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Conducted Emissions of Low Power Variable Speed Drives

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The thesis work was done for ABB Oy, Drives, R&D department in Helsinki. The purpose of the work was to examine small power variable speed drive performance of the conducted emissions. Variable speed drives were chosen according to their EMC performance. Conducted emissions are a problem with many electrical devices and the limits defined by the standard must not be exceeded. If these limitations are not met the use of the electrical devices is forbidden in certain environments or cannot be used at all.

In the beginning of the thesis work the best EMC performing devices were chosen: this was total of six devices. Then conducted emissions test was performed and the common mode currents were measured. After this, the devices were taken apart the devices and the EMC filters were examined. In the end, the common mode chokes of the EMC filters were measured with an impedance analyzer.

At the beginning of the work, the operating principle, structure and components of the frequency converter were reviewed. This was followed by an introduction to EMC theory, testing, and standards. Then the measurement methods and test equipment were introduced. After that measurement results were compared among each other and analyzed. Finally, the main circuit topologies of the devices and their effect on EMC performance were compared.

As a result of the thesis work, information was gained on the EMC performance of the variable speed drives from different manufacturers. The analysis of the results revealed similarities and anomalies in the implementation of EMI filters and their effects on performance. The results added understanding of emissions, occurring phenomenons and differences. The results of the work can be used as a guide for designing an EMI filter for variable speed drive in future product planning.

Keywords	Variable Speed Drive, Electromagnetic compatibility, Conducted emissions

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Työ tehtiin ABB Oy, Drives, R&D -yksikölle Helsingissä. Työn tarkoituksena oli tutkia pienitehoisten taajuusmuuttajien suorituskykyä johtuvien emissoiden osalta. Laitteet valittiin työhön niiden EMC-suorituskyvyn mukaan. Johtuvat emissiot ovat ongelma monilla sähkölaitteilla, ja standardin asettamia rajoja ei saa ylittää. Jos standardin asettamat rajat ylitetään, ei laitetta voi käyttää tietyissä ympäristöissä tai ei jopa ollenkaan.

Työn alussa valittiin parhaat EMC-suorituskyvyn omaavat laitteet, joita työhön löytyi yhteensä kuusi. Tämän jälkeen laitteille suoritettiin johtuvien emissoiden testit ja mitattiin niiden yhteismuotovirrat. Tämän jälkeen laitteet purettiin osiin ja EMI-suodatinta tutkittiin. Lopuksi työssä mitattiin EMI-suodattimien yhteismuotokuristimet impedanssianalysaattorilla.

Työn aluksi käytiin läpi taajuusmuuttajan toimintaperiaatetta, rakennetta ja komponentteja. Tämän jälkeen perehdyttiin EMC-teoriaan, -testaukseen ja -standardeihin. Tämän jälkeen tarkasteltiin mittausmenetelmät ja testilaitteet. Sen jälkeen mittaustuloksia vertailtiin keskenään ja niitä analysoitiin. Lopuksi työssä vertailtiin laitteiden pääpiiri topologioita ja niiden vaikutusta EMC-suorituskykyyn.

Työn tuloksena saatiin tietoa pienitehoisten taajuusmuuttajien EMC-suorituskyvystä eri valmistajien osalta. Tuloksien analysoinnissa selvisi samankaltaisuuksia ja poikkeavuuksia EMI-suodattimien toteutuksessa ja niiden vaikutuksista suorituskykyyn. Saadut tulokset lisäsivät ymmärrystä johtuvista emissioista, tapahtuvista ilmiöistä ja eroavaisuuksista. Työn tuloksia voidaan käyttämää suunnittelun apuna tulevaisuuden tuotekehityksessä taajuusmuuttajan EMI-suodatuksen suunnittelussa.

Avainsanat	taajuusmuuttaja, sähkömagneettinen yhteensopivuus, johtuvat emissiot

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List of Abbreviations

AC	Alternating Current
AFD	Adjustable Frequency Drive
CMC	Common Mode Choke
CM	Common Mode
DC	Direct Current
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EUT	Equipment Under Test
IGBT	Insulated-Gate Bipolar Transistor
I/O	Input / Output
PMW	Pulse-Width Modulation
RF	Radio Frequency
SRF	Self Resonant Frequency
ZCM	Common Mode Impedance
UDC_+	DC Link Voltage Plus
UDC_-	DC Link Voltage Minus
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

1 Introduction

Variable speed drive (VSD), variable frequency drive (VFD), adjustable-frequency drive (AFD) or inverter-drive is an electrical device used to control mostly altering current (AC) motors by adjusting the voltage and frequency. VSDs are used mainly for controlling AC motors in various systems in the industry. This kind of systems are conveyors, blowers, pumps, machine tools and other systems that need unfixed torques with unfixed speeds.

Electromagnetic interference is a serious and increasing form of environmental pollution. That interference is created by electrical devices. There are two different kinds of interference: conducted and radiated. In this thesis work, we are focusing on conducted interference.

Conducted interference is a known issue of electrical devices, and it requires attention when designing and installing these products. Conducted emissions area unintentional energy created by electrical device and carried out via the power cables to the electrical grid. Electrical devices cannot cause too much interference to the electrical grid. The interference limits are defined in the IEC61800-3:2017 standard for both conducted and radiated emissions.

The purpose of this thesis work was to measure and examine different VSDs according to their conducted emissions. The goal was to gain information about different electromagnetic interference (EMI) filter designs found in the selected VSDs, and how the different designs of the EMI filter affect the conducted emissions. The second purpose was to examine how the motor cable lengths or the setup placement itself is affecting conducted emissions.

In this work, conducted emission measurements were performed with electromagnetic interference test receiver and common mode currents were measured with an oscilloscope. After these measurements, the devices were opened, and their common mode chokes were measured with the impedance analyser.

Variable speed drives chosen for this study were already ordered for ABB for research purposes. In total, we had at first 14 different drives from various manufacturers in the same power category. From those drives, we chose the drives that, according to their manuals, had the best EMC performance.

2 Variable Speed Drive

2.1 Principle of Variable Speed Drive

Variable speed drive is a device that is used to control the electric motor by changing the constant voltage from the mains to the desired amplitude and frequency. With the use of VSD, the speed and torque of the AC motor can be adjusted as desired. The most typical variable speed drive is a voltage-source inverter which we are using in this study. The other type of VSD is a current source inverter. The typical efficiency of voltage-source VSDs is around 97%-99% at nominal power. [1.]

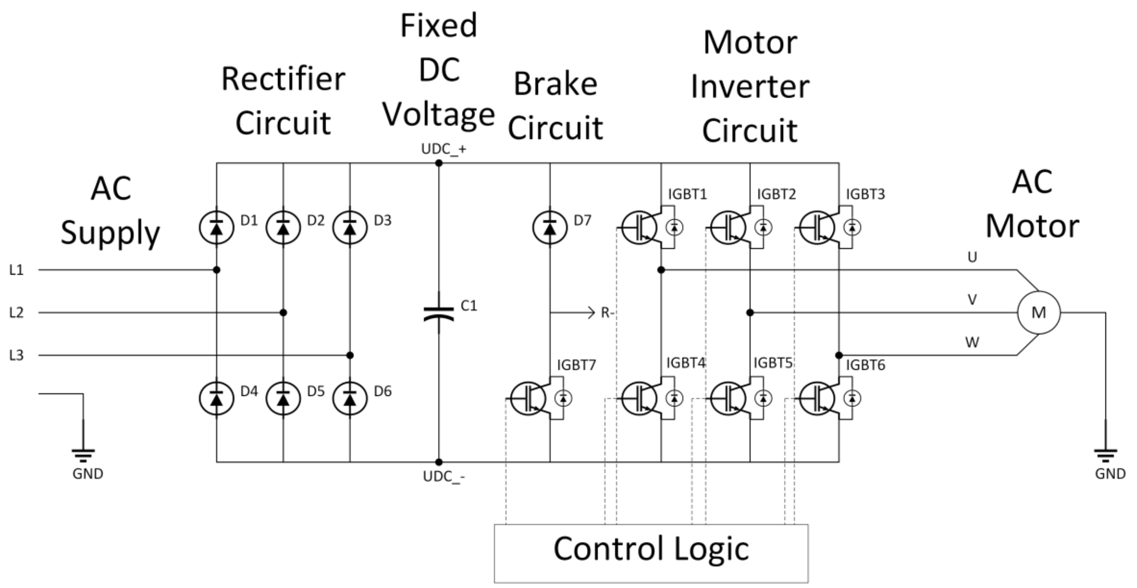

Figure 1 General schematic of VSD

Variable speed drive consists of mainly four sections: rectifier circuit, intermediate circuit, inverter circuit and control logic, as shown in Figure 1. The general schematic of VSD shows the basic principle of how the circuit works. The rectifier circuit is first used, changing the alternating current (AC) to direct current (DC). Then the DC supply is smoothed by the large capacitance which is called DC-link capacitor. Then the inverter circuit forms the DC back to AC for the motor. This inverter circuit is controlled with pulse-width modulation (PWM) by switching insulated bipolar transistors (IGBT) rapidly to create pulsating sinusoidal AC output form. PWM control means that inverter switches IGBTs by modulating narrow voltage pulses and controlling the width of the pulses to create varying voltage and frequency for the motor. IGBTs are typically switched with the switching frequency from 2 to 20 kHz. The higher switching frequency means better transient response, but efficiency drops because of the switching losses and extra heat generated. The control logic controls the gates of the IGBTs with switches that are controlled by a microprocessor. [1.]

2.2 Main Components

2.2.1 IGBT power module

The IGBT power module is the main part of the VSD, consisting of a rectifier circuit, a motor inverter circuit and a brake circuit. Some of the VSDs have an intelligent power module (IPM) used instead of a normal IGBT power module. The difference between these two is that IPM modules have also some of the control logic and self-protection functions integrated with them.

Figure 2 Semikron SKiiP 11NAB065V1 IGBT power module [2]

Figure 2 shows an IGBT power module that ABB, for example, uses inside their small VSDs analyzed in this work. The other manufacturers used all similar components as in Figure 2, except Lenze, which used individual diodes for the rectifier circuit and discrete IGBTs for the motor inverter circuit and the brake circuit.

2.2.2 Electromagnetic Interference Filter

EMI filters remove the unwanted interference that electrical devices create. Typically, noise is in the range of 9kHz to 10GHz. The low frequency noise can cause loss of power quality as well. EMI filters can be an external unit between the AC supply and the electrical device, or they can be integrated inside the device before or after rectifier circuit. [3.]

EMI filters provide a low impedance path to the noise and reduce it by cancelling its line and neutral components or by grounding it. EMI filter acts as a low pass filter that blocks the high frequency flow of “noise” while passing the low frequency AC power 50Hz/60Hz which is the cut-off frequency of the filter. An ideal filter will reduce the amplitude of all the “noises” greater than cut-off frequency. EMI filters ability to remove unwanted noise from the circuit is called its insertion loss or attenuation. An insertion loss is a power loss in a transmission line resulting from the insertion of a device, and it is presented in decibels (dB) over the frequency range (Hz). The EMI filter is the most effective tool to reduce low frequency conducted emissions from 9kHz to 30MHz. For radiated emissions which are in the range of 30 to 1000MHz, the physical placement of the filter and the isolation or shielding input and output wires are more critical factors to reduce radiated emissions than the insertion loss performance. [3.]

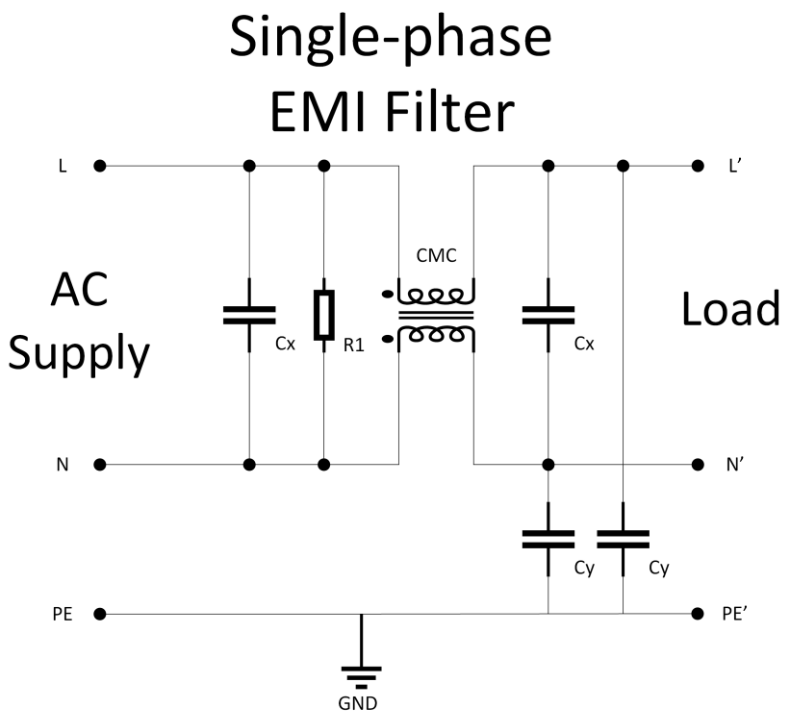

Figure 3 Typical schematic single-phase EMI filter

EMI filter consists of various components. Figure 3 shows the typical parts inside the EMI filter. The filter consists of C_x-capacitors, C_y-capacitors, resistors, and common mode choke. The X and Y marking of the capacitors mean their safety certified rating depending on their position in the circuit. The resistor R_1 of the circuit is used to discharge the X-capacitor so there will be no potentially dangerous voltage on the AC connection.

Common mode noise occurs in the line and neutral wires to ground. Flow of the current has same direction in live wire and neutral wires. Common mode noises are damped by the nominal inductivity of the CMC and by C_y-capacitors to ground. The C_y-capacitor give the current a path to ground and closes the loop. To achieve a good effective attenuation performance, return path to the noise source must be as short as possible. [4.]

Differential noise occurs in the across power supply lines and the current flow of the noise is the same as the AC supply current. Differential noise is damped C_x-capacitor is used to attenuate differential mode noise, signals, and spikes that appear from line to neutral created by rapid changes in the current within the converter. [4.]

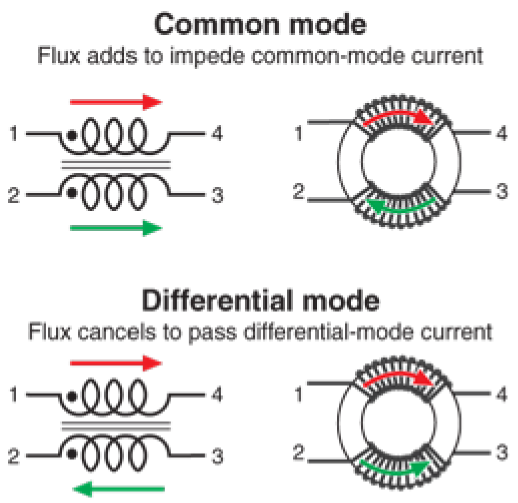

Figure 4 Principle of CMC [4]

The CMC is the core part of the EMI filter. In common mode, the noise current travels through both windings in the same direction, as shown in Figure 4. A CMC has two or more windings arranged in a form that the current, creating a magnetic flux in the opposite direction, reduces any increased common mode current. The combined magnetic flux adds an opposing field to block the noise of the current. The noises, transferred in differential mode current, move to opposite directions and the magnetic flux reduces or cancels out, so the field does not oppose the normal mode. When using these current compensated chokes to decrease common mode noise, high impedance is required at the unwanted frequencies to reduce that unwanted noise. [5.]

Typical CMC design have wires wound on a toroidal core, gapless H core and EE core. Toroidal core CMC is the most seen in the VSDs. The core material used in this CMC design is usually a manganese zinc ferrite. This material is low-cost and offers a good permeability and temperature properties. The permeability for this type of core material is usually around 5000 to 15000µ. There are also other types of materials used as core material, such as Co-based amorphous, Fe-based amorphous and Fe-based nanocrystalline. These have much higher permeability ranging from 20 000 to 200 000µ. Because of this, the impedance increases over the noise frequency spectrum, which means better attenuation. These cores also have higher saturation flux (1.25T), over twice as high as than ferrite (0.5T). This means that it can withstand higher noise amplitudes and noise currents. The last major benefit of using nanocrystalline core is temperature stability. The working temperature of these cores is up to 200°C, while for ferrite cores it is only 120°C.

The only disadvantages of these types of cores are availability and price. Co-based amorphous, Fe-based amorphous and Fe-based nanocrystalline cores are usually seen in applications that require very high performance like military, medical and aerospace applications. [6.]

3 Electromagnetic compatibility

3.1 Emissions from Electrical and Electronics Appliances

Electromagnetic compatibility or EMC means that the electrical equipment or system can function adequately in its electromagnetic environment. Most of the electrical devices cause radiated or conducted emissions to the surrounding environment or supply network. The term radiated emissions applies when switching voltages and currents causes an unintentionally produced electromagnetic field. The frequency range for these unwanted radiated emissions is in the range of 30 to 1000MHz. Conducted emissions are electromagnetic energy conducting via cables back to supply network and appear in the range of 9kHz to 30MHz.The source of these interferences is typical for switch mode power supplies, micro-controllers, data transmissions and electrical motors.

3.2 EMC Standards

Two different standards define EMC for VSD: The International Special Committee on Radio Interference (CISPR) and, the International Electrotechnical Commission (IEC). The CISPR is part of the IEC. In this study, we are focusing on IEC61800-3:2017, which is the standard for adjustable speed electrical power drive systems for EMC requirements and specific test methods. [7.]

The IEC standard separates EMC environments in two main areas: first environment and second environment. Domestic premises and establishments that are connected directly to a public low-voltage line supply without the use of an intermediate transformer belong to the first environment. These places are, for example, houses, apartments, and offices.

In the specification of the second environment, are industrial areas and technical areas of buildings that are supplied by an assigned transformer. [7.]

There are four different categories of conducted emission limits: C1, C2, C3 and C4. The first categories, C1 and C2, belong to the first environment and are both under 1000V rated voltage systems. The second environment covers categories C3 and C4. The C3 category includes under 1000V rated voltage systems, while over 1000V voltage systems are for C4 category. It is possible to find the specific limits for the conducted emissions in Table 1 below. [7.]

Table 1 Conducted Emission Limits from IEC61800- 3:2017 Standard [7]

	Category C1		Category C2		Category C3		Category C4[1]	
Frequency Band MHz	Quasi Peak dB(μV)	Aver-age dB(μV)	Quasi Peak dB(μV)	Aver-age dB(μV)	Quasi Peak dB(μV)	Aver-age dB(μV)	Quasi Peak dB(μV)	Aver-age dB(μV)
0,15 ≤ f < 0,50	66	56	79	66	100	90	100	90
0,5 ≤ f ≤ 5,0	56	46	73	60	86	76	86	76
5,0 < f < 30,0	60	50	73	60	90	80	90	80

Table 1 defines all the emissions limits for the different categories. In the standard IEC61800-3:2017 the category C3 has two sets of limits but the table 1 only shows the lower limits which are for devices that have input currents <100A. The upper limits are for devices that have input current >100A. Table 1 reports only the lower limits since this study consists only of low power VSDs. [7.]

[1] Category C4 follows the same requirements as Category C3, but if the category C3 requirements are not met, special requirements specified in the standard IEC61800-3:2017 chapter 6.5 shall be used.

In the frequency range from 9kHz to 150kHz, the limits are not specified in the standard, but this may change in the future.

4 Measuring Procedure and Devices

4.1 Measuring Devices

4.1.1 Line Impedance Stabilization Network (LISN)

The LISN is a measurement device usually placed between the power source (AC or DC) and the equipment under test (EUT). It provides a connection for oscilloscope or spectrum analyzer by creating a radio frequency (RF) noise measurement port.

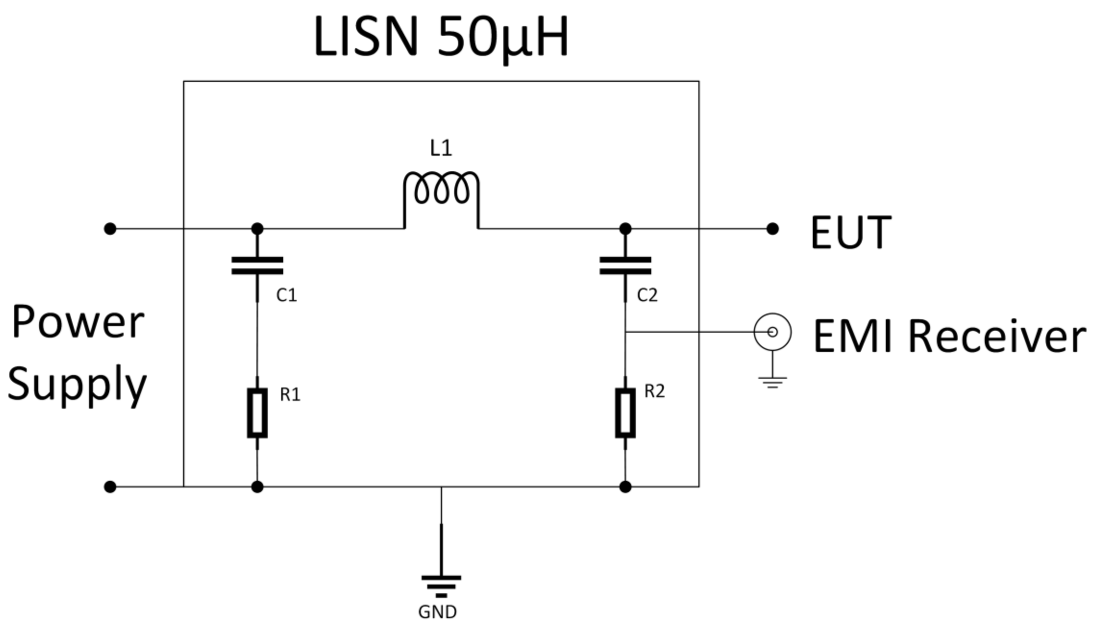

Figure 5 General schematic of the LISN

Figure 5 shows the simplified schematic of the LISN device. Since the LISN acts as a low pass filter, it allows the power to pass through and it filters the high-frequency noise from the supply source. Keeping the impedance constant between the supply and the EMI receiver is important because this may vary between different AC sources. The type of LISN is 50µH as defined in the IEC standard. [8.]

In this work, Rohde & Schwarz ESH2-Z5 LISN was used. The LISN had two power cords plugged in, one for the LISN internal electronics and one for the EUT. The EMI test receiver was connected using high-frequency coaxial cable with BNC connectors. This LISN has a switch for changing the desired phase for measurement, and it can be controlled manually or using external input. EMI test receiver was connected to the LISN with a serial cable to switch automatically between phases when the EUT was under measurement. [8.]

4.1.2 EMI Test Receiver, Oscilloscope and Impedance Analyzer

Rohde & Schwartz ESW EMI Test Receiver ESW8 (Figure 6) is the measurement device that we used to test the conducted emissions of the different VSD’s. Its frequency range is from 1Hz to 8 GHz.

Figure 6 Rohde & Schwartz ESW EMI Test Receiver used for measurements [9]

Tektronix MSO56 was the oscilloscope used to measure currents in this work. Current probes used with the oscilloscope were Tektronix TCP0150. They are a hall-effect type of current probes. Agilent 4294A Precision Impedance Analyzer was used to measure common mode chokes impedances. Figure 7 shows the measuring setup with the analyzer.

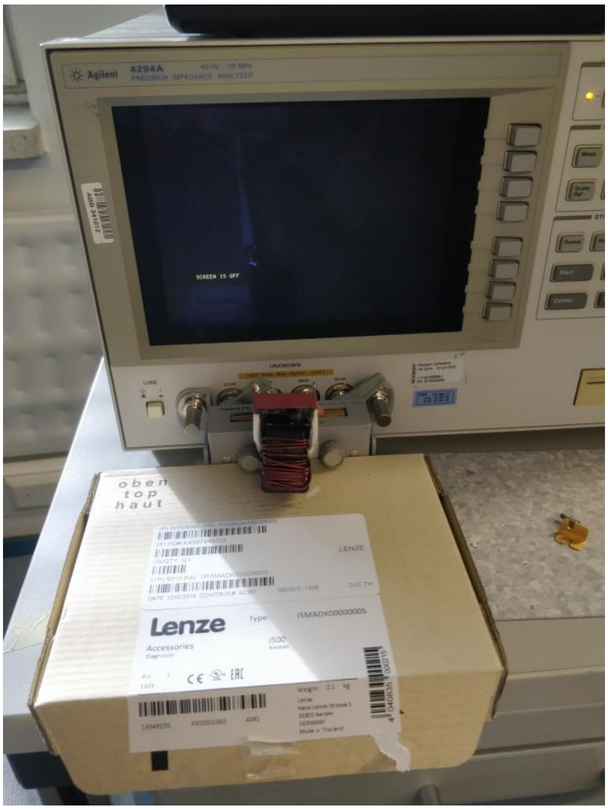

Figure 7 Testing setup with impedance analyzer with common mode choke

All the measurement devices were officially calibrated and evaluated fully working before testing was started.

4.1.3 The Cables and Motor

The supply cable was an 80cm long Eucaflex H07RN-F 4G2.5. Motor cable type was Draka MCCMK-HF C-Pro 3x2.5/2.5 and the lengths were ranging from 10m to 50m. The motor cables had always fixed 50cm diameter loop, so the measurements stayed consistent.

Figure 8 Motor cable loop jig

Figure 8 shows the cable jig that was used to make a consistent loop of the motor cables. The jig was created by using DIN-rails and plastic standoffs. The motor cable was wrapped around the jig and then secured with wide zip ties.

Other cables used in this setup were the coaxial cable from the EMI test receiver to the LISN and the attenuator/limiter combination to protect the EMI test receiver device. The limiter prevents EMI test receiver from getting destroyed if the EUT is causing very high pulse energy.

The motor used in the setup was an ABB M2AA071B 3GAA072002-ASA 4-pole inductance motor with the following specification:

- 380-420V Y, 50Hz, 1410rpm, 0.37kW, 1.2A, cos φ0.70

4.1.4 Other Equipment

Other equipment was also used in the setup. As for protection, a plastic cover was used to insulate the EUT and the connectors up to 1kV, crowd control stanchions to restrict the area and LED hazard warning lights to indicate live electrical equipment. For insulating the motor and the motor cables from the metal floor, two pieces of 150mm Finnfoam was used. For insulating the EUT for the ground, a 600mm high wooden table was used.

4.2 Equipment Under Test

EUTs were chosen according to their ability to meet the C2 EMC requirements for long motor cables. For example, ABB's ACS380 VSD was capable of meeting C2 requirements with a cable length of 10m according to the manual [10].

Figure 9 All the VSD's under measurement

Figure 9 shows all the VSDs that were measured. There were in total six different drives, including ABB's own. Manufacturers were ABB, Lenze, KEB, Danfoss, Siemens, Yaskawa. They were all in the same power class except KEB and Siemens because they do not offer drive size 0.37kW. Table 2 presents the specific data about all the VSDs, such as currents, voltages, model and type numbers and power.

Table 2 List of VSD's and rated values [10-15]

Manufac-turer	Model	Type	Power (kW)	Input Voltage (3-Phase)	Output Cur-rent (A)
ABB	ACS380	ACS380-042N-01A8-4	0.37	400-480	1.8/1.6
Danfoss	FC 280	FC-280PK37T4E20H1BXCXXXSXXXXAX	0.37	380-480	1.2/1.1
KEB	G6	07G6CDA-3A10	0.55	400-480	2.6
Lenze	i550	I55AE137F1AV10001S	0.37	400-480	1.3/1.1
Siemens	G120C	1P 6SL3210-1KE11-8AB2	0.55	400-480	1.7
Yaskawa	GA500	CIPR-GA50C4001EBAA-BAAASA	0.37	380-480	1.2

Table 3 shows the maximum cable lengths to be used for the drives so that they still meet the requirements of the C2 conducted emissions category, which was the focus of the thesis work. Some of the drives did not require any specific or maximum switching frequency, but others did, so all the measurements were made by using 4kHz switching frequency. It was not possible to change to 4kHz switching frequency with the Danfoss FC 280 VSD, so we used 6kHz switching frequency instead for the testing.

Table 3 Advised maximum cable lengths and recommended types for the motor cables [10-15]

Manufac-turer	Model	Type	Maximum motor cable length (m) to meet the (IEC61800-3 Cat-egory C2) conducted emissions requirements, switching fre-quency 4kHz
ABB	ACS380	ACS380-042N-01A8-4	10
Danfoss	FC 280	FC-280PK37T4E20H1BXCXXXSXXXXAX	25
KEB	G6	07G6CDA-3A10	50(standard line/100(low-capacity)
Lenze	i550	I55AE137F1AV10001S	15
Siemens	G120C	1P 6SL3210-1KE11-8AB2	25
Yaskawa	GA500	CIPR-GA50C4001EBAA-BAAASA	20

The motor cables were always shielded MCCMK cable and a 360-degree clamp grounding was used by the requirements of the manuals. The KEB was the only one which had two different maximum cable lengths to meet C2 category. In this study we were not able to use low-capacity cable, so we used “normal” MCCMK cable. 20m MCCMK cable was chosen for the comparison measurements between drives.

4.3 Test Place and Setup

Test place was EMC laboratory at ABB. The laboratory has its own transformer so there is less interference for testing. Laboratory supply network is TN-S and the test area has a conductive metal surface floor. The supply for the LISN was taken from the 32A socket with 400V nominal voltage and 5kA short circuit capacity. The testing place meets the requirements of the standardized test place according to IEC 61800-3:2017 standard.

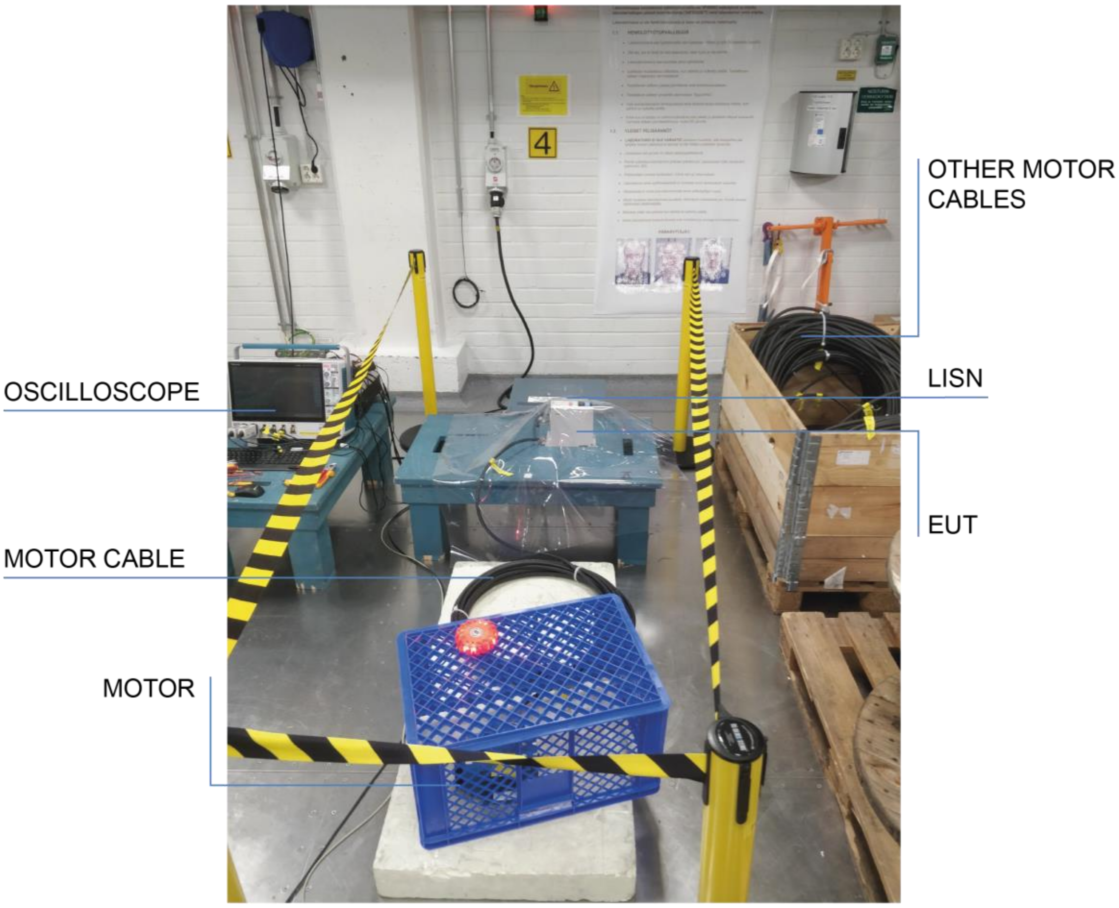

Figure 10 Example test setup with ABB VSD

Figure 10 shows used test setup for measuring the conducted emissions and leakage current measurements. EMI test receiver that was used does not show in the picture, but it was on the right back side of the setup picture. The probes were always disconnected when measuring conducted emissions to eliminate any possible extra interference.

The motor is under the blue box which was used to cover the whole motor for safety reasons. Also, the area was isolated with the crowd control stanchions and LED hazard warning lights were used for indicating live electrical equipment.

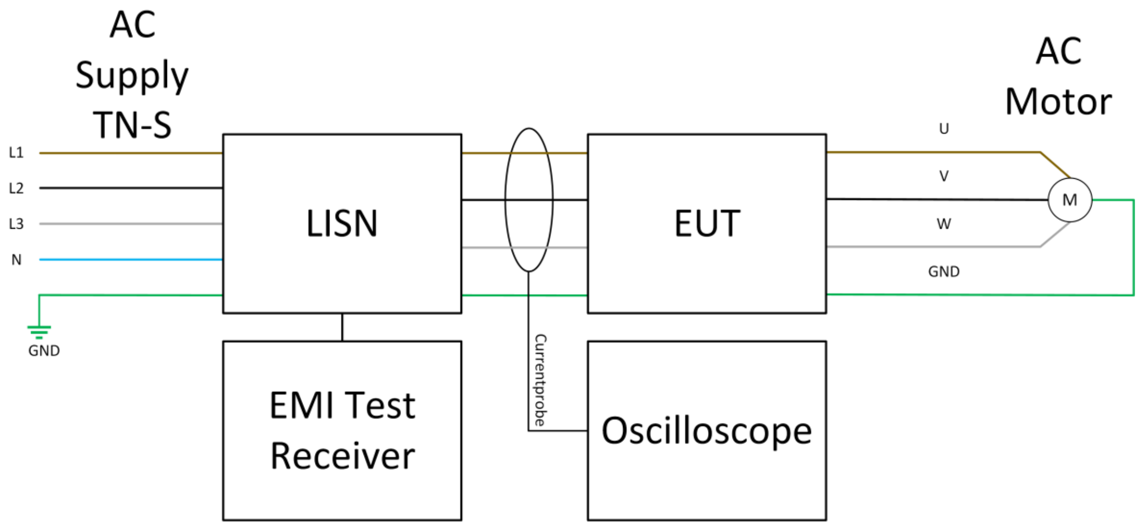

Figure 11 Block diagram of the setup

In Figure 11, the setup is displayed as a block diagram. It consists of all the measuring devices that were used in this work. Current probes were clamped over all the input and output wires and measured with an oscilloscope. Oscilloscope and the current clamps were used to measure common mode currents. Only input common mode currents were displayed in the results because they are relevant for the conducted emissions testing.

4.4 Peak, Quasi-Peak and Average Detection

There are three standardized methods defined by the standard CISPR16-1-1 to detect noise when measuring conducted emissions. Peak detection was not used when testing since the standard does not specify limits for with peak detection. Average and quasi-peak detection were used to measure conducted emissions in this thesis work. Figure 12 shows the graphical description of peak, quasi-peak and the average detection.

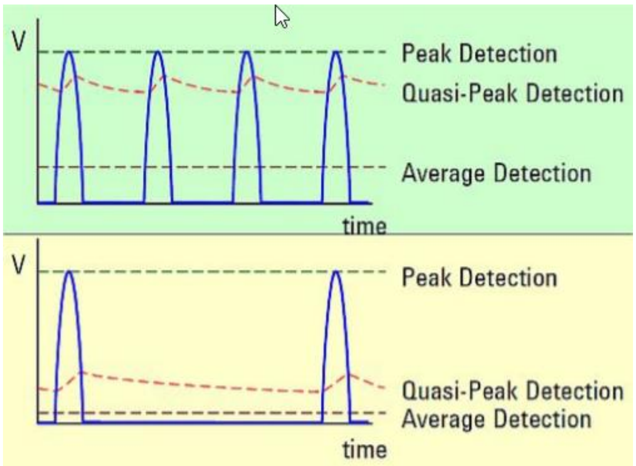

Figure 12 Graphical description of peak, quasi-peak and average detection [16]

Peak detector detects the peak amplitude of the signal (noise). Peak detector is independent for the pulse repetition frequency (PRF) and therefore it outputs maximum amplitude of the signal at any moment. Average detector outputs the average amplitude of the signal proportional to the PRF. [17.]

Quasi-peak detector outputs the signal amplitude depending on PRF. The more pulses appearing in a certain time, the higher the output reading of the quasi-peak detector will be. The Quasi-peak detector has a charge time and discharging time and the weighing characteristic that are defined in the standard CISPR16-1-1 table 3. The charge time constant for quasi-peak detector is 1ms and discharge time constant is 160ms when measuring conducted emissions. The more pulses within will appear the higher output voltage reading the quasi-peak detector will be. [17.]

5 Measurements Results

5.1 Results of the Conducted Emissions Measurement.

The reason why naming of the devices with VSD + letter combination is used, is not to point out in this thesis that one manufacturer's device performs better or worse than the other.

Testing was done without applying any load to the motor. Scalar motor control or volts per hertz control was used throughout the testing with all the VSDs. The reason for this was that one of the VSDs did not provide vector control or field-oriented control. The output frequency was 35Hz throughout the testing. Use of the output frequency was determined by doing first measurements with one VSD with different output frequencies ranging from 25 to 50Hz. Then we compared those results against each other and saw the largest interference levels with 35Hz output frequency. Though the interference differences between various output frequencies were not significant.

A MATLAB script to display and compare the results. Figure 13 and 14 show the measurement results of the conducted emissions between all VSDs. The black dash line is showing C2 limits for the quasi-peak detector and the solid black line is showing the C2 limits for the average detector. The initials AVG means average and QP means quasi-peak. Amplitude amount is measured as signal voltage (dBµV), and it refers to decibels relative to one microvolt across 50-ohm resistance. The standard provides the limits with the same values, so it is effortless to compare the measurements results with the limits.

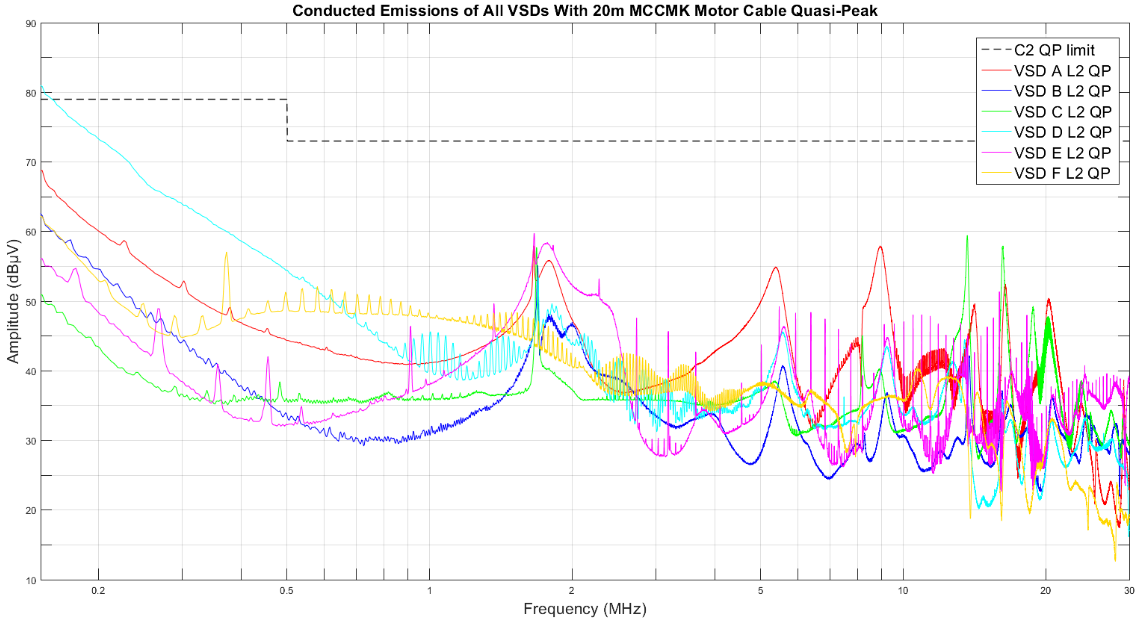

Figure 13 Conducted emissions results with 20m MCCMK motor cable quasi-peak

The conducted emissions were measured with each phase and then determined which phase was the noisiest phase by comparing the results against each other. Phase L2 was chosen as the one to examine in the comparisons because it caused overall, the highest interference out of all the 3 phases among each EUT. Although there were differences in the phases, they were not significant. Measurement results with all three phases for each VSD can be seen in the figures 23 to 33 in appendix 1.

Figure 14 shows that VSD D was not able to meet the requirements for passing the conducted emissions. In Figure 14, its average values were within the acceptable range, but the quasi-peaks in Figure 13 are over the limits. Other five VSDs passed the test.

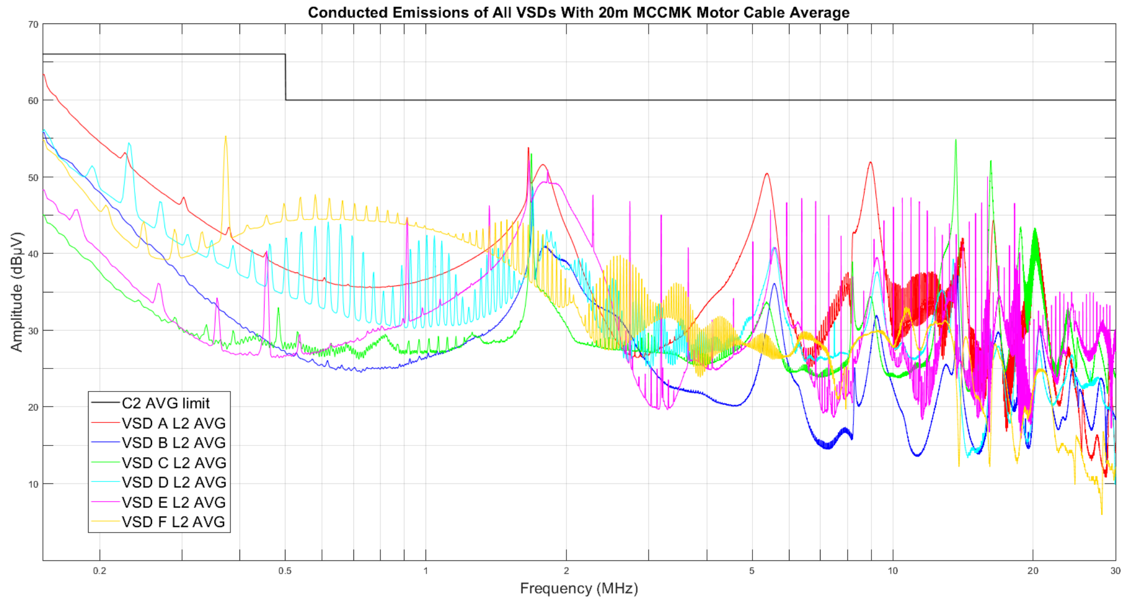

Figure 14 Conducted emissions results with 20m MCCMK motor cable average

The results show similar interferences between all VSDs throughout the whole frequency spectrum. Almost all the drives share the same sharp spike around the same frequency area, which is around 1.8MHz. That is due to the resonant current caused likely by the floor. This phenomenon was determined by opening the motor cable loop and setting it in different positions. This affected the amplitude of the interference spike. Next to the 1.8MHz spike, another spike, caused by the cable resonance, can be seen with an almost as high amplitude as the 1.8MHz spike. VSD F was the only drive which did not have this phenomenon. Most likely the reason is that of the VSD has a CMC which is placed after the Y-capacitor, so the generated common mode noise interference has an extra filtering.

Higher frequency noises are caused by unknown reasons. With VSD C a reduction of these high frequency noises were seen in 10 to 30MHz area by using long I/O-cables (3m long) for controlling the drive. All the results shown in the thesis were tested by controlling VSDs with short as possible I/O jumper wires or using the control panel of the drive. When comparing different setups, it became clear that the emissions are sensitive to the way the setup is assembled.

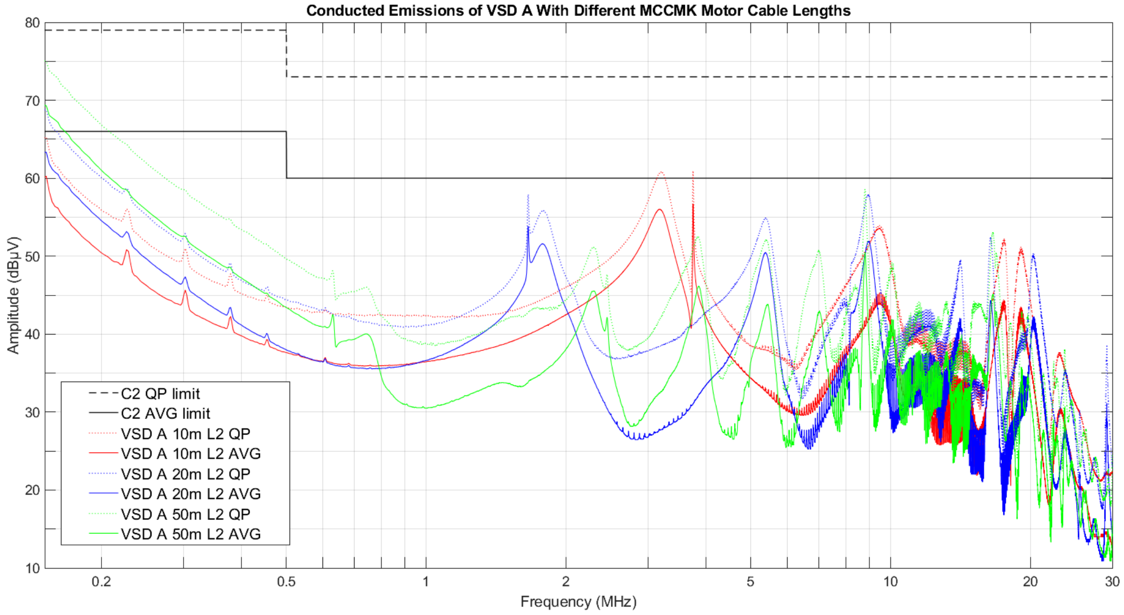

Figure 15 Conducted emissions results with different cable lengths

Figure 15 shows how conducted emissions change depending on the motor cable length in use. The “floor” and the cable resonance spikes are now in a different frequency area when different motor cable lengths are used. When 20m motor cable is used the spikes can be seen in the 1.8MHz frequency area as seen in the previous Figure 13 and 14. When 10m cable is used, the same interference spikes appear in higher frequencies area around 2.5 to 3.0MHz. The position of the cable resonance changes to lower frequencies because the motor cable capacitance increases. The increased capacitance will make the CM currents higher which in turn will affect the interference levels. They will rise as the cable length grows longer. This is increase CM current is caused by the stray capacitance between the cable phase conductors and the shield. The reason why lowered amplitude of these interferences when longer motor cable was used was likely due to the performance of the EMI filter which is better in the lower frequencies. When these interferences appear at a lower frequency they have been filtered more effectively.

5.2 Common Mode Currents

In the ideal world, the common mode currents would be zero. In the real world, this is not possible because of the parasitic capacitance. For these measurements, same setup was used as for the conducted emissions measurements.

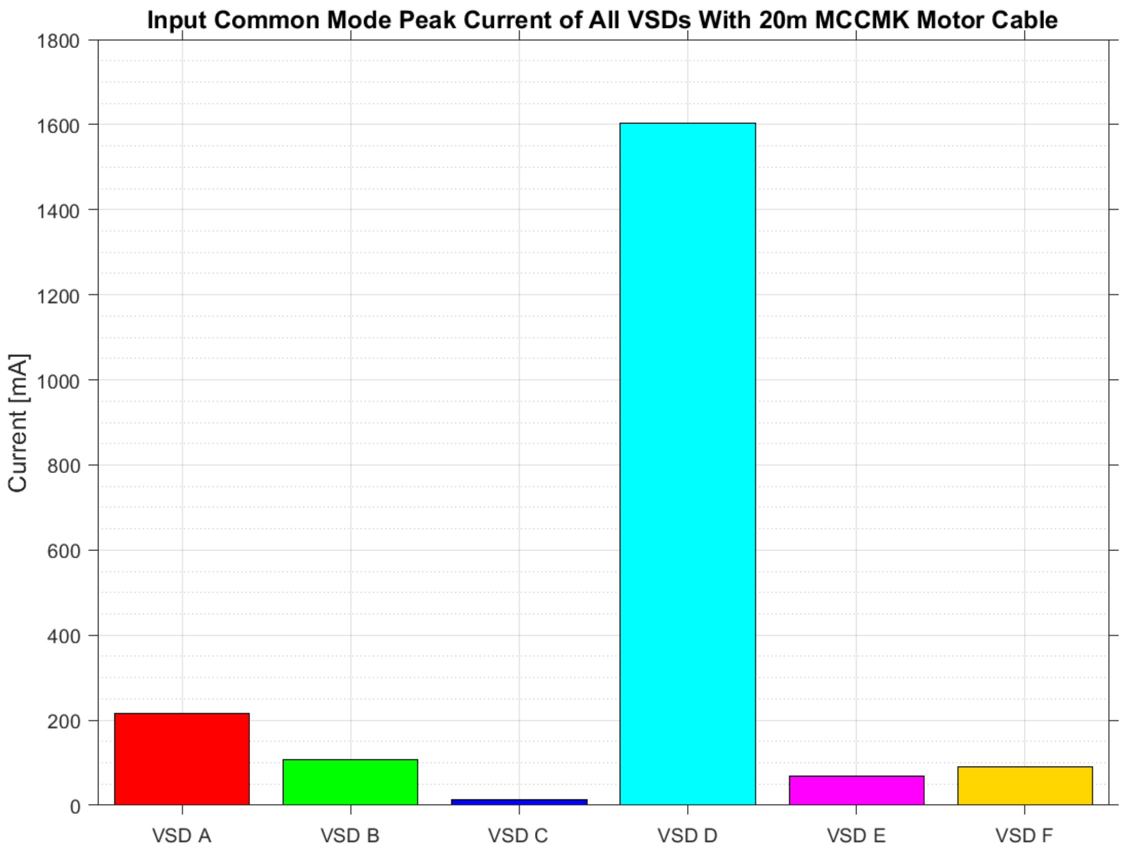

Figure 16 Input common mode currents of tested VSDs

Figure 16 shows the measured input common mode peak currents of tested VSDs. The lowest peak current is with VSD C, which was only 15mA, while the VSD D had the highest current of 1600mA. VSD E, F, and B had current values ranging from 69 mA to 107mA. VSD A peak current was 215mA.

The much larger common mode peak current with VSD D is probably caused by the low performing common mode choke. The high noise amplitude is causing the CMC core material to go to the saturation state. In this state the increase in the applied external magnetizing field cannot increase the magnetization of the material and, therefore, the magnetic flux gets to a stable level. That causes magnetic permeability to drop. When it happens the high noise current is not filtered anymore by the CMC and it is shown as a high peak common mode current in Figure 16. When the amplitude of the noise reduces, the CMC returns to the original state. This conclusion was made because the average results of conducted emission were within the limit, but the quasi-peak limit was exceeded. The saturation of the CMC is so fast that only quasi-peak detector recognizes it. One solution would be using better designed CMC, which most likely prevent this phenomenon. [18.]

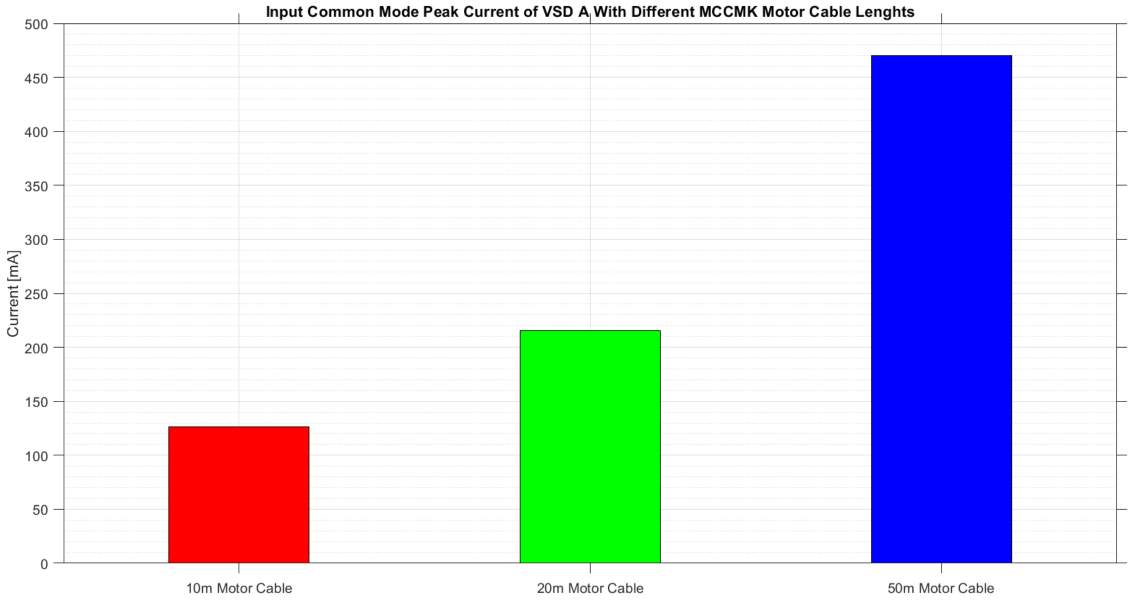

Figure 17 Input common mode current of VSD A with different motor cable lengths

Figure 17 shows the common mode currents with various motor cable lengths measured with the VSD A. The same setup and measuring procedures was used as before but now using different lengths for the motor cables and analyzed how that affects the common mode currents. As shown in Figure 17, the currents increase almost linearly with the length of the motor cable. The increased length of the motor cable enhances the parasitic capacitance of the motor cable, causing higher common mode currents to occur.

5.3 Impedance Measurements of Common Mode Chokes

We performed impedance measurements for the common mode chokes to characterize them. After having completed the testing, VSDs were opened and CMCs were detached from the PCB boards. Then we measured the chokes using Agilent impedance 4294A impedance analyzer.

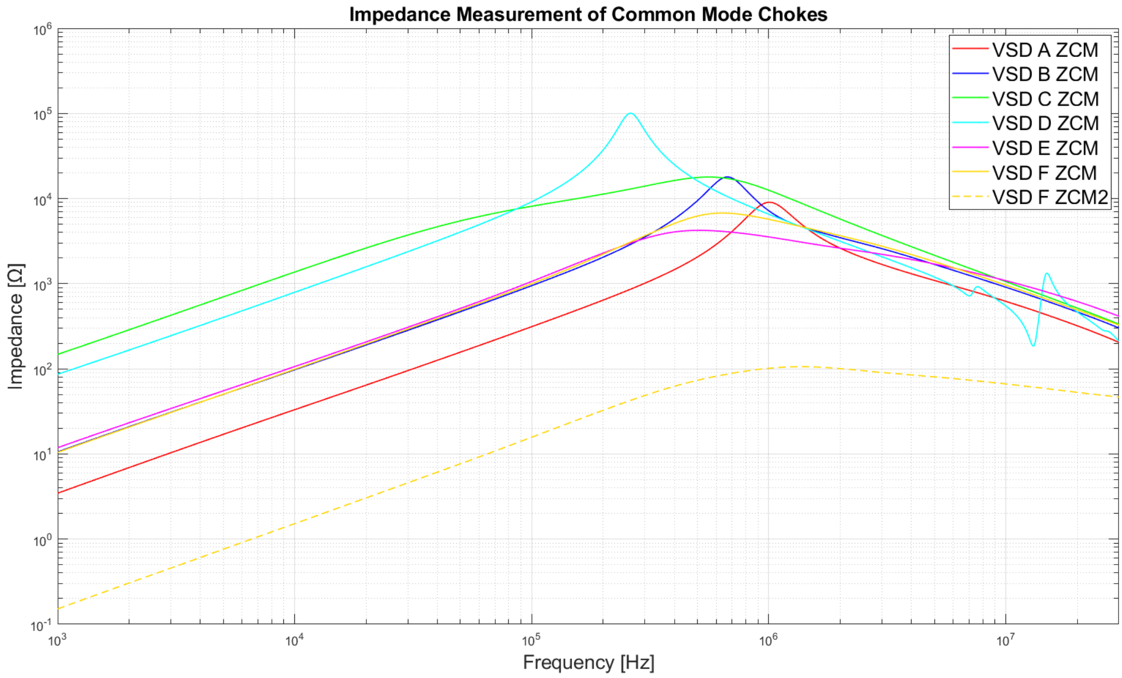

Figure 18 Impedances of the common mode chokes

The Figure 18 shows the results of the common mode choke impedance measurements. The measured values are common mode impedance values (ZCM). The performance of the CMC is often expressed by the common mode impedance over the frequency spectrum. It can also be expressed as an insertions loss (dB) over the frequency range.

The self-resonant frequency (SRF) of the inductor is a frequency area when inductor has its highest impedance. In that frequency area when the impedance is high inductor is used as a choke to attenuate the noises. The SRF of the common mode choke should be in close to the frequency where the highest noise amplitude occurs. This SRF frequency in Hz follows this equation:

$$SRF = \frac{1}{2\pi\sqrt{(LC)}} \quad (1)$$

L is the inductance in Henries and C is the capacitance in Farads. Capacitance is the parasitic capacitance of the choke and the inductance can be calculated with equation below:

$$L = Z/(2\pi f) \quad (2)$$

Z is the impedance of the choke in Ohms and f is the frequency in Hertz. Figure 18 shows that most common mode chokes had their SRFs around 0.6 to 1 MHz except VSD D, which had SRF lower frequency area at 0.2MHz. The structure of the VSD F's second common mode choke is such that is has single winding through the ferrite core. Because of this structure the choke has a low impedance since it does not have almost capacitance at all. This type of CMC structure shows basically the resonant frequency of the material. [19.]

The choke of the VSD D has the highest impedance which indicates a good filtering performance but also increase the amount of the common mode currents. The noise currents must take consideration in the design of CMC. Measured common mode noises were too high according to the standard limits because the choke being in the saturation state.

Measurements results show that the VSD C is the best choke since it has the highest impedance throughout the whole frequency spectrum. The worst performing choke is in the VSD A, which had the lowest impedance over the frequency spectrum.

6 Main Circuit and EMI Filter Schematics

After the emissions tests were completed the VSDs were disassembled. Disassembly of the VSDs gave insight on the main circuit designs and EMI filter designs. There were similarities and differences in the designs. All testes VSDs had EMI filtering on the AC side except VSD D. The EMIs were mostly CLC filtering circuits with some extra filtering after rectifier circuit. The capacitors used in the main circuits for filtering were all film capacitors. They offer high frequency range, high insulation and good temperature stability. Electrolytic capacitors were used for DC-link because they provide high capacitance for their size.

The common mode choke is in the filter design to reduce the common mode noise. The CMC lies between a first set of X-capacitors and a second set of X-capacitor as in Figure 19. These common mode chokes were around the same physical sizes among all the devices, but the number of winding turns, and the core material were different. The chokes were the most dominant feature of EMC performance since the capacitors were mostly similar among each other.

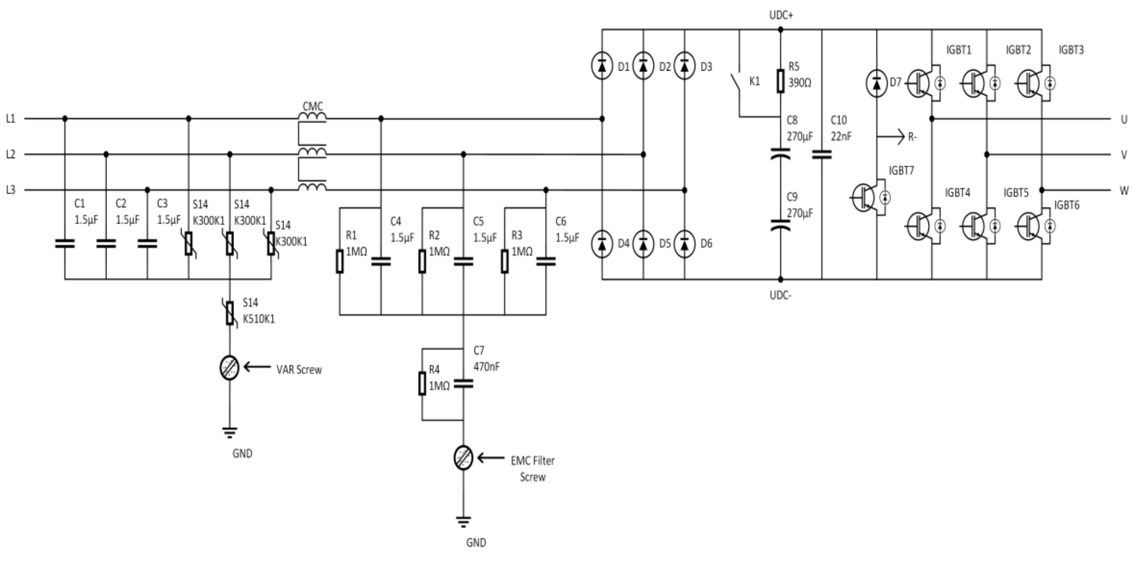

Figure 19 Schematic of the main circuit of VSD A

Above, Figure 19 shows the schematic of the VSD A design of the main circuit and EMI filtering before the rectifier circuit. It has an EMC screw that connects the Y-capacitors to the ground when it is installed to the normal TN-C/S environment. That element is unscrewed when the IT network is in use. All tested VSD shared protection against the voltage surges and transients form the electrical grid using metal oxide varistors (S14) connected phase to phase. The VSD A and F were the only ones that were equipped parallel varistors connected to ground with a fourth varistor. In the design of VSD A, that is controlled with extra VAR screw. The VSD C was the only one having varistor protection in DC side between UDC+ and UDC- to give extra DC voltage stabilization.

In the filter design, there are C1 to C6 X-capacitors to attenuate the differential mode noise between the phases. They also act as extra protection against voltage transients and power surges. When the X-capacitor fails, under normal stress voltages, it should fail to open state, but with high enough overvoltage they may fail to close state. If the component fails to close state, this causes AC supply fuse or a circuit breaker to open. All tested VSDs had this design. [20.]

In Figure 19, the Y-capacitor C7 acts as a bypass capacitor for the common mode noise to have a return path to the ground. It connects the parallel C4, C5, C6 X-capacitors to ground via Y-capacitor. Only the Y-capacitor should play this kind of role because of its design. Under failure, the capacitor is designed to open itself, avoiding the risk of an electric shock. The X-capacitor can fail, leaving an open or short-circuit state. Some of the VSDs, like VSD B and E, had more than one Y-capacitor to connect the line to ground. VSD B had two extra capacitors to ground, and one of them had a connection to the ground even without EMC screw. [20.]

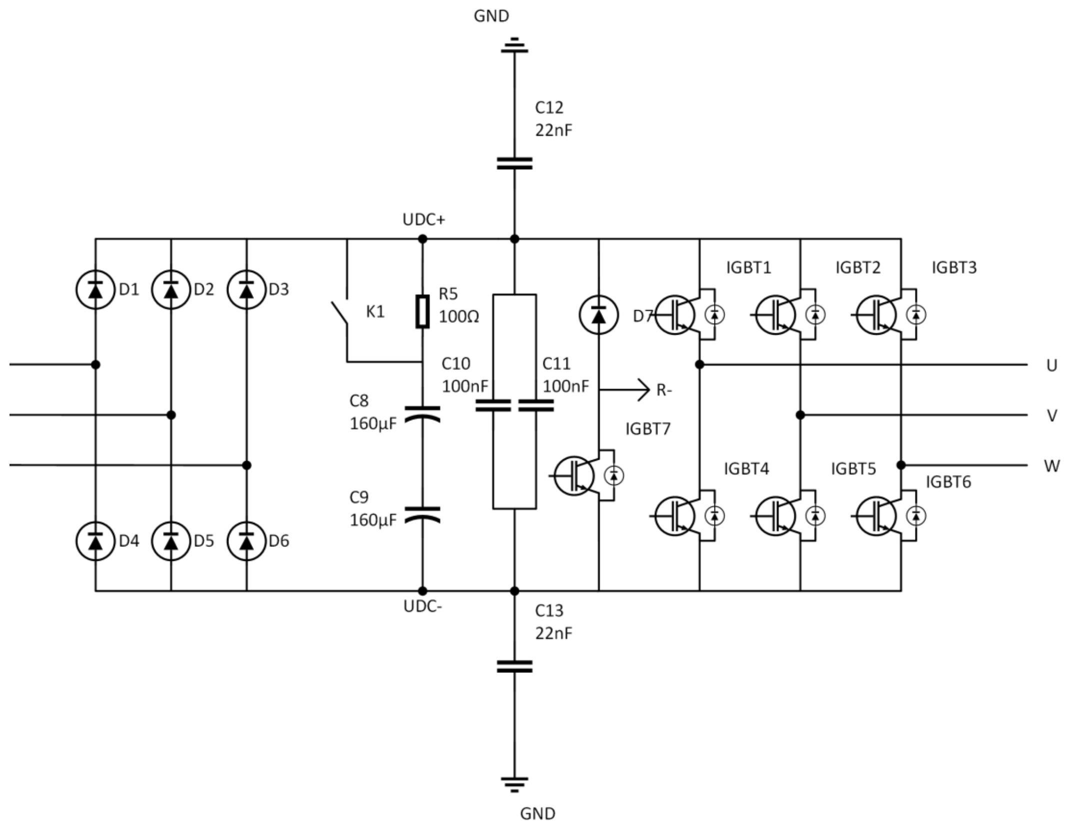

Figure 20 DC side schematic of the main circuit and EMI filter of VSD E

Figure 20 shows a schematic of the VSD E after the rectifier circuit. The VSD E was the only drive that had Y-capacitor going to ground also in the rectified side. That adds extra attenuation for the common noise currents. VSD E's large electrolytic capacitors (C8 and C9) are used for smoothening the ripple after the rectifier circuit. All the tested VSDs shared similar design for this purpose, and the values of these electrolytic capacitors were ranging from 110 to 270μF.

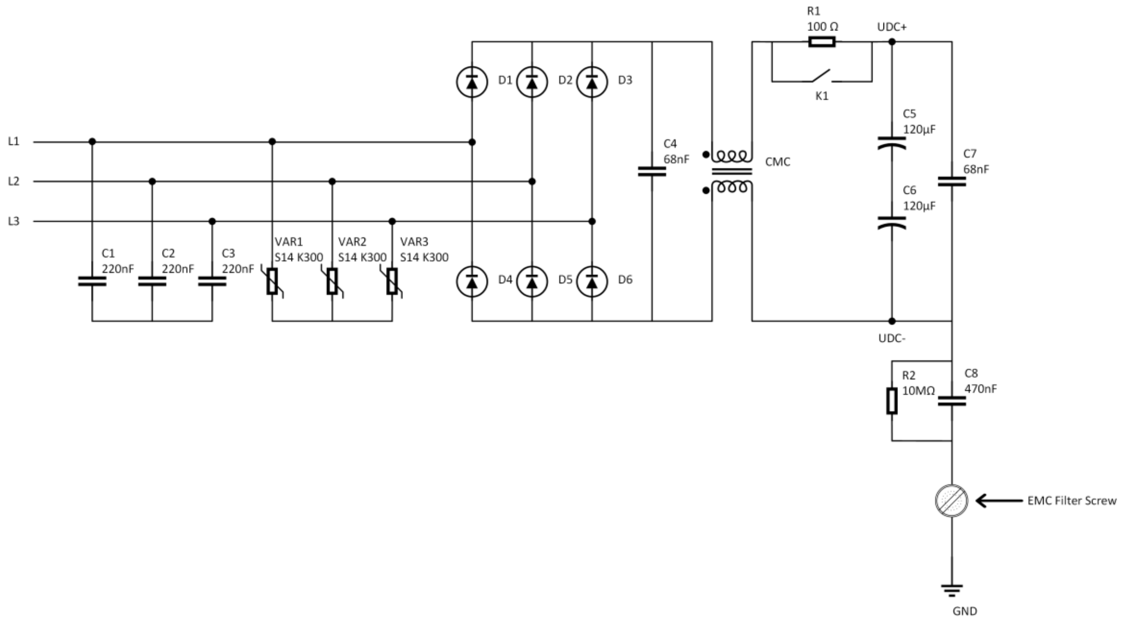

Figure 21 Schematic of the main circuit and EMI filter of VSD D

Figure 21 shows that the schematics of VSD D differs the most from the other schematics. In VSD D design most of the EMI filtering is executed after the rectifier, not in the AC side. The C1 to C3 capacitors are dampening the differential noise. Overvoltage protection with varistors is similarly made than with others. After the rectifier circuit, similar design of a CLC filtering is used to suppress EMI. C4 and C7 are attenