mean square
PCB	Printed circuit board
PD	Partial discharge
PFTE	Polytetrafluoroethylene
SiCFET	Silicon carbide MOSFET
SOT	Small outline transistor
U	Voltage

1 INTRODUCTION

1.1 Background

Visedo Oy is Finnish company founded in 2009 specializing in high efficiency hybrid electric and electric drivetrains for heavy mobile work machines and marine vessels. The focus of the company is to offer system level solutions and it manufactures all the components required for a completely in-house manufactured electric drivetrain including power converters, energy storage units and electric motors. PowerMASTER is Visedo's power conversion unit especially designed for use in hybrid electric and electric drivetrains for mobile work machines and marine vessels. Different software options allow the converter to be used for motor control, generator control, as an active line rectifier with bidirectional power flow (AFE, active front end) and for creating a microgrid. Same hardware with an external series inductance can also be used as a DC/DC converter under the name PowerBOOST. In late 2017, Visedo was acquired by Danfoss and continues its operations from Finland by the name Danfoss Editron Oy. After the Danfoss acquisition, the existing product catalog was renamed and rebranded. The current product name for the converter hardware used in PowerMASTER and PowerBOOST products is EC-C1200-450. In this thesis it is still being referenced as PowerMASTER or converter.

Distribution voltages higher than the rated voltages of currently available PowerMASTER are commonly used in marine vessels and industrial applications such as mining machinery. To allow Danfoss Editron to offer system solutions with in-house components to these applications, equipment with higher voltage rating is needed. For example, larger marine vessels typically operate as series hybrid with onboard diesel generators supplying a local electricity distribution grid with propulsion motor drives and other electric equipment as consumers. Series hybrid operation is used because it allows for use of diesel fuel for energy storage with high energy density compared to batteries, localized energy conversion to electrical power with easier distribution, better controllability of electrical motors compared to diesel motors and operating point efficiency optimization for the diesel generators. Grid voltage commonly used in these applications is 690 V phase-to-phase, which is higher than the rated voltage of currently available power conversion equipment offered by Danfoss

Editron. Equipment with suitable rated voltage can be powered directly from the local distribution grid without the need for additional equipment for voltage conversion. The electronic equipment, e.g. converters, available for these applications usually lacks sufficient degree of environmental protection and must be located in a separate space reserved for it. PowerMASTER converter's compact design, high power density and high level of protection from environmental conditions allow it to be placed in the same space as the driven equipment and makes it very competitive in applications where space is at a premium. These attributes are especially beneficial in case of converting existing equipment to hybrid electric of full electric drivetrains since there's no space planned for the electronics originally. The new design is based on the existing device and basic functionality of the converter is intended to remain the same. No changes unrelated to achieving the new voltage rating are planned.

1.2 Goals and delimitations

The goal of this thesis is to determine the required safety related and functional changes to the existing PowerMASTER PCB (printed circuit board) and related electronic components to achieve a new product with same functionality for higher voltage rating. The focus is on compliance to the relevant electrical safety standards and if this can be achieved using the existing converter frame. Insulation coordination of mechanical parts such as device enclosure, busbars and connection box for power connectors are not considered. Functional testing of prototype devices is planned to verify if the functionality related design goals for the device are met. Other required type testing for electronic equipment such as vibration and shock withstand, electromagnetic compatibility (EMC) and IP-rating (ingress protection) testing are omitted from the scope of this thesis. No additional functionality compared to the existing design which the device based on is planned.

The approach of this thesis is design science with literary review as the main source of information. Literary sources include legislation, standards, component data sheets and application notes published by component manufacturers.

1.3 Structure of the thesis

The structure of this thesis is as follows:

Chapter 2 describes the safety requirements imposed on electrical equipment by European Commission and the relevant standards. The terms that are needed to understand insulation coordination are described. Different classes of insulation and methods of realizing insulation are presented.

Chapter 3 focuses on classification of the device under inspection (PowerMASTER) within the framework set by the relevant standards. Insulation coordination of the existing PowerMASTER converter is evaluated. Safety related design choices including component selection and dimensioning of clearance and creepage distances are defined. The influence of the higher voltage rating on safety requirements and the required changes to the existing design are considered. Changes required for functional reasons are also determined.

Chapter 4 details the findings and results of inspection and functional testing of the prototype units.

Chapter 5 concludes the insulation coordination analysis and design goals of the new device.

2 ELECTRICAL SAFETY REQUIREMENTS

Main source of safety requirements on electrical equipment sold on the European market is *Directive 2014/35/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits*. It is known in short as the Low Voltage Directive (LVD) and is referred as such from now on in this thesis. It covers the health and safety risks on almost all electrical equipment designed for use with voltage rating between 50 and 1000 V_{AC} and between 75 and 1500 V_{DC}. The term electrical equipment is not defined in the Directive but according to LVD Guide, International Electrotechnical Commissions (IEC) definition is used (European Commission, 2018b). IEC defines electrical equipment as an item used for generation, conversion, transmission, distribution or utilization of electrical energy (IEC 2004). Voltage rating for the equipment refers to either rated input voltage or rated output voltage or both. Higher voltages than the rated voltage may appear inside the equipment. Equipment can have multiple rated voltages and falls within the scope of LVD if the highest rated voltage is within the range specified by LVD. Despite applicable voltage range, not all electrical equipment is governed by the LVD. Electrical equipment exempt from the scope of the Directive is listed in the Annex II of the Directive. (European Parliament and the Council of the European Union 2014)

According to article 3 of the Directive, electronical equipment can only be sold on the EU market if it has been designed and manufactured following good engineering practices in safety matters and doesn’t endanger the health and safety of persons, domestic animals or property when installed properly and maintained and used as intended. The safety objectives are discussed in further detail in Annex I of the directive. It is responsibility of the manufacturer that the electrical equipment complies with the safety objectives of the directive. Article 6 states that manufacturer must create technical documentation defined in Annex III of the directive and conformity assessment procedure referred in Annex III must be carried out by the manufacturer or an external body on behalf of the manufacturer. This technical documentation includes general description of the electrical equipment, conceptual design and manufacturing drawings, list of standards applied to the design, results of design calculations made and test reports. When conformity has been demonstrated, EU declaration of conformity shall be drawn up and CE marking affixed to the equipment. Manufacturer must keep the technical documentation and the EU declaration of conformity available for ten years after the electrical equipment is placed on the market. According to article 12 of the directive, electronic equipment which conforms to the relevant harmonized standards published in the Official Journal of the European Union can be presumed to conform to the safety objectives of the directive. (European Parliament and the Council of the European Union 2014)

List of harmonized standards under the directive is published in Official Journal of the European Union. Standards listed in *Official Journal of the European Union, C 326, 14 September 2018* concerning electrical safety and relevant to the device (PowerMASTER) include *IEC61800-5-1 Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy* and possibly *IEC 62477-1:2012 Safety requirements for power electronic converter systems and equipment - Part 1: General* and *IEC 61204-7:2016 Low-voltage switch mode power supplies - Part 7: Safety requirements* for DC/DC converter operation (European Commission 2018a). Standard *IEC60664-1 Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests* was previously listed under harmonized standards for LVD but has since been removed. Contents of IEC60664-1 are referenced in both IEC61800-5-1 and IEC 62477-1:2012 and it is listed as a normative reference essential for understanding parts of the standard. Scope of IEC60664-1 is limited to equipment with rated voltage up to 1000 V_{AC} or up to 1500 V_{DC} and rated frequencies up to 30 kHz. IEC61800-5-1 specifies safety requirements for adjustable speed power drive systems and their elements.

Electrical equipment can only be placed on the Union market if it has been constructed in accordance to good engineering practices in matters relating to safety, health and environmental protection (European Commission 2018b). Manufacturers are responsible for carrying out conformity assessment and providing the technical documentation. CE-marking is affixed to the product to signify that it meets the relevant requirements.

According to the European Commission (EC) there are six steps for manufacturers to follow to affix the CE-marking to their product:

“

1. Identify the applicable directives and harmonized standards
2. Verify the product specific requirements
3. Identify whether an independent conformity assessment (by a notified body) is required
4. Test the product and check its conformity
5. Draw up and keep available the required technical documentation
6. Affix the CE-marking and draw up the EU Declaration of Conformity

“ (European Commission n.d.)

CE-marking implies that the product complies to all Directives of which scope the product falls under. By affixing the CE-marking to a product, manufacturer declares that the product conforms to all applicable EU legislative requirements and appropriate conformity assessment has been done. CE-marking must only be affixed to a product if falls under the scope of at least one related directive. (European Commission 2016)

Power electronic converters fall under Electromagnetic Compatibility (EMC) Directive 2014/30/EU which sets limits for electromagnetic emissions from the equipment and requirements for immunity to electromagnetic interference (EMI) from other sources. Separate EU declaration of conformity must be drawn for EMC directive. Tests to verify compliance to EMC Directive are required for affixing CE-marking to the product but EMC related issues are omitted from the scope of this work.

If UL approval is required for North American market, product must comply to relevant UL standards which include *UL840 Insulation coordination including clearances and creepage distances for electrical equipment* and *UL61800-5-1 Adjustable Speed Electrical Power Drive Systems – Part 5-1: Safety Requirements – Electrical, Thermal and Energy*. UL standards are often not based on international IEC or European EN standards and the design requirements for safety in differ from those of European standards and the design and conformity assessment need to be redone regarding the UL standards (Weiss 2017).

2.1 Description of the relevant terms

This chapter describes the terms used in the standards in scope required to understand insulation coordination. IEC66064-1 defines insulation coordination itself as “selection of insulation characteristics of the equipment with regard to its application and in relation to its surroundings” (IEC2007a). This means that the insulation is dimensioned to withstand the expected voltage stress applied to it over its anticipated lifetime taking in accord properties of the insulating material, expected voltage applied across the insulation and environmental factors affecting the insulation such as temperature, humidity, atmospheric pressure and pollution.

Rated voltage is the voltage assigned by the manufacturer to which operation and performance characteristics of the equipment are referred. Rated voltage of the equipment refers to the input and/or output voltage of the equipment and higher voltages may be present inside the equipment. Equipment can have multiple rated voltages or a range of rated voltage. In these cases, the safety requirements are for the highest value of rated voltage (IEC 2007a).

Decisive voltage class (DVC) of a circuit is based on the voltage of the circuit and is used to determine the required protective measures against electric shock for the given circuit. In addition to the DVC of the circuit, these required protective measures can also influenced by DVC of adjacent circuits if any. Electrical circuits are considered separate when there is no direct connection or connection via parts other than those used for isolation between the circuits. Protective impedance is not considered a conductive connection and the circuits are considered separate. (IEC 2007b)

Overvoltage categories are used for equipment energized directly from the low-voltage mains. They are used for dimensioning insulation regarding impulse voltage. Transient overvoltages in large and complex systems such as low-voltage mains can only be assessed on statistical basis. Overvoltage category of equipment is determined by the intended location of installation of the equipment. Four different overvoltage categories have been defined and equipment installed closer to the origin of the installation will have a higher overvoltage category. Overvoltage category IV is for equipment connected directly at the origin of installation, overvoltage category III is for equipment connected to fixed installation or subject to special requirements regarding reliability, overvoltage category II is for equipment connected to the installation by plug or other detachable means and in overvoltage category I transient overvoltages are suppressed below required level by external means. Required impulse withstand voltage is then determined by the overvoltage category and the rated voltage of the equipment (IEC 2007a). Impulse voltage testing is done by using a waveform of a specific transient profile with a 1.2 µs rising edge and a 50 µs falling edge. This is intended to simulate overvoltages of atmospheric origin i.e. voltage induced on the power lines by direct or indirect lightning strikes. The rated impulse voltage refers to the peak value of this waveform.

2.2 Insulation

Insulation is defined as a part of an electrotechnical equipment that separates conducting parts of different electrical potentials (IEC 2007a). Insulation requirements within equipment can be divided into three insulation classes. Insulation is considered functional when it’s located between live parts of different electrical potentials and required for the equipment to function as intended but the breakdown of such insulation does not lead to hazardous voltages in any accessible parts of the equipment. Basic insulation is required between hazardous live parts and accessible conductive parts that have been earthed such as metallic device enclosure. Fault of basic insulation does not lead to hazardous voltages in accessible parts of the equipment due to protective earthing. Protective separation is required between hazardous live parts and non-earthed accessible conductive parts or control circuits of lower voltage within the equipment. Protective separation can be realized as a double insulation, reinforced insulation or protective impedance. Double insulation consists of basic insulation and supplementary insulation with equal level of protection to that of basic insulation between the hazardous voltage and the user. With double insulation failure of one insulation barrier doesn’t expose the user to hazardous voltages. Reinforced insulation is a single insulation with degree of protection and reliability requirements equivalent to that of double insulation. Protective separation consisting of multiple layers of insulation which cannot be tested separately is considered reinforced insulation in regard to testing. (IEC 2007b)

Insulation can be realized as clearance in air, creepage along the surface of an insulating material or solid insulation. Liquid and gas insulation are also used in high-voltage equipment such as switchgear but are outside of the scope of the relevant standards and not intended to be used in this design.

2.2.1 Clearance

Clearance is defined as the shortest distance in air between two conductive parts. The breakdown voltage for a given distance in gas depends on pressure of the gas as per Paschen’s Law. The use pressurized air as an insulating medium is not included in the scope of the aforementioned standards and not considered. The clearance distances listed in the standards are applicable up to altitudes of 2000 m from sea level. Air pressure is affected by the altitude of the installation and the lower air pressure at higher altitudes leads to a lower breakdown voltage for given clearance distance. For equipment intended for use in altitudes higher than 2000 m from sea level, an atmospheric correlation factor must be used when dimensioning clearances. (IEC 2007a)

Clearances are to be dimensioned to withstand the required impulse withstand voltage. If a steady-state RMS voltage, a temporary overvoltage or recurring peak voltage requires larger clearance, that shall be used to dimension the clearance distance. (IEC 2007a).

2.2.2 Creepage and tracking

Creepage is defined as the shortest distance along the surface of an insulating material between two conductive parts. Creepage distance is dimensioned to avoid failure due to tracking. Tracking can be described as a progressive degradation of the surface of an insulating material causing a conductive path across insulation. It’s caused by surface scintillations damaging the surface of the insulating material. These scintillations happen when a leakage current path formed by pollution and humidity dries out breaking the current

(IEC 2011). Deterioration of the surface requires that the voltage across the insulation is sufficient to break down the gap formed in the leakage path and the current available is sufficient to provide enough energy to thermally decompose the surface of the insulating material (IEC 2007a).

For dimensioning creepage according to the conditions of the microenvironment, the following four degrees of pollution in microenvironment are established:

- Pollution degree 1, in which no pollution or only dry non-conductive pollution occurs. This pollution has no effect on requirements for insulation.
- Pollution degree 2, in which only dry non-conductive pollution occurs. This pollution can be temporarily made conductive by condensation when the equipment has been out of use.
- Pollution degree 3, in which conductive pollution or non-conductive pollution expected to be made conductive by condensation occurs.
- Pollution degree 4, in which continuous conductivity occurs due to conductive dust, rain or other wet conditions.

Depending on the enclosure of the equipment, the microenvironment inside the equipment can be influenced by macroenvironment present at the location of the installation. (IEC2007a)

Insulating materials can be categorized according to their tendency to track under voltage stress. Testing methods described in IEC60112 standard can be used to assign a comparative tracking index (CTI) to the material. Comparative tracking index has no unit, but the value refers to the test voltage with 600 V being the highest test voltage. Higher values represent higher resistance to tracking. For the dimensioning of creepage distances insulating materials are divided in to four different material groups according to their CTI:

- Material group I: $600 \leq CTI$
- Material group II: $400 \leq CTI < 600$
- Material group IIIa: $175 \leq CTI < 400$
- Material group IIIb: $100 \leq CTI < 175$

(IEC 2007a).

Inorganic insulation materials such as glass and ceramics do not track because the energy of scintillations does not damage the surface of the material (IEC 2011). For these materials, the creepage distances can be dimensioned according to the associated clearance distances (IEC 2007a).

Tracking of an insulating material occurs progressively over time. Long term voltage stress is the decisive in tracking of the insulation material and creepage distances are dimensioned according to RMS voltages expected to occur across them. Since it’s physically impossible for the creepage path to be shorter than the associated clearance, creepage distance shall be increased to match the required clearance distance if it is longer. (IEC2007a)

2.2.3 Solid insulation

Solid insulating materials have permittivity much higher than air allowing for insulating distances much smaller than those realized as clearance in air. Unlike air, solid insulation is not self-renewable and the expected degradation of the insulation over the expected lifetime of the equipment must be considered when dimensioning the insulation. Causes for degradation of the solid insulating material include voltage, thermal and mechanical stress. Minimum thickness for solid insulation cannot be calculated and performance of solid insulation must be verified by testing. (IEC 2007a)

2.2.4 Insulation coordination on printed circuit boards

Printed circuit boards are a special case considering insulation coordination with some differing dimensioning rules compared to other insulation with equivalent material group and pollution degree. Insulation on PCB can be realized as clearance, creepage or solid insulation. On inner layers of multilayer PCBs insulation between two potentials can also be considered as either clearance or solid insulation.

On the outer layers of the PCB, insulation between traces and other copper areas of different electric potential shall be considered as clearance in air. The required creepage distances on the outer layers of PCB in pollution degrees 1 and 2 are reduced compared to the required creepage distances on other materials of equivalent material group. These reduced creepage distance values have been determined by testing and apply also to components and parts on the PCB and other creepage distances with comparable tolerances. Reduced creepage distances on PCB are determined up to 1250 V in IEC 61800-5-1. With higher voltages than 1250 V or under pollution degrees other than 1 or 2, the general values used for dimensioning creepage distance apply. (IEC 2007b)

Printed circuit boards consist of stacked electrical layers made of copper with insulating layers between the electrical layers. Insulation between electrical layers is considered as solid insulation and consist of either PCB core material or prepreg. PCB core consists of insulating laminates made of fiber material and thermoset resin with copper foil plated on one or both sides. Prepreg is fiber material sheet impregnated with thermoset resin similar to the core material but has not been fully cured and is used in multilayer PCB manufacturing between adjacent PCB cores to attach them together and to insulate them from each other. Prepreg is also used between outer layer copper foil and adjacent PCB core. (Advanced Circuits 2009)

Due to the lamination process used in assembling multilayer PCBs, core material thickness and insulating properties have less variance. Core insulating material is fully cured and copper foil is laminated evenly across the entire surface area when PCB cores are manufactured. Prepreg is placed between one or two etched copper layers. Etched copper shapes sink into the prepreg during lamination and final thickness of the insulation between the copper layers at each given spot is dependent on the initial prepreg thickness and shape and thickness of the etched copper. The thickness of the PCB core can be several millimeters whereas thickness of the prepreg material is in the range of hundred micrometers. Several sheets of prepreg material can be stacked between conducting copper layers to achieve required insulation withstand voltage and desired PCB thickness.

The insulation between traces and coppers located on the same inner layer of a multilayer PCB can be considered as clearance in air and creepage in pollution degree 1. The insulation on the inner layers can also be considered as solid insulation (IEC 2007b). In this case the same requirements as for any other solid insulation apply. When PCB laminate material is considered as a solid insulation material between copper areas of different electrical potentials on inner layers of the PCB or between the layers, its voltage withstand capability must be tested to meet the requirements.

3 CASE POWERMASTER

PowerMASTER is Visedo's liquid cooled heavy duty converter especially designed for use in electric or hybrid electric drive trains for mobile work machines, busses and marine vessels. It can be used for motor drive, generator control, active front end or creating a microgrid. The most common use case for the PowerMASTER hardware is to be used as a motor drive. Enclosure of the PowerMASTER along with the physical dimensions can be seen in Figure 3.1 and Figure 3.2.

Figure 3.1 PowerMASTER converter (Danfoss 2019a)

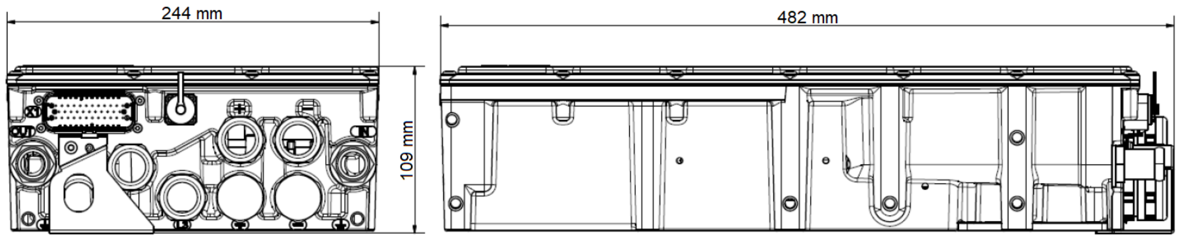

Figure 3.2 Dimensions of the PowerMASTER converter (Danfoss 2019a)

The high-level schematic of the PowerMASTER converter can be seen in Figure.3.3. The device has connections for DC-voltage and three-phase AC-voltage which is also used for lower voltage side when the device is operated as a DC/DC-converter. Depending on the application either side can be considered as input or output in terms of power and the direction of power can also change during operation for example regenerative braking of electrical motor.

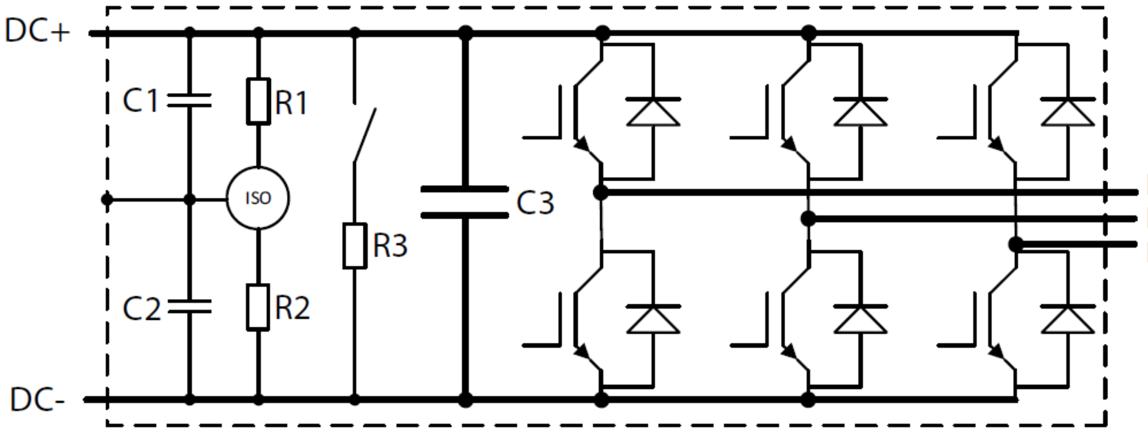

Figure.3.3 Functional schematic of the PowerMASTER converter. (Danfoss 2019a)

The basic standard, *IEC 60664 Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests,* applies to PowerMASTER in every intended use. The most common use for the converter is motor drive and the product standard, *IEC61800-5-1 Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy*, applies.

The rated voltages for power input/output connections of the device are 0-850 V_{DC} with nominal voltage of 750 V_{DC} for the DC-side and 0-560 V_{AC} nominal 500 V_{AC} for the AC-side. The AC-voltages specified are line-to-line voltages. Even though the hardware stays unchanged, different software control options allow the device to function as multiple different devices. The operating conditions and requirements of each of these different intended use cases must be considered in designing and assessing the insulation coordination of the devices. Insulation must be dimensioned according to the application with the most severe requirements so that all use cases are covered. When the device is operated as an active front end or used to create a non-isolated microgrid, it is connected to the low-voltage mains. IEC60664-1 requires that an overvoltage category must be specified for equipment connected and energized from the low-voltage mains (IEC 2007). The required impulse withstand voltage of the equipment is defined by its overvoltage category and rated voltage. Overvoltage category is defined by the location of the installation. As the device is to be used in fixed installations in industrial environment, it will be assigned in overvoltage category III. According to IEC61800-5-1 4.3.6.2.1 and IEC60664-1 Table B.1 and Table F.1, the rationalized nominal voltage for dimensioning impulse withstand voltage of the system is 300 V when connected to 230/400 V or 277/480 V supply mains. For three-phase normal-earthed TN and TT systems, the system voltage used for dimensioning temporary overvoltage is RMS value of the rated voltage between a phase and earth. For corner-earthed TN systems, the system voltage used for dimensioning temporary overvoltage is the RMS value of the rated phase-to-phase voltage. In three-phase IT systems, system voltage used for determination of impulse voltage is the RMS value of the rated voltage between a phase and an artificial neutral point. For most systems, this value is the RMS value of the rated phase-to-phase voltage divided by $\sqrt{3}$. For determination of temporary overvoltage in IT systems, the RMS value of the rated phase-to-phase voltage is to be used. If the supply voltage is rectified AC voltage, system voltage is the RMS value of the source AC voltage before rectification and taking into account the earthing system of the supply.

According to IEC61800-5-1, a standard power drive system shall be designed for operation in pollution degree 2. Pollution degree 3 shall be used for dimensioning the insulation for safety reasons. Insulation can be dimensioned according to pollution degree 2 if one of the following applies: Instructions provided with the power drive system specify operation in pollution degree 2 only, intended installation application of the device is known to be in pollution degree 2 environment or adequate protection against the environmental conditions at the location of the installation is provided by the device installation. (IEC 2007b)

The enclosure of the PowerMASTER converter has been classified for IP68 rating. This means the enclosure is sealed from dust and moisture. Due to this, the microenvironment inside the device can be considered unaffected by macroenvironment at the location of the installation and the insulation can be designed according to pollution degree 2.

3.1 Voltage and isolation on the main PCB

IEC61800-5-1 uses decisive voltage classification to determine the insulation requirement for circuits within equipment. Decisive voltage class of a circuit is determined by limits of the working voltage within the circuit. Five different galvanically isolated circuits can be defined on the main circuit board of the PowerMASTER converter:

1. Main control circuit, consisting of the control and communication electronics and power supplies for the PCB
2. Isolated IO
3. Isolated CAN A
4. Isolated CAN B
5. Main power stage and auxiliaries, consisting of IGBT gate drivers, IGBT temperature measurements, DC link voltage measurement, enclosure voltage measurement and DC link discharge resistor control

Drawing of the PCB with different circuits marked is presented in the Appendix 1. Main control circuit has rated input voltage of 7 – 33 V_{DC} and no higher voltages are present in the circuit. Isolated IO, as well as the two identical isolated CAN circuits are supplied through an isolated voltage supply from the main control circuit. The voltage supplies for these circuits are separate but identical with a supply voltage of 7.5 V_{DC}. This places all these circuits within the voltage range of 0 – 60 V_{DC} of decisive voltage class A. Power circuit has a maximum DC link voltage of 850 V_{DC} and maximum AC output voltage of 560 V_{AC}. Its voltage falls within the range of DVC C which covers circuits with voltages 50 – 1000 V_{AC} and 120 – 1500 V_{DC}. Per IEC61800-5-1, circuits of decisive voltage class A need to be insulated from earth only if it is required for the functionality of the equipment. Insulation between separate circuits of the decisive voltage class A is also required only for functional reasons. Protective separation is required between circuits of decisive voltage class A and adjacent circuits of decisive voltage class C. This protective separation is to be dimensioned regarding the circuit of higher voltage. Basic insulation is required between circuits of decisive voltage class C and earth. Communication signal needed to pass through protective separation can been seen in the schematic of the converter in Figure 3.4.

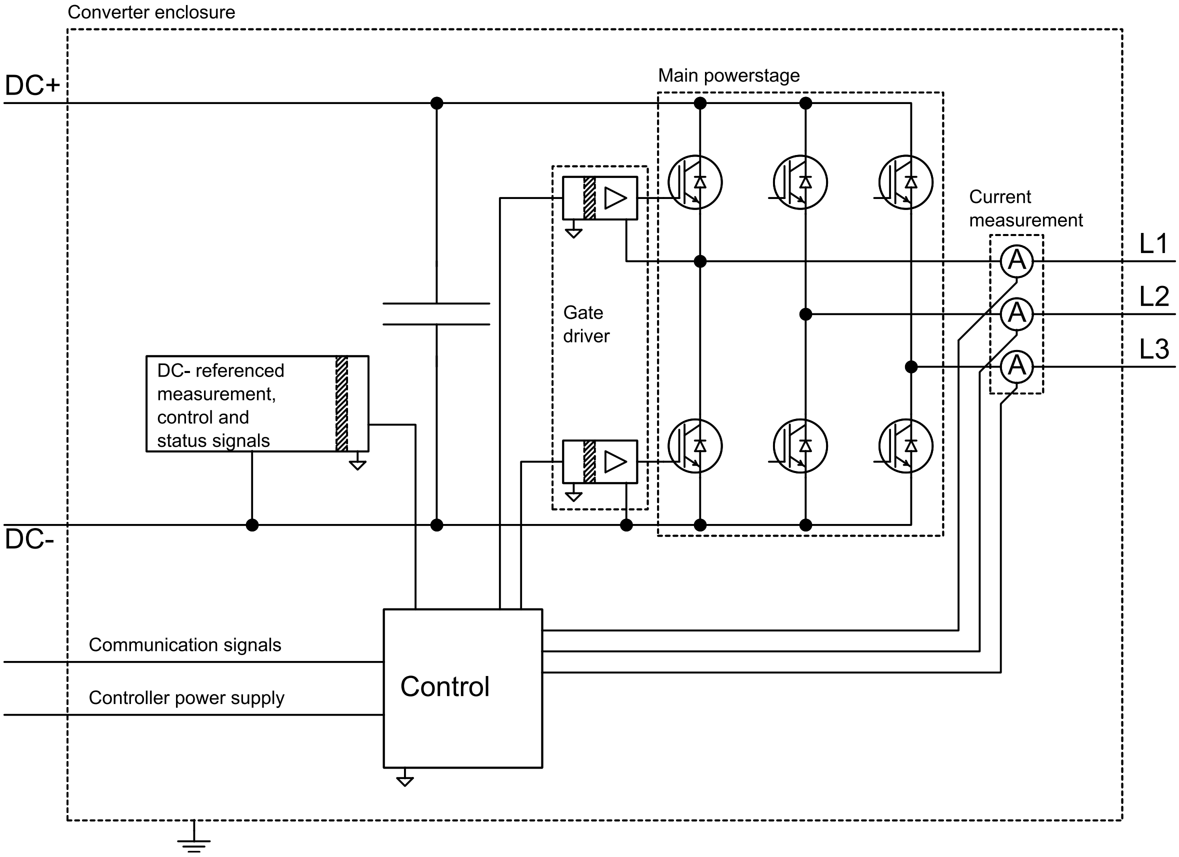

Figure 3.4 Schematic of the converter where signals between main power circuit and control circuit are visible.

For the circuits of decisive voltage class A only functional insulation is required between different potentials within the circuit, between adjacent circuits of decisive voltage class A and between circuits and earth. In the project files of PCB CAD (computer aided design) program, the allowed minimum clearance between parts of different electric potentials was defined as 0.15 mm so no smaller clearances are found on the PCB. According to IEC61800-5-1 Table 9 columns 2 and 5, minimum clearance distance requirement on PCBs up to working voltage of 110 V is 0.1 mm in pollution degree 2. The smallest creepage distance for PCBs in pollution degree 2 listed in IEC61800-5-1 Table 10 is 0.04 mm and this is applicable up to working voltage up to 50 V. The minimum clearance distance of 0.15 mm defined in the PCB design rules complies with both required clearance and creepage distances.

For circuits of decisive voltage class C basic insulation to earth is required. From IEC61800-5-1 Table 7 the required rated impulse voltage is 4 kV for basic insulation. This corresponds to the minimum clearance distance of 3.0 mm according to Table 9. For system voltage of 300 V the short-term temporary overvoltage is 2120 V/1500 V (crest value/ RMS) according to IEC61800-5-1 Table 7. These values correspond to nominal system voltage U_n + 1200 V. Linear interpolation using the values given in Table 9 results in clearance distance of

$$d = 1.5\ \mathrm{mm} + \frac{3\ \mathrm{mm} - 1.5\ \mathrm{mm}}{2600\ \mathrm{V} - 1600\ \mathrm{V}} \times (2120\ \mathrm{V} - 1600\ \mathrm{V}) = 2.28\ \mathrm{mm}. \qquad (1)$$

This applies when the device is connected to a neutral-earthed grid. If used in a non-earthed three-phase IT system, the system voltage is 600 V and the short-term temporary overvoltage 2550 V/1800 V. Clearance distance required for basic insulation in IT systems is

$$d = 1.5\ \mathrm{mm} + \frac{3\ \mathrm{mm} - 1.5\ \mathrm{mm}}{2600\ \mathrm{V} - 1600\ \mathrm{V}} \times (2550\ \mathrm{V} - 1600\ \mathrm{V}) = 2.93\ \mathrm{mm}. \qquad (2)$$

The clearance distance of 3.0 mm resulting from the required rated impulse voltage is the most severe requirement and shall be used for dimensioning clearance for basic insulation.

For reinforced insulation the required rated impulse voltage is 6 kV and the corresponding clearance distance 5.5 mm. The voltage used for dimensioning clearance distance of reinforced insulation for short-term temporary overvoltage is 1.6 times the voltage used for dimensioning basic insulation. Linear interpolation results in a required clearance of

$$d = 3\ \mathrm{mm} + \frac{5.5\ \mathrm{mm} - 3\ \mathrm{mm}}{3700\ \mathrm{V} - 2600\ \mathrm{V}} \times (3392\ \mathrm{V} - 2600\ \mathrm{V}) = 4.8\ \mathrm{mm}. \qquad (3)$$

Dimensioning clearance for short-term temporary overvoltage for reinforced insulation in IT system leads to

$$d = 5.5\ \mathrm{mm} + \frac{8\ \mathrm{mm} - 5.5\ \mathrm{mm}}{4800\ \mathrm{V} - 3700\ \mathrm{V}} \times (4080\ \mathrm{V} - 3700\ \mathrm{V}) = 6.37\ \mathrm{mm}. \qquad (4)$$

Highest recurring peak voltage to be expected across reinforced insulation is the same as the peak voltage across basic insulation but for dimensioning clearance distance this voltage shall be doubled. The most severe requirement is given by short-term temporary overvoltage in IT system and it shall be used in dimensioning clearance for reinforced insulation.

For functional insulation the worst-case peak voltage is limited to the blocking voltage of Semikron SKiM459GD12E4 IGBT-module which is 1200 V. Linear interpolation from Table 9 results in clearance of

$$d = 0.5\text{ mm} + \frac{1.5\text{ mm} - 0.5\text{ mm}}{1600\text{ V} - 960\text{ V}} \times (1200\text{ V} - 960\text{ V}) = 0.875\text{ mm}. \qquad (5)$$

Creepage distance requirement is dependent on RMS value of the voltage across the insulation and must be evaluated on a case-by-case basis for the different potentials of the circuit. For the main power circuit, functional insulation is required between phase to phase, phase to DC-, phase to DC+ and DC+ to DC-. Measurement and control circuitry related to the main power circuit and its power supply is approximately at DC- potential and is treated as part of DC-. Phase potential in regard to the main PCB refers to upper gate driver circuitry of the corresponding phase. Basic insulation is required between phase to earth, DC+ to earth and DC- to earth. Reinforced insulation is required between all potentials of the main power circuit and other circuits within the device. RMS values of these voltages must be calculated in each of the possible operation modes of the device and creepage distance dimensioned according to the highest voltage.

The required creepage distances can be read from IEC61800-5-1 Table 10. Linear interpolation of the values given in the table is explicitly permitted. For functional and basic insulation, the required creepage distances are the same. For reinforced insulation the values given by the table must be doubled. Insulation between conductors on the inner layers of a PCB can be treated as either solid insulation or clearance in air and creepage in pollution degree 1. All creepage distances calculated here are rounded up to same number of digits as values found in the Table 10 of IEC61800-5-1. Creepage distances for outer layers of the PCB are calculated according to pollution degree 2 and according to pollution degree 1 for inner layers.

Required creepage distance from DC- to DC+ must be determined at the maximum rated DC voltage of 850 V. Linear interpolation results in a required creepage of

$$d = 4\ \mathrm{mm} + \frac{5\ \mathrm{mm} - 4\ \mathrm{mm}}{1000\ \mathrm{V} - 800\ \mathrm{V}} \times (850\ \mathrm{V} - 800\ \mathrm{V}) = 4.3\ \mathrm{mm} \tag{6}$$

for outer layers and

$$d = 2.4\ \mathrm{mm} + \frac{3.2\ \mathrm{mm} - 2.4\ \mathrm{mm}}{1000\ \mathrm{V} - 800\ \mathrm{V}} \times (850\ \mathrm{V} - 800\ \mathrm{V}) = 2.6\ \mathrm{mm} \tag{7}$$

for inner layers.

For RMS value of voltage from one phase to either DC- or DC+, multiple different operational modes must be considered. When the device is supplied from 400 V phase-to-phase grid without load, rectified DC link voltage equals the peak value of phase-to-phase voltage and RMS value of phase-to-DC voltage is the quadratic sum of the voltage from DC to neutral and the voltage from phase-to-neutral

$$U_{\mathrm{DC,L}} = \sqrt{\left(0.5 \times \sqrt{2} \times 400\ \mathrm{V}\right)^2 + \left(\frac{400\ \mathrm{V}}{\sqrt{3}}\right)^2} = 365\ \mathrm{V}. \tag{8}$$

When the device is operating as a motor drive at the maximum rated DC voltage supply of 850 V and maximum AC output of 560 V, RMS value of phase-to-DC voltage is

$$U_{\mathrm{DC,L}} = \sqrt{(0.5 \times 850\ \mathrm{V})^2 + \left(\frac{560\ \mathrm{V}}{\sqrt{3}}\right)^2} = 534\ \mathrm{V}. \tag{9}$$

This is assuming sinusoidal output voltage. The actual AC voltage waveform is created by two-level pulse-width modulation. Because the device under investigation has no internal filtering for low-order harmonics of output voltage, ignoring transient conditions, voltage at a phase terminal is either at DC- or DC+ potential. Assuming no DC-bias, the average duty for phase is 0.5 for periods much longer than the period of the fundamental frequency of the output voltage. This leads to RMS value of

$$U_{\mathrm{DC,L}} = \sqrt{(0.5 \times \mathrm{U_{DC}})^2 + (0.5 \times \mathrm{U_{DC}})^2} = U_{\mathrm{DC}} \times \sqrt{0.5} \tag{10}$$

which is independent of the output voltage. This is true for sinusoidal pulse-width modulation. RMS voltage between phase and DC-link is dependent on length of the evaluation period, carrier frequency, output frequency, DC-link voltage and the modulation scheme.

When the device is used as DC/DC converter, both output and input voltages are referenced to the DC- and the voltages can be expressed as

$$U_{\mathrm{DC-,LV+}} = U_{\mathrm{LV+}} \tag{11}$$

$$U_{\mathrm{DC+,LV+}} = U_{\mathrm{DC+}} - U_{\mathrm{LV+}} \tag{12}$$

where U_{DC+} is the higher DC voltage and U_{LV+} the lower DC voltage. Maximum voltage for both sides is the maximum rated DC voltage of 850 V. Maximum conversion ratio from the lower voltage side to the higher voltage side is specified as 1:10. These result in the following maximum average voltages

$$U_{\mathrm{DC-,LV+}} = U_{\mathrm{LV+}} = 850\ \mathrm{V} \tag{13}$$

$$U_{\mathrm{DC+,LV+}} = U_{\mathrm{DC+}} - U_{\mathrm{LV+}} = 850\ \mathrm{V} - 85\ \mathrm{V} = 765\ \mathrm{V}. \tag{14}$$

When the device is operating as a boost converter, i.e. power is transferred from the lower voltage side to the higher voltage side, switch duty for lower side switch in continuous conduction mode is given by the equation

$$D = 1 - \frac{U_{\mathrm{LV+}}}{U_{\mathrm{DC+}}} \tag{15}$$

In DC/DC operation the device is operated as a parallel multiphase converter. The basic functional schematic of a single phase in boost converter operation can be seen in Figure 3.5.

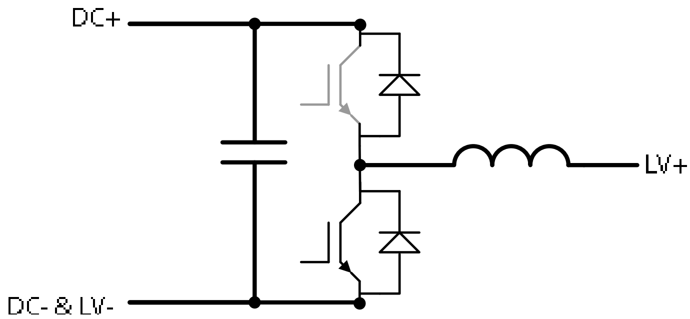

Figure 3.5 Single phase of the converter operated as a boost converter. Upper IGBT is not switched.

Maximum duty ratio is achieved at the maximum conversion ratio of 1:10 between input and output voltages,

$$D_{\mathrm{max}} = 1 - \frac{1}{10} = 0.9. \tag{16}$$

RMS values of the voltages from phase to DC+ and from phase to DC- can be calculated as follows

$$U_{\mathrm{DC+,LV+}} = U_{\mathrm{DC+}} \times \sqrt{D_{\mathrm{max}}} \tag{17}$$

$$U_{\mathrm{DC-,LV+}} = U_{\mathrm{DC+}} \times \sqrt{1 - D_{\mathrm{max}}}. \tag{18}$$

At maximum rated DC-link voltage of 850 V these values are

$$U_{\mathrm{DC+,LV+}} = 850\ \mathrm{V} \times \sqrt{0.9} = 807\ \mathrm{V} \tag{19}$$

$$U_{\mathrm{DC-,LV+}} = 850\ \mathrm{V} \times \sqrt{0.1} = 267\ \mathrm{V}. \tag{20}$$

With conversion ratio of 1, i.e. output voltage is equal to input voltage,

$$U_{\mathrm{DC+,LV+}} = 0\ \mathrm{V} \tag{21}$$

$$U_{\mathrm{DC-,LV+}} = 850\ \mathrm{V}. \tag{22}$$

When device is operated as a buck converter, i.e. power flow is from the higher voltage to the lower voltage, duty cycle of the higher switch when operating in continuous conduction mode is given by the equation

$$D = \frac{U_{\mathrm{LV+}}}{U_{\mathrm{DC+}}}. \tag{23}$$

Functional schematic of the buck converter can be seen in Figure 3.6.

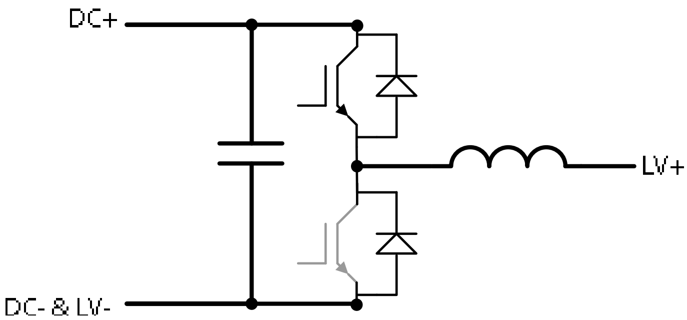

Figure 3.6 Single phase of the converter in buck converter operation. Lower IGBT is not switched.

With maximum conversion ratio of 1:10

$$D_{\mathrm{min}} = \frac{1}{10} = 0.1 \tag{24}$$

RMS values of the voltages from phase to DC+ and from phase to DC- can be calculated as follows

$$U_{\mathrm{DC+,LV+}} = U_{\mathrm{DC+}} \times \sqrt{1 - D_{\mathrm{min}}} \tag{25}$$

$$U_{\mathrm{DC-,LV+}} = U_{\mathrm{DC+}} \times \sqrt{D_{\mathrm{min}}}. \tag{26}$$

At maximum rated DC-link voltage of 850 V these values are

$$U_{\mathrm{DC+,LV+}} = 850\ \mathrm{V} \times \sqrt{0.9} = 807\ \mathrm{V} \tag{27}$$

$$U_{\mathrm{DC-,LV+}} = 850\ \mathrm{V} \times \sqrt{0.1} = 267\ \mathrm{V}. \tag{28}$$

With conversion ratio of 1, i.e. output voltage is equal to input voltage, the values are

$$U_{\mathrm{DC+,LV+}} = 0\ \mathrm{V} \tag{29}$$

$$U_{\mathrm{DC-,LV+}} = 850\ \mathrm{V}. \tag{30}$$

Voltage conversion direction is unidirectional and phase to DC- voltage will always be lower than the DC-link voltage. Buck and boost operating modes are not separate and the device switches between them in DC/DC converter operation depending on the direction of the current and power transfer. Direction of the power transfer does not influence the RMS voltage of the phase output relative to DC+ and DC-.

Operation as a DC/DC converter results in the highest possible RMS values of voltage from phase to DC- and DC+. Required creepage distance from phase to DC- is the same as from DC+ to DC-, 4.3 mm on the outer layers and 2.6 mm on the inner layers. Creepage from phase to DC+ is

$$d = 4\ \mathrm{mm} + \frac{5\ \mathrm{mm} - 4\ \mathrm{mm}}{1000\ \mathrm{V} - 800\ \mathrm{V}} \times (807\ \mathrm{V} - 800\ \mathrm{V}) = 4.1\ \mathrm{mm} \tag{31}$$

for outer layers and

$$d = 2.4\ \mathrm{mm} + \frac{3.2\ \mathrm{mm} - 2.4\ \mathrm{mm}}{1000\ \mathrm{V} - 800\ \mathrm{V}} \times (807\ \mathrm{V} - 800\ \mathrm{V}) = 2.5\ \mathrm{mm} \tag{32}$$

for inner layers.

According to IEC61800-5-1, usage of creepage distances shorter than those given by Table 10 are allowed for functional insulation if all the following conditions are met:

- flammability rating of the PCB is V-0 according to IEC 60695-11-10
- the CTI of the PCB material is at least 100
- the device passes the PCB short-circuit test detailed in the standard

PCB short-circuit test requires every creepage distance shorter than those given by Table 10 to short-circuited individually while the device is in use. Short-circuit is maintained until no further damage occurs. The purpose of the test is to verify that no ignition or electric shock hazard is caused by the short-circuit. The device is allowed to be damaged by the testing and does not have to remain functional. (IEC 2007b)

For basic insulation the voltage used for dimensioning creepage distance for system of nominal supply voltage of 300 V is 320 V according to IEC60664-1 Table F.3b. This applies for both phase-to-phase and phase-to-earth voltages for three-phase systems. When operating at the maximum output voltage of 560 V_{AC} phase-to-phase, the RMS value of phase-to-earth voltage becomes:

$$U_{\mathrm{L,Earth}} = \frac{560\ \mathrm{V}}{\sqrt{3}} = 323\ \mathrm{V}. \tag{33}$$

This assumes sinusoidal output voltage which does not correspond to the actual voltage waveform present at the converter phase terminals. Due to the layout of the main PCB, phase voltages are not located adjacent to earth potential and $U_{\mathrm{L,Earth}}$ doesn’t need to be considered for dimensioning creepage for basic insulation. For dimensioning creepage for reinforced insulation, voltage between phases and circuits of DVC A can be assumed to be approximately $U_{\mathrm{L,Earth}}$.

Due to the balancing resistors and y-capacitor, DC-link voltage should be balanced around the earth potential and voltage from both DC+ and DC- to earth half of the DC-link voltage.

$$U_{\mathrm{DC,Earth}} = \frac{850\ \mathrm{V}}{2} = 425\ \mathrm{V} \tag{34}$$

The internal balancing resistance is relatively high at 12 MΩ or 240MΩ and balancing can be heavily influenced by the power supply of the system. It can be earthed or non-earthed and either low voltage mains, generator, or DC-supply such as an external rectifier, a battery or a DC/DC converter.

One typical application for the converter is regenerative frequency converter system depicted in Figure 3.7 consisting of 2 converters, electric motor and grid filter. One converter acts as a regenerative grid rectifier while the other works as a motor drive. For sake of simplicity, control of the converters is omitted, and the voltage waveforms are plotted assuming sinusoidal pulse width modulation (SPWM). Figure 3.8 and Figure 3.9 show the three-phase SPWM and switch commands of the active front end.

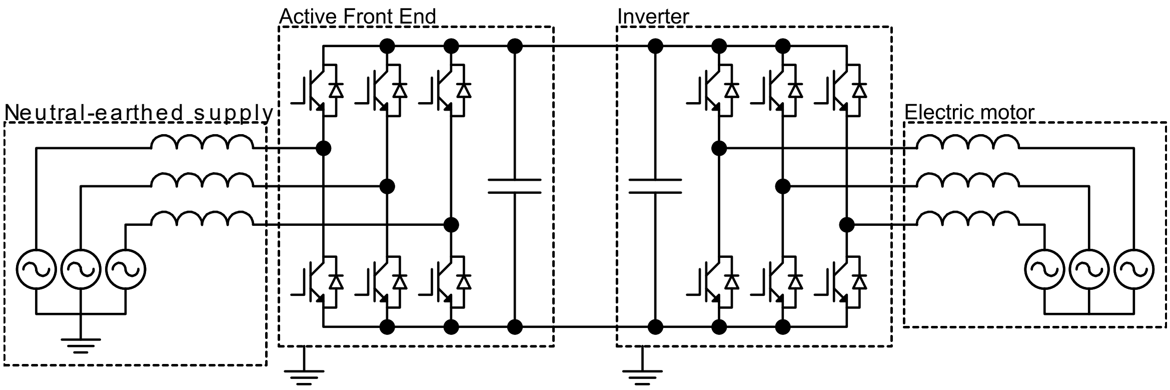

Figure 3.7 Typical grid-connected motor drive system with two PowerMASTER-converters.

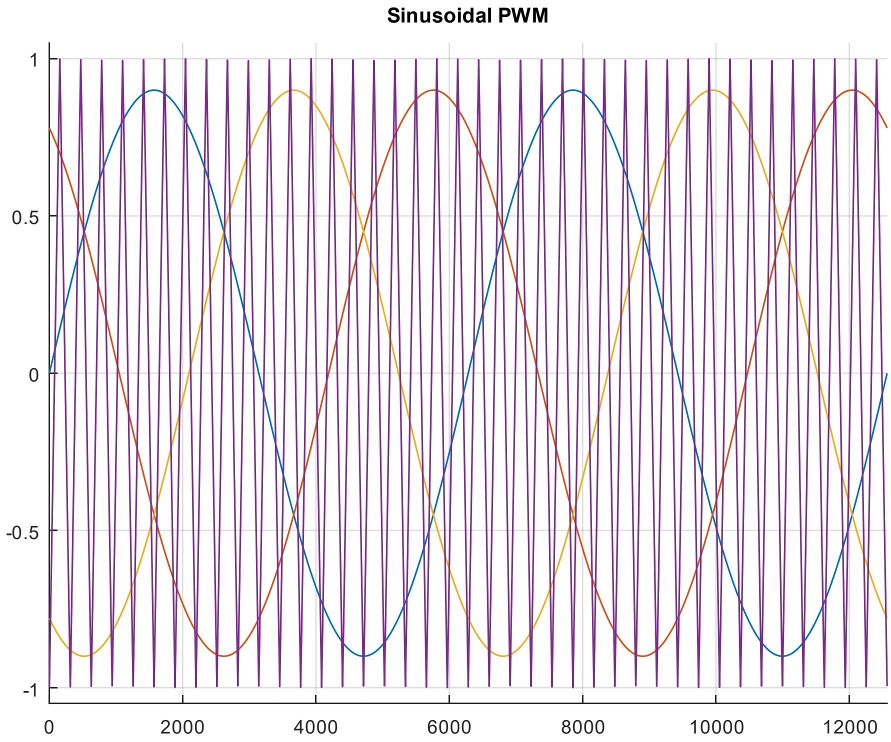

Figure 3.8 Three-phase sinusoidal modulation with triangular carrier.

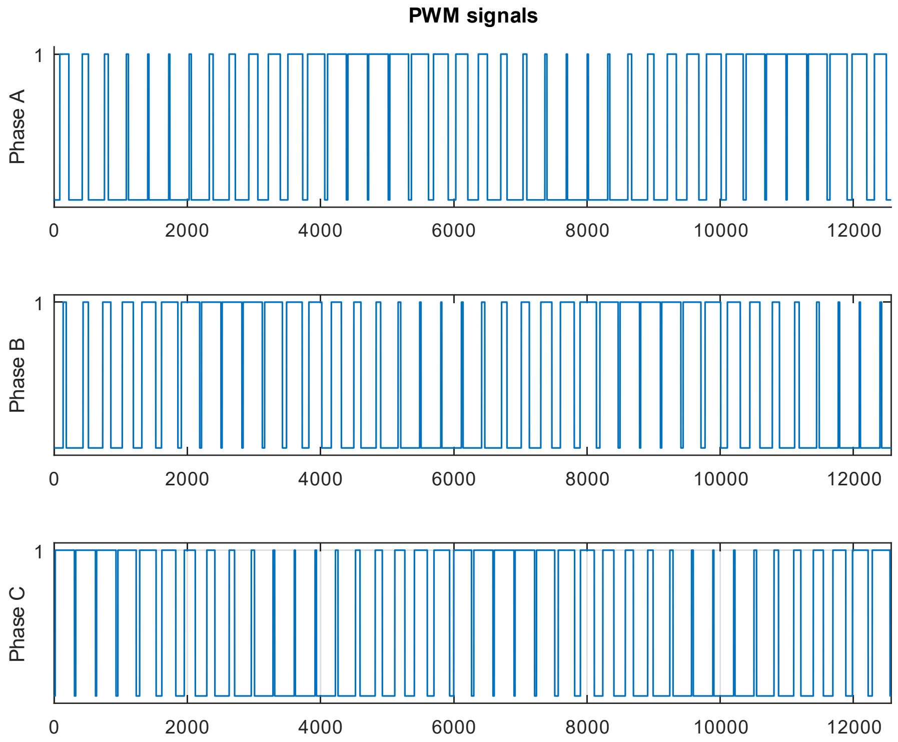

Figure 3.9 Switch commands of the AFE acquired by SPWM

DC-link common-mode voltage of the system caused by modulation of the active front end can be seen in Figure 3.10. Depending on switching states, possible values for DC-link common-mode voltage are ±1/6 and ±1/2 of the DC-link voltage. Phase-to-earth voltage of phase A of the active front end can be seen in Figure 3.11. This is the sum of the DC-link common-mode voltage and ±0.5 of the DC voltage depending on the switch state.

Phase voltage of the inverter can have values ±0.5 of the DC voltage depending on the switch state. The DC-link common-mode voltage is mostly influenced by switching of the AFE and the phase-to-earth voltage of the inverter is the sum of DC-link common-mode voltage and ±0.5 of the DC voltage resulting in possible values of values 0, ±1/3, ±2/3 and ±1 of DC-link voltage. Inverter's phase-to-earth voltage can be seen in Figure 3.12.

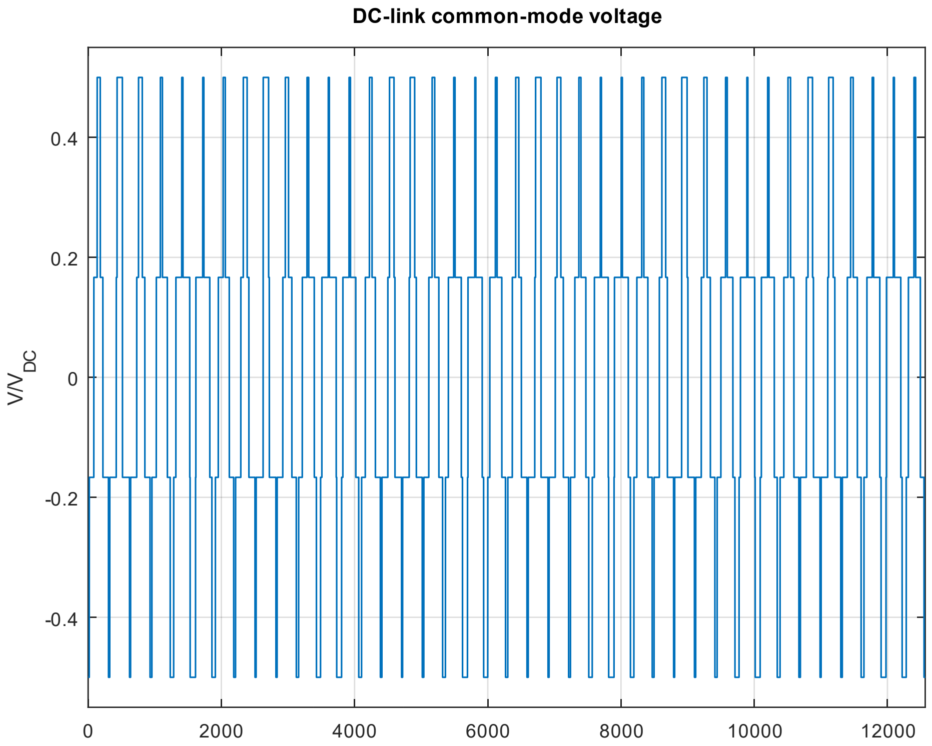

Figure 3.10 Common-mode voltage of the DC-link caused by AFE operation

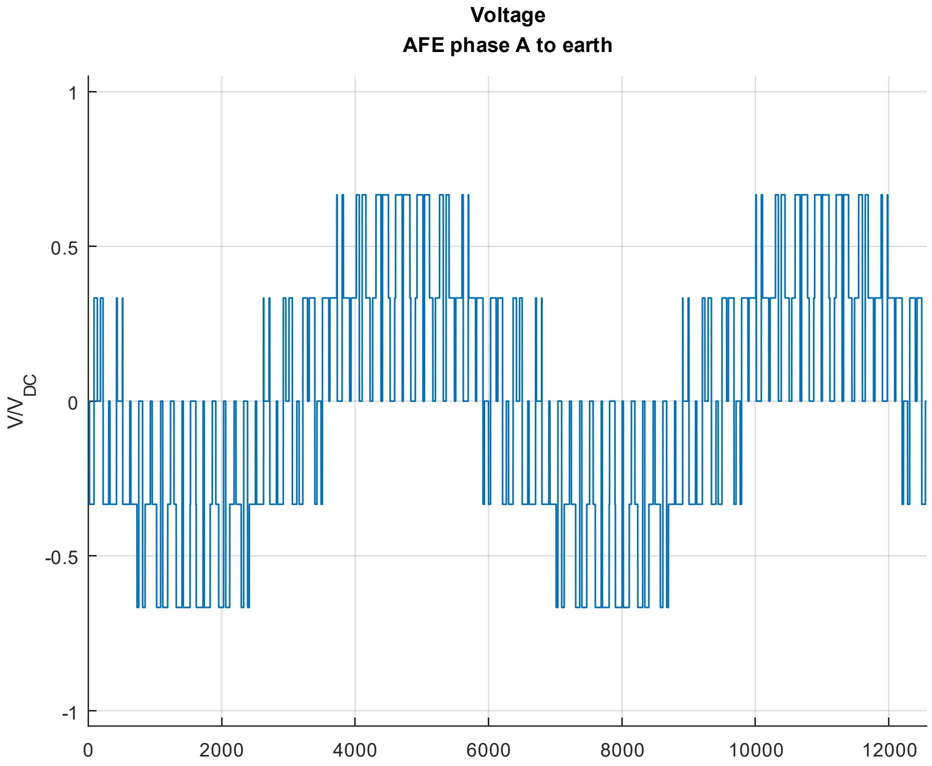

Figure 3.11 Voltage between AFE phase A and earth.

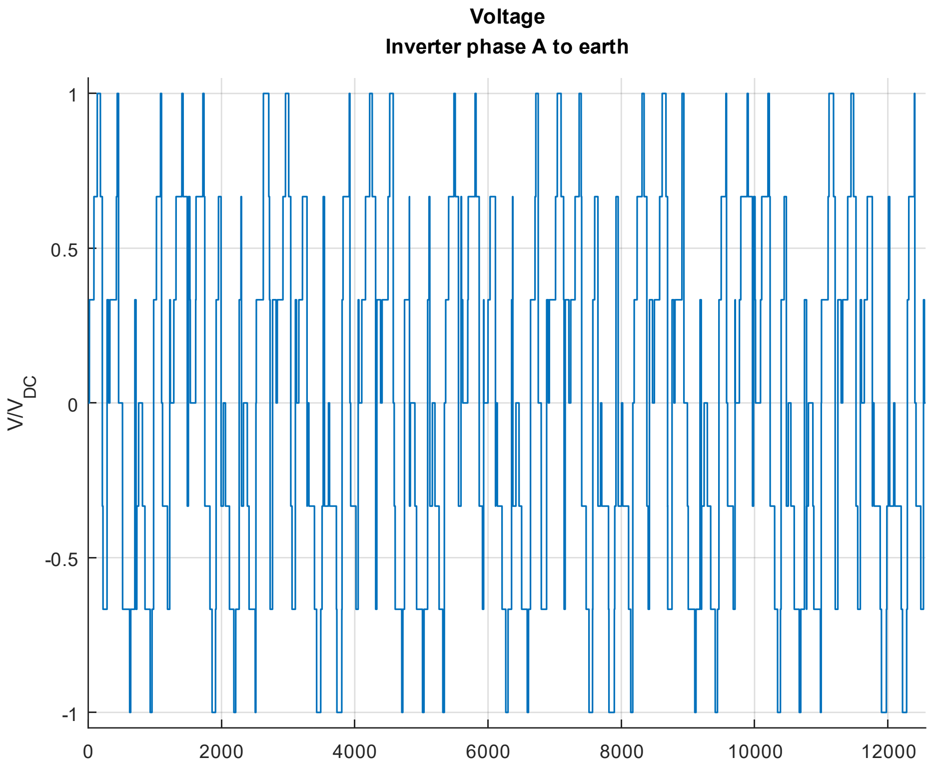

Figure 3.12 Voltage between inverter phase A and earth.

It's clear that the power supply and the system to which the equipment is connected play a role on the voltages applied across the insulation barriers. For example, passive six pulse diode bridge rectifier would result in much lower common-mode voltage at third harmonic of the grid frequency. Common-mode voltage and its influence on phase-to-earth and DC-to-earth voltage can affect the recurring peak value and RMS value of voltage over basic and reinforced insulation and thus increase requirements for solid insulation and creepage distance. The standards do not address this and only use the nominal supply voltage as a basis for dimensioning insulation.

The highest recurring peak of working voltage to be expected across basic and reinforced insulation is caused by common-mode voltage from active front end modulation and equal to the DC- link voltage. Due to ringing caused by parasitic circuit elements the actual peak value of voltage across basic insulation can be nearly twice the DC-link voltage.

When operating as a DC/DC converter, the RMS value of the phase voltage ranges from 1:10 of the DC-link voltage to full DC-link voltage. The maximum RMS value of phase to earth voltage in DC/DC converter operation is

$$U_{\mathrm{L,Earth}} = U_{\mathrm{DC,Earth}} = 425\ \mathrm{V}. \tag{35}$$

Assuming DC-link voltage is balanced symmetrically around earth potential, the maximum RMS value of $U_{\mathrm{L,Earth}}$ is limited to half of the DC-link voltage and the voltage used for dimensioning creepage for basic insulation for all main power circuit is 425 V. This results in the required creepage distance of

$$d = 2\ \mathrm{mm} + \frac{2.5\ \mathrm{mm} - 2\ \mathrm{mm}}{500\ \mathrm{V} - 400\ \mathrm{V}} \times (425\ \mathrm{V} - 400\ \mathrm{V}) = 2.2\ \mathrm{mm} \tag{36}$$

for outer layers and

$$d = 1\ \mathrm{mm} + \frac{1.3\ \mathrm{mm} - 1\ \mathrm{mm}}{500\ \mathrm{V} - 400\ \mathrm{V}} \times (425\ \mathrm{V} - 400\ \mathrm{V}) = 1.1\ \mathrm{mm} \tag{37}$$

for inner layers.

For reinforced insulation, the creepage distance values given by Table 10 are to be doubled according to IEC61800-5-1 4.3.6.5.1. Required creepage distance from main power circuit to other circuits on the PCB is

$$d = 2 \times \left(2\ \mathrm{mm} + \frac{2.5\ \mathrm{mm} - 2\ \mathrm{mm}}{500\ \mathrm{V} - 400\ \mathrm{V}} \times (425\ \mathrm{V} - 400\ \mathrm{V})\right) = 4.3\ \mathrm{mm} \tag{38}$$

on the outer layers and

$$d = 2 \times \left(1\ \mathrm{mm} + \frac{1.3\ \mathrm{mm} - 1\ \mathrm{mm}}{500\ \mathrm{V} - 400\ \mathrm{V}} \times (425\ \mathrm{V} - 400\ \mathrm{V})\right) = 2.2\ \mathrm{mm} \tag{39}$$

on the inner layers.

In case of a system like one demonstrated in Figure 3.7, average values of the voltages across basic and reinforced insulation stay the same as with balanced DC-link but common-mode voltage ripple of the DC-link like seen in Figure 3.10 heavily influences the RMS values of voltages across basic and reinforced insulation. This has no effect on compliance of the PCB since creepage distances on the existing PCB are dimensioned large enough to withstand full DC-link voltage across basic and reinforced insulation.

As it is physically impossible for a creepage distance to be shorter than the associated clearance, comparison between the required clearance distances and the required creepage distances at each insulation barrier shows that the calculated creepage distance requirement is only relevant in dimensioning functional insulation. In all other cases the required clearance is greater than the required creepage.

Clearance and creepage distances required between different electrical potentials are summarized in Table 3.1. The clearance and creepage distances required by different conditions are evaluated and the ones resulting in the most severe dimensioning requirement are marked in yellow and compared against the existing clearance and creepage distances on the PCB. As can be seen in the Table 3.1, required clearance and creepage distances are met.

Table 3.1 Comparison between insulation requirements and insulation found on the PCB

		Required clearance [mm]			**Required creepage [mm]**		**Minimum distance [mm]**		**Distance on PCB [mm]**	
		working voltage	temporary overvoltage	impulse voltage	outer layers	inner layers	outer layers	inner layers	outer layers	inner layers
Functional insulation	phase-to-DC-	0,875			4,3	2,6	4,3	2,6	4,5	4,5
	phase-to-DC+	0,875			4,1	2,5	4,1	2,5	4,5	4,5
	DC+-to-DC-	0,875			4,3	2,6	4,3	2,6	4,4	4,2
Basic insulation	earth-to-DC+		2,3	3	2,2	1,1	3	3	4,7	5,7
	earth-to-DC-		2,3	3	2,2	1,1	3	3	4,5	4,5
Reinforced insulation	DVC A-to-phase		4,8	5,5	4,3	2,2	5,5	5,5	8	8
	DVC A-to-DC+		4,8	5,5	4,3	2,2	5,5	5,5	29,6	29
	DVC A-to-DC-		4,8	5,5	4,3	2,2	5,5	5,5	8	8

Solid insulation is used for basic and functional insulation on the PCB for circuit of decisive voltage class C. PCB trace connected to the earthed device enclosure located on the inner layer 6 is surrounded by plane area connected DC- on both adjacent PCB layers. The layers are separated by FR-4 grade glass-reinforced epoxy laminate material with thickness of 0.28 mm on one side (prepreg) and 0.2 mm on the other side (core). FR-4 has a minimum dielectric strength of 30 kV/mm per IPC-4101E (IPC 2017). Given the material thickness used, this should result in dielectric strength of approximately 8.4 kV and 6 kV between earth and DC- which exceeds the 2550 V overvoltage and 4 kV impulse voltage requirement for basic insulation. PCB is also used for functional insulation between upper gate drivers, which float at the potential of their corresponding phase, and DC- and DC+ potentials. According to IEC60664-1 5.3.1 it is not possible to calculate required thickness for solid insulation and all solid insulation used basic, supplementary and reinforced insulation must be verified by testing.

3.2 Voltage rating and insulation of safety critical components

Components that bridge either basic or reinforced insulation are exposed to the same voltages as the insulation and are required to comply to the same voltage withstand, clearance and creepage distance requirements. These components include the discharge resistor, Y-capacitors mounted on a separate PCB used for EMI suppression, digital isolators for measurement and gate drive signals, transformers for isolated power supply and current transducers.

The internal solid insulation of the chassis-mounted discharge resistor between terminals and baseplate is exposed to the $U_{\mathrm{DC,Earth}}$ when the discharge is not active. Discharge resistor assembly has the same temporary overvoltage withstand requirement 2550 V and impulse withstand voltage requirement of 4 kV as other basic insulation. Datasheet for the discharge resistor used, Vishay RTOP200, specifies a dielectric strength of 2500 V between connection and chassis, tested according to MIL-STD-202 Method 301. This can either be DC voltage or RMS value at power frequency of 60 Hz. Compliance of the discharge resistor assembly to the impulse voltage requirement has to be verified by testing. The creepage distance between terminals and baseplate is not given in the datasheet. CTI of resistor casing is not mentioned either. Inspection of component 3D-model leads to 9.6 mm clearance and 16.6 mm creepage between the terminals and 8.7 mm clearance and creepage between baseplate and terminals. Assuming worst-case scenario with insulating material of the resistor casing being of the material group IIIb, the 8.7 mm creepage distance between terminals and base plate still allows for 870 V RMS value of working voltage which is much higher than half of the maximum allowed DC-link voltage of 850 V.

Components bridging reinforced insulation on the PCB include SI866xBD-B-IS digital isolators used for isolated measurements, SI8631BD-B-IS digital isolators used for gate driver signal and transformers used for powering gate drivers and isolated measurement circuits. Current is measured using LEM HAFS 600-S/SP8 hall effect current sensors which attach to the main control circuit by cable.

SI866xBD-B-IS has a rated maximum working insulation voltage V_{IORM} of 1200 V, transient overvoltage V_{IOTM} of 6000 V peak and surge voltage V_{IOSM} of 3077 V peak according to the datasheet (Silicon Labs 2018a). SI8631BD-B-IS has a rated maximum working insulation voltage V_{IORM} of 1200 V, transient overvoltage V_{IOTM} of 6000 V peak and surge voltage V_{IOSM} of 4000 V peak according to the datasheet (Silicon Labs 2018b). Maximum working insulation voltage V_{IORM} corresponds to the working voltage across the reinforced insulation. Transient overvoltage V_{IOTM} corresponds to the system level temporary overvoltage requirement and 6000 V peak is more than the minimum requirement for short-term temporary overvoltage across reinforced insulation which is 5090 V. Surge voltage V_{IOSM} corresponds to the system-level rated impulse withstand voltage (Kannath & Soundarapandian, 2014) which is 6 kV for reinforced insulation. Since the rated surge voltages V_{IOSM} of the digital isolators are only 3077 V and 4000 V they do not meet the impulse voltage requirement of the system level standard. IEC60664-1 allows for substituting impulse voltage test with AC voltage test at power frequency and with the peak value of the AC voltage being equal to that of the impulse voltage (IEC 2007a). Since the isolators have been tested for transient overvoltage V_{IOTM} with 6000 V peak, they fulfill this requirement.

Converter has also a separate PCB for Y-capacitors connected from both DC+ and DC- to earthed device enclosure. Clearance and creepage distance from DC+ to DC- is 5.1 mm. Clearance and creepage distance from both DC+ and DC- to enclosure connection plane is 7 mm. In the converter assembly one edge of the PCB is located against the earthed device enclosure. Distance from DC+ to this edge 4.7 mm. Y-capacitors used are Epcos

B81123C1332M, which are Y1-rated and have rated AC voltage of 500 V (Epcos 2018).

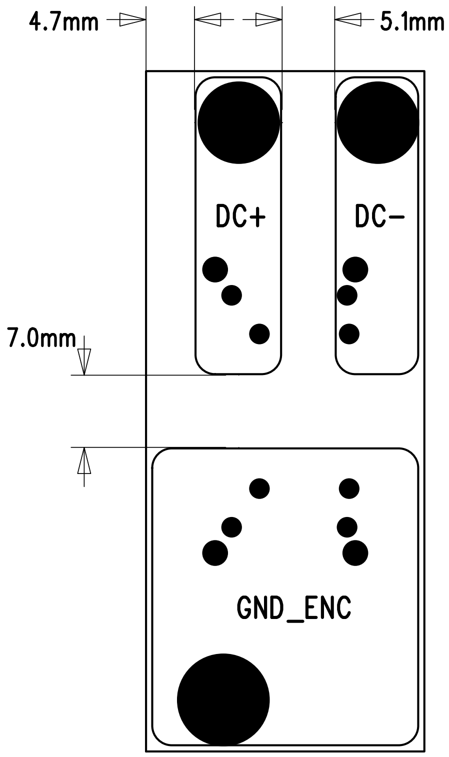

Figure 3.13 Y-capacitor PCB with copper planes and component pads visible. Names of electrical nets and the associated clearance and creepage distances are marked.

Transformers used for supplying power across reinforced insulation to the electronics on DVC C circuit is customer specific component which has been designed and for which the materials have been specified by the customer i.e. Visedo Oy. No voltage classification is given by the component manufacturer. The manufacturing datasheet specifies that all production units must undergo routine testing for partial discharge with voltage of 4 kV RMS for 2 seconds. According to IEC61800-5-1 4.3.6.8.2.2 partial discharge testing is required for solid insulation used as reinforced insulation if recurring peak working voltage across the insulation is greater than 750 V and the voltage stress on the insulation is greater than 1 kV/mm. Primary of the transformer is wound with triple-insulated wire with FEP (Fluorinated ethylene propylene) insulation. With total diameter of the wire being 0.79 mm and the diameter of the copper 0.32 mm, the total thickness of the insulation layers is 0.235 mm. Secondary side of the transformer is wound with single-insulated PTFE (Polytetrafluoroethylene) wire with total diameter of 0.40 mm and copper diameter of 0.125

mm leading to insulation thickness of 0.1375 mm. In worst-case the primary and secondary windings run adjacent to each other and the minimum total thickness of solid insulation from primary to secondary is the sum of the wire insulations which is 0.3725 mm. According to IEC60664-1 6.1.3.1 partial discharge test is required to verify that no partial discharges are maintained in solid insulation at the maximum steady-state voltage, long-term temporary overvoltage or recurring peak voltage. The highest of these voltages shall be used for determining the partial discharge test voltage. Long-term temporary overvoltage is defined in IEC60664-1 5.3.3.2.3 as nominal system voltage U_n + 250 V for durations longer than 5 s. Reinforced insulation must withstand voltage equal to twice this value. IEC60664-1 uses multiplication factors F_1, F_2, F_3 and F_4 specify test voltage. These multiplication factors are described as follows:

- F_1 is a basic safety factor for partial discharge testing which takes into account influence of environmental conditions such as temperature on the partial discharge extinction voltage. The value of F_1 is 1.2.
- F_2 is a hysteresis factor which takes into account the difference between partial discharge inception and extinction voltages. Empirical evidence suggests that a value of 1.25 for F_2 is adequate cover this.
- F_3 is additional safety factor for testing partial discharge in solid insulation used for reinforced insulation. The value of F_3 is 1.25.
- F_4 is factor that covers voltage deviation of the low-voltage mains. This can be ±10 % so the value used for F_4 is 1.1.

(IEC 2007a)

The required minimum partial discharge extinction voltage U_e is the highest of maximum steady-state voltage, long-term temporary overvoltage or recurring peak voltage across the insulation multiplied by basic safety factor F_1. For testing reinforced insulation, the test voltage U_t is the required partial discharge extinction voltage U_e multiplied by the additional safety factor F_3 for reinforced insulation. To account for the hysteresis between partial discharge inception voltage U_i and partial discharge extinction voltage U_e the voltage is linearly increased to U_t multiplied by the hysteresis factor F_2 at the start of the partial discharge testing and held at that value for a maximum time of 5 s. If no partial discharges are detected the voltage is decreased to zero and the test is passed. If partial discharges occur during this period, the voltage is decreased to U_t and held at that value for a maximum time of 15 s. If no partial discharges occur, the test is passed. The voltage used in partial discharge testing is specified as a peak value of sinusoidal AC voltage with frequency of 50 Hz or 60 Hz.

For PowerMASTER converter, the rated nominal system voltage U_n is 300 V_{AC} and the long-term temporary overvoltage is 550 V with peak value of 778 V. In case of IT supply system, the long-term temporary overvoltage is 850 V with peak value of 1202 V. The maximum recurring peak voltage across the transformer is the maximum DC-link voltage of 850 V with transient overshoot and ringing superimposed on top. Using the IT system long-term overvoltage of 1202 V as the maximum recurring peak voltage, multiplication with factors F_1 and F_3 yields minimum test voltage U_t of 1803 V. When multiplied by the hysteresis factor F_2, the voltage for testing must be 2254 V. Since the 4 kV RMS voltage used in production testing is much higher than this value, the transformer can be used for reinforced insulation in this application.

For the planned device, the rated nominal system voltage U_n is 600 V_{AC} and the long-term temporary overvoltage is 850 V with peak value of 1202 V. In case of IT supply system, the long-term temporary overvoltage is 1250 V with peak value of 1768 V. Using the IT system long-term overvoltage of 1768 V as the maximum recurring peak voltage, multiplication with factors F_1 and F_3 yields minimum test voltage U_t of 2652 V. When multiplied by the hysteresis factor F_2, the voltage for testing must be 3315 V. This is still lower than the routine test voltage of 4 kV RMS used in production and the same transformer can be used in the planned device.

Reinforced insulation is also required between primary and secondary side of the current transducer LEM HAFS 600-S/SP8. Datasheet of the transducer lists following values:

- U_d RMS voltage of AC insulation test, 50 Hz, 1 min 4.6 kV
- U_e Partial discharge extinction RMS voltage >1 kV
- $\hat{U}_w$ Impulse withstand voltage 1.2/50 µs 8.7 kV
- d_{Cp} Creepage distance >9 mm
- d_{Cl} Clearance >9 mm
- CTI Comparative tracking index (group IIIa) 275

(LEM 2014).

Since no filter is in place between phase output and current measurement, peak value of voltage from primary to secondary side of the current transducer is similar to that of the power supply transformers and digital isolators. RMS value of 4.6 kV is higher than the short-term temporary overvoltage requirement of 3600 V RMS for reinforced insulation in IT systems. Impulse withstand voltage of 8.7 kV fulfills the 6 kV requirement of reinforced insulation. Clearance of 9 mm is higher than the 5.5 mm required for reinforced insulation and creepage distance of 9 mm is higher than the 8.5 mm required for reinforced insulation for material group IIIa in pollution degree 2. Datasheet specifies that the rated insulation voltage for reinforced insulation is 450 V RMS according to EN 50178 standard. Partial discharge requirement is similar to the transformers meaning that the minimum partial discharge extinction voltage U_e is 1442 V (IT system long-term overvoltage peak value multiplied by F_1). Datasheet does not specify how the partial discharge extinction voltage is measured.

3.3 Voltages and insulation requirements for the planned device

For the new device the planned voltage ratings are 0 – 1200 V_{DC} with nominal voltage of 1050 V_{DC} for the DC-side and 0 – 800 V_{AC} with nominal voltage of 690 V for the AC-side. AC voltage values are specified line-to-line. The rationalized system voltage for the new device is 600 V according to IEC61800-5-1 4.3.6.2.1 and IEC60664-1 Table B.1 and Table F.1 when connected to 400/690 V supply mains. Intended use and location of installation is similar to the existing device and place the device in overvoltage category III. Device enclosure is unchanged compared to the existing device. This means that due to high degree of protection from external environmental conditions the insulation can dimensioned according to pollution degree 2. Basic layout and design of the main PCB remain unchanged and the same five galvanically isolated circuits can be found. Insulation has to be re-evaluated only for the power circuit which is of decisive voltage class C.

For circuits of decisive voltage class C basic insulation to earth is required. From IEC61800-5-1 Table 7 the required rated impulse voltage is 6 kV for basic insulation. This corresponds to the minimum clearance distance of 5.5 mm according to Table 9. For system voltage of 600 V the short-term temporary overvoltage is 2550 V/1800 V (crest value/RMS) according to IEC61800-5-1 Table 7. These values correspond to nominal system voltage U_n + 1200 V. Linear interpolation using the values given in Table 9 results in clearance distance of

$$d = 1.5\ \mathrm{mm} + \frac{3\ \mathrm{mm} - 1.5\ \mathrm{mm}}{2600\ \mathrm{V} - 1600\ \mathrm{V}} \times (2550\ \mathrm{V} - 1600\ \mathrm{V}) = 2.93\ \mathrm{mm}. \tag{40}$$

For evaluating short-term temporary overvoltage when connected to non-earthed IT supply system, the system voltage is 1000 V and short-term temporary overvoltage is 3110 V/2200 V (crest value/RMS) and the required clearance distance for basic insulation is

$$d = 3\ \mathrm{mm} + \frac{5.5\ \mathrm{mm} - 3\ \mathrm{mm}}{3700\ \mathrm{V} - 2600\ \mathrm{V}} \times (3110\ \mathrm{V} - 2600\ \mathrm{V}) = 4.16\ \mathrm{mm}. \tag{41}$$

The clearance distance of 5.5 mm resulting from the required rated impulse voltage is more severe and shall be used for dimensioning clearance for basic insulation.

For reinforced insulation, the required rated impulse voltage is 8 kV and the corresponding clearance distance is 8 mm. The voltage used for dimensioning clearance distance of reinforced insulation for short-term temporary overvoltage is 1.6 times the voltage used for dimensioning basic insulation. Linear interpolation results in a required clearance of

$$d = 5.5\ \mathrm{mm} + \frac{8\ \mathrm{mm} - 5.5\ \mathrm{mm}}{4800\ \mathrm{V} - 3700\ \mathrm{V}} \times (4080\ \mathrm{V} - 3700\ \mathrm{V}) = 6.36\ \mathrm{mm} \tag{42}$$

for reinforced insulation in neutral-earthed systems.

In non-earthed IT systems, the clearance required for reinforced insulation be short-term temporary overvoltage is

$$d = 8\ \mathrm{mm} + \frac{14\ \mathrm{mm} - 8\ \mathrm{mm}}{7400\ \mathrm{V} - 4800\ \mathrm{V}} \times (4976\ \mathrm{V} - 4800\ \mathrm{V}) = 8.4\ \mathrm{mm}. \tag{43}$$

In the case of reinforced insulation, short-term overvoltage gives the most severe requirement for insulation and the corresponding value 8.4 mm shall be used for dimensioning clearance. If operation is specified for neutral-earthed supply systems only, clearance for reinforced insulation can be reduced to 8 mm required by the impulse withstand voltage.

For functional insulation the worst-case peak voltage is limited to the blocking voltage of Semikron SKiM429GD17E4HD IGBT-module which is 1700 V. Linear interpolation from Table 9 results in clearance of

$$d = 1.5\ \mathrm{mm} + \frac{3\ \mathrm{mm} - 1.5\ \mathrm{mm}}{2600\ \mathrm{V} - 1600\ \mathrm{V}} \times (1700\ \mathrm{V} - 1600\ \mathrm{V}) = 1.65\ \mathrm{mm}. \tag{44}$$

Required creepage distance from DC- to DC+ must be determined at the maximum rated DC voltage of 1200 V. Linear interpolation results in a required creepage of

$$d = 5\ \mathrm{mm} + \frac{6.3\ \mathrm{mm} - 5\ \mathrm{mm}}{1250\ \mathrm{V} - 1000\ \mathrm{V}} \times (1200\ \mathrm{V} - 1000\ \mathrm{V}) = 6.1\ \mathrm{mm} \tag{45}$$

for outer layers and

$$d = 3.2\ \mathrm{mm} + \frac{4.2\ \mathrm{mm} - 3.2\ \mathrm{mm}}{1250\ \mathrm{V} - 1000\ \mathrm{V}} \times (1200\ \mathrm{V} - 1000\ \mathrm{V}) = 4\ \mathrm{mm} \tag{46}$$

for inner layers.

When the device is supplied from 690 V phase-to-phase grid without load, RMS value of phase-to-DC voltage is

$$U_{\mathrm{DC,L}} = \sqrt{\left(0.5 \times \sqrt{2} \times 690\ \mathrm{V}\right)^2 + \left(\frac{690\ \mathrm{V}}{\sqrt{3}}\right)^2} = 630\ \mathrm{V}. \tag{47}$$

When the device is operating as a motor drive at the maximum rated DC voltage supply of 1200 V and maximum AC output of 800 V, RMS value of phase-to-DC voltage is

$$U_{\mathrm{DC,L}} = \sqrt{(0.5 \times 1200\ \mathrm{V})^2 + \left(\frac{800\ \mathrm{V}}{\sqrt{3}}\right)^2} = 757\ \mathrm{V}. \tag{48}$$

Assuming similar limitations for DC/DC converter operation as in the case of existing converter, i.e. maximum rated DC-link voltage and voltage conversion ratio from 0.1 to 1, the maximum RMS voltages from phase to DC- and DC+ are as follows:

$$U_{\mathrm{DC-,LV+}} = U_{\mathrm{LV+}} = 1200\ \mathrm{V}, \tag{49}$$

which happens at conversion ratio 1 and

$$U_{\mathrm{DC+,LV+}} = U_{\mathrm{DC+}} \times \sqrt{0.9} = 1200\ \mathrm{V} \times \sqrt{0.9} = 1138\mathrm{V}, \tag{50}$$

which happens at conversion ratio 0.1.

As is the case with the existing hardware, DC/DC converter operation sets the most severe requirements for creepage distances. Creepage distance requirement from phase to DC- is the same as from DC- to DC+ potential, 6.1 mm on the outer layers and 4 mm on the inner layers. Required creepage distance from phase to DC+ is

$$d = 5\ \mathrm{mm} + \frac{6.3\ \mathrm{mm} - 5\ \mathrm{mm}}{1250\ \mathrm{V} - 1000\ \mathrm{V}} \times (1138\ \mathrm{V} - 1000\ \mathrm{V}) = 5.8\ \mathrm{mm} \tag{51}$$

for outer layers and

$$d = 3.2\ \mathrm{mm} + \frac{4.2\ \mathrm{mm} - 3.2\ \mathrm{mm}}{1250\ \mathrm{V} - 1000\ \mathrm{V}} \times (1138\ \mathrm{V} - 1000\ \mathrm{V}) = 3.8\ \mathrm{mm} \tag{52}$$

for inner layers. The safe option is to increase all these creepage distances for functional insulation to the values required by the maximum DC-link voltage of 1200 V so that all possible operating points are covered.

For basic insulation, creepage distances need to be dimensioned for RMS values of voltages $U_{\mathrm{DC\text{-},Earth}}$ and $U_{\mathrm{DC+,Earth}}$. With no DC-link common-voltage, the voltage used for dimensioning creepage distance for basic insulation is

$$U_{\mathrm{DC,Earth}} = \frac{U_{\mathrm{DC,max}}}{2} = \frac{1200\ \mathrm{V}}{2} = 600\ \mathrm{V}. \tag{53}$$

With maximum specified output voltage at 800 $\mathrm{V_{AC}}$ phase-to-phase, RMS value of voltage between phases and earth is

$$U_{\mathrm{L,Earth}} = \frac{800\ \mathrm{V}}{\sqrt{3}} = 462\ \mathrm{V}. \tag{54}$$

As with the existing device, due to the layout of the main PCB, $U_{\mathrm{L,Earth}}$ does not need to be considered for dimensioning creepage for basic insulation. IEC60664-1 Table F.3b specifies that the rationalized voltage to be used for dimensioning creepage for basic insulation is 630 V for nominal system voltage of 600 V. According to IEC65800-5-1 Table 10, the required creepage distance for 630 V is 3.2 mm in pollution degree 2 which applies for the outer layers and 1.8 mm in pollution degree 1 which applies for the inner layers. For reinforced insulation these values are to be doubled to 6.4 mm and 3.6 mm respectively.

Clearance and creepage distance requirements between different electrical potentials for the new device are summarized in Table 3.2. The clearance and creepage distances required by different conditions are evaluated and the ones resulting in the most severe dimensioning requirement are marked in yellow.

Table 3.2 Required insulating distances for the planned device.

		Required clearance [mm]			Required creepage [mm]		Minimum distance [mm]	
		working voltage	temporary overvoltage	impulse voltage	outer layers	inner layers	outer layers	inner layers
Functional insulation	phase-to-DC-	1,65			6,1	4	6,1	4
	phase-to-DC+	1,65			5,8	2,6	5,8	2,6
	DC+-to-DC-	1,65			6,1	4	6,1	4
Basic insulation	earth-to-DC+		4,16	5,5	3,2	1,8	5,5	5,5
	earth-to-DC-		4,16	5,5	3,2	1,8	5,5	5,5
Reinforced insulation	DVC A-to-phase		8,4	8	6,4	3,6	8,4	8,4
	DVC A-to-DC+		8,4	8	6,4	3,6	8,4	8,4
	DVC A-to-DC-		8,4	8	6,4	3,6	8,4	8,4

As with the existing device, DC-link common-mode voltage influences the RMS value of voltage across basic and reinforced insulation. RMS value of $U_{\mathrm{L,Earth}}$ should be tested or simulated in these operating conditions for more accurate dimensioning of the required creepage. The safe option of dimensioning creepage distance for full DC-link voltage across reinforced insulation limits component choice for passing signals and electric power across reinforced insulation greatly. This is true also for the 8.4 mm clearance requirement of short-term temporary overvoltage in IT supply systems, since this rules out the use of digital isolators in widely available DW SOIC component package which has a clearance of 8 mm.

3.4 Functional and safety critical changes required to components

Y-capacitor PCB dimensions and clearances are limited by the existing mechanics. Distance between attachment points on DC-link busbars for Y-capacitor PCB is 5.1 mm. This does not fulfill the creepage distance requirement of 6.1 mm required at the maximum rated DC-link voltage of 1200 V. Creepage distance is increased by cutting a slot between DC+ and DC- connections. Outline of the new PCB can be seen in Figure 3.14. Clearance distance from DC+ potential to device enclosure is 4.7 mm when 5.5 mm is required to fulfill the requirement of basic insulation. This clearance distance cannot be increased without changes to existing mechanics due to how the Y-capacitor PCB attaches to the DC-link busbars. This is remedied by adding an extension lip to the insulation foil between the IGBT module and driver PCB which folds between the Y-capacitor PCB and device enclosure.

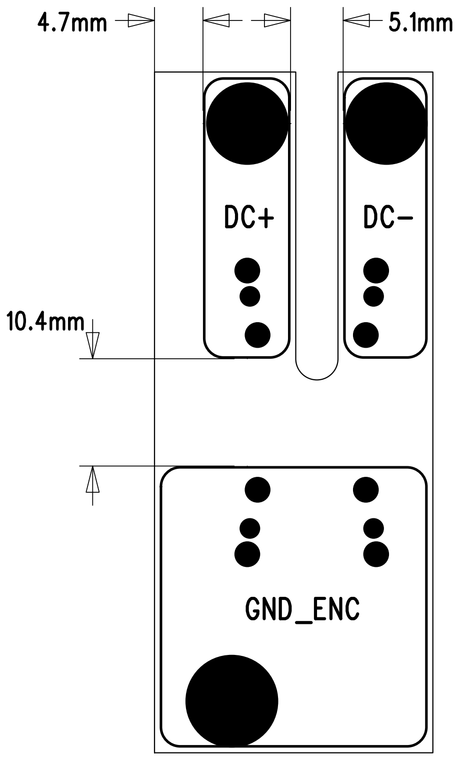

Figure 3.14 New Y-capacitor PCB with slot routed between the DC terminals. Clearance distance remains unchanged but creepage is increased.

The width of the slot between the DC-connections is 4.1 mm, which results in a creepage path length of

$$d = \frac{4.1\ \mathrm{mm}}{2} \times \pi = 6.44\ \mathrm{mm} \tag{55}$$

along the edge of the half-circle at the end of the slot which is greater than the required creepage of 6.1 mm. Actual creepage path includes also distance from the edge of the slot to the DC copper planes.

Due to Y-capacitors connected from DC+ and DC- to the earthed device enclosure, touch current in case of protective earthing conductor exceeds 3.5 mA AC limit specified for touch current in case of failure of the protective earthing conductor in IEC 61800-5-1. This is required to mentioned in the installation and maintenance manuals of the device. The device has two dedicated grounding points where connection of protective earthing conductor possible by means of M8 threaded bolt which fulfills the requirement of a fixed connection and provision of an additional terminal for a second protective earthing conductor of the same cross-sectional area as the original protective earthing conductor. Manual of the device states that the cross-sectional area of the protective earthing conductor has to be at least equal to that of the incoming supply conductors (Danfoss 2019b).

Digital isolators used for transmitting gate drive, measurement and status signals across the reinforced insulation barrier between the power circuit with DVC C and the main control circuit with DVC A need to be able to withstand the same voltage stress as the PCB. The Silicon Labs SI866xBD-B-IS and SI8631BD-B-IS digital isolators used on the existing PCB have rated surge voltages V_{IOSM} of 3077 V and 4000 V (Silicon Labs 2018a, 2018b). Surge voltage corresponds to rated impulse withstand voltage for which the requirement is 8000 kV in this application and these digital isolator ICs cannot be used. Texas Instruments ISO784x-series digital isolators are a pin compatible alternative for these and have a rated surge voltage V_{IOSM} of 8000 V which meets the impulse withstand voltage (Texas Instruments 2016). The DW SOIC-16 component package of the isolator provides clearance and distance creepage distance of 8 mm which fulfills the clearance and creepage requirement for reinforced insulation in this application for neutral-earthed supply systems. These components are also available in DWW SOIC-16 component package which increases the clearance and creepage to 14.5 mm if required by higher system voltage or operation at higher altitudes. Texas Instruments has done testing on these isolators, where it was shown that electrical overstress failure on one side of the device doesn't lead to short-circuit across the isolation barrier (Kamath, Bhardwaj and Soundarapandian 2018). This enhances safety by maintaining the isolation in case of collector-base breakdown of IGBT.

The DC link discharge resistor is controlled IRG4BH20K-SPbF IGBT. It has a maximum blocking voltage of 1200 V (Infineon 2010). Simplified schematic of the discharge circuit can be seen in Figure 3.15. Full DC link voltage appears across this transistor while the discharge is not active, and the transistor needs to be replaced with one of a higher blocking voltage.

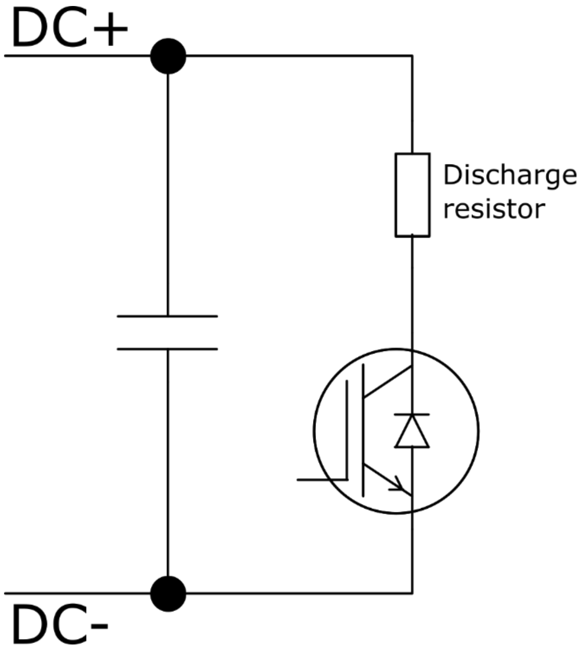

Figure 3.15 Simplified discharge circuit schematic.

D2PAK (TO-263, TO=Transistor Outline) component package used by the transistor doesn't support creepage distance of 6.1 mm required by DC link voltage of 1200 V. Creepage distance along the PCB is 5.08 mm using the minimum component footprint recommended by the manufacturer while the actual creepage distance on the PCB is 5.1 mm. Creepage distances from collector to emitter and from collector to gate on the component package is far less at 2.54 mm. Since this component is in series with the discharge resistor, the short-circuit current is limited and this reduced creepage distance could be approved by carrying out PCB short-circuit test. Because of the blocking voltage requirement, the discharge control transistor is changed to Cree C2M1000170J silicon carbide MOSFET with same blocking voltage of 1700 V as the main power semiconductors. The TO-263-7 package used by this component allows for creepage distances up to 7 mm (Cree 2018). Silicon carbide semiconductors are generally more expensive than silicon semiconductors and have better dynamic properties. Since the discharge circuit is not operated at a high frequency, this is not relevant for the application. Component choice here is mainly influenced by blocking voltage and creepage distance compared to the size of the component package. Price of the component is also not prohibitive compared to IGBT switches of similar blocking voltage.

Discharge resistor is mounted to the earthed device enclosure to allow efficient cooling of the resistor. It is electrically connected directly to DC+ potential as can be seen from Figure 3.15. This means that the insulation of the resistor must meet the same requirements as the basic insulation of the converter assembly. Temporary overvoltage requirement for basic insulation for system voltage of 600 V is 2600 V and impulse withstand voltage is 6000 V. EBG AXP-100B was chosen as a discharge resistor for the prototype units. It has a base 5 kV DC dielectric strength between terminals and case with higher values available on request (EBG 2019). According to IEC-60664-1 6.1.1 impulse voltage test of solid insulation can be substituted by DC voltage test. Manufacturer confirmed that the resistor is capable of withstanding 6 kV DC voltage. Connection to resistive element is done by insulated wires molded into the component casing. Due to no exposed electrical conductors being present on the device, clearance and creepage distances of the component casing do not need to be considered. Component package of the resistor is proprietary but with similar mounting hole placement to SOT-227. The overall dimensions of the component package are also similar enough so that the SOT-227 resistor used previously can be replaced without need for mechanical changes.

Desaturation monitoring circuit shown in the Figure 3.16 is used for protecting IGBT switches in case of load short circuit. In normal operating conditions voltage drop over the IGBT is in a range of 1-3 Volts when the switch is turned on. In case of load short-circuit the voltage over the IGBT rises rapidly. Desaturation protection works by monitoring the IGBT voltage when the switch is turned on and if the voltage exceeds a preset limit, this is interpreted as a short-circuit. IGBT is then turned off through additional gate resistance to reduce the $\frac{dI}{dt}$ when turning off large currents associated with short-circuits to reduce the voltage overshoot.

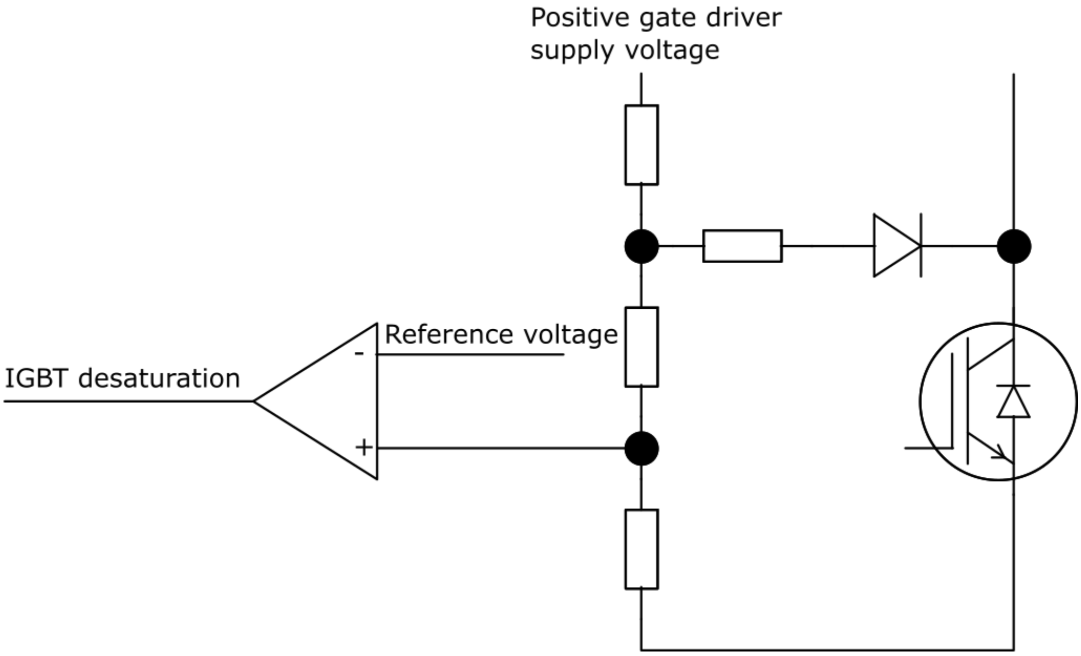

Figure 3.16 Desaturation monitoring circuit used for short circuit protection.

The voltage across the diode used in desaturation monitoring circuit is approximately the same as the voltage over the associated IGBT. The diodes used are STMicroelectronics STTH212S in SMC component package. The blocking voltage of these diodes is 1200 V which is lower than the blocking voltage of the main power module (STMicroelectronics 2017). Very few surface mounted diodes are available with blocking voltage of 1700 V or higher. It is possible to use multiple diodes in series to achieve the required blocking voltage. STMicroelectronics STTH112A is a diode with similar blocking voltage and switching characteristics but with a smaller forward current of 1 A and is available in smaller SMA component package (STMicroelectronics 2009). Series connection of two STTH112A diodes was chosen to be used on the prototype PCBs. Recommended footprint for SMC has a clearance and creepage of 5.11 mm and recommended footprint of SMA has a clearance and creepage of 2.63 mm. The reverse voltage across the series connected diodes can be assumed to be evenly distributed. The creepage distance requirement is not met with two diodes in SMA component package and third diode must be connected in series or diodes with different component package with longer creepage have to be used.

DC-link capacitor for the new prototype converter has rated voltage of 1200 V and the same mechanical dimensions as the 900 V DC-link capacitor currently used. According to the preliminary datasheet of the capacitor, terminal to terminal clearance and creepage distance is ≥ 5 mm and CTI of the capacitor is ≥ 600 which places it in material group I. Mechanical drawing of the capacitor shows that the terminal to terminal distance is 6 mm with a tolerance of ± 1 mm. Interpolating from IEC61800-5-1 Table 10, the required creepage distance along insulating material of material group I for a voltage of 1200 V in pollution degree 2 is 6.1 mm. This requirement is not guaranteed to be met, based on the information given in the capacitor's datasheet. Creepage distance could possibly be increased by reducing the width of the capacitor terminals or by adding an insulating sleeve around capacitor terminals near the capacitor body when molding the capacitor. The capacitor terminals could also be coated with suitable insulating coating material where not in contact with DC-link busbars or semiconductor module to increase creepage distance between the terminals.

According to IEC61800-5-1, capacitors within PDS must be discharged below 60 V or the residual charge stored in the capacitors to be under 50 μC within 5s from removal of power from the PDS. With DC-link capacitor of 550 μF, the charge left in the capacitor at 60 V is

$$q = CV = 550\ \mu\text{F} \times 60\ \text{V} = 33\ \text{mC} \tag{56}$$

which means the capacitor voltage is the determining factor in capacitor discharge time. With 100 kΩ discharge resistor, the discharge time from maximum allowed DC-link voltage of 1200 V to 60 V is

$$t = -\ln\frac{U}{U_0} \times RC = -\ln\frac{60\ \text{V}}{1200\ \text{V}} \times 100\ \text{k}\Omega \times 550\ \mu\text{F} = 165\ \text{s}. \tag{57}$$

This much higher than the 5 s specified in the standard and requires marking on the device and information in the manual.

4 PROTOTYPE EVALUATION, TESTING AND CONCLUSIONS

Testing of new prototype converter units revealed that the electromagnetic interference withstand capability of the previously used power supply design for gate drivers and isolated measurement was inadequate at higher electromagnetic interference levels caused by higher DC-link voltage. At DC-link voltage levels exceeding 1000 V, the unit started reporting DC overvoltage faults which were confirmed to be spurious by measurements from another device connected to the same DC-link. Spurious isolated supply voltage faults were also observed. This was traced down to unconnected manual reset pin of the IC used for monitoring supply voltage for isolated measurements. This pin is active-low and has a weak internal pull-up resistor. When external pull-up was connected to the pin, isolated side supply faults were no longer observed. Units reported gate driver power supply faults and two prototype devices were destroyed by apparent phase shoot-through caused by interference. Both destructive faults appeared in similar operating conditions with the unit operating as an active front end with nominal DC-link voltage of 1050 V and when the current reference was increased above 0.3 of the nominal current.

The low-side gate driver and isolated measurement power supply design was changed by separating the rectifiers between them on the secondary side of the isolation transformer. This allowed operation at the specified maximum DC-link voltage and maximum current. Further improvement to gate driver power supply included separate transformers for each gate driver and one for measurement circuits. These transformers are equipped with two secondary windings for providing both positive and negative gate drive voltage for the IGBT drivers without the need for a rail-splitter circuit.

Under some operating conditions within the rated voltage of the device, RMS value of the working voltage can exceed what creepage distance for functional insulation between upper gate drivers and DC- allows for according to Table 10 of IEC61800-5-1. The PCB has to be tested to pass PCB short-circuit test or redesigned for creepage distance of 6.1 mm. Limiting operating conditions to those in which RMS value of working voltage stays within allowed values by means of software parameters is also an option.

Creepage distance requirement between the DC-link capacitor terminals is not guaranteed to be met under the given manufacturing tolerances. Possible solutions are reducing the width of the terminal or coating the terminals with suitable insulating coating except for contact surfaces.

PCB is installed into complex molded aluminum frame which resulted in some oversights in dimensioning clearance and creepage distances for the prototypes. Insufficient clearance for basic insulation was caused by shelves on the inside of the device enclosure not being considered in PCB layout design. Stiffening ribs on the inside of the enclosure cover above the PCB caused a similar issue with insufficient clearance for basic insulation. When dimensioning insulation on PCB it needs to be examined in 3D environment with its surroundings. This can be done quite conveniently in the design phase using 3D CAD program if 3D model of the device exists and PCB CAD software supports exporting 3D models of the design.

Transformers used for isolated measurement and gate driver power supply have to be type tested for partial discharge. Type testing required by IEC61800-5-1 is to be done on the complete converter assembly. For CE-marking, converter has to undergo relevant EMC testing.

5 SUMMARY

Basis for safety requirements imposed on the planned device were determined. The main source for these is the Low Voltage Directive and harmonized standards listed under it. Out of these standards, IEC61800-5-1: Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy, was found applicable to the device. Classification of the device was done and required safety measures were determined within the framework of the standard. Upon evaluation of the first prototype device, most but not all of the safety requirements were met. The requirements that were not met were due to design oversights and the further changes needed to achieve compliance to isolation requirements set by the standards for the new rated voltage are possible within the constraints set by existing mechanics, e.g. aluminum frame and busbar assemblies. Most of the design goals for the new device were met. Functional prototype was achieved after changes to the gate driver power supply. Required type testing for compliance to LVD and to other relevant Directives are to be done for CE-marking and EU Declaration of Conformity.

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APPENDIX 1. Circuits of the main PCB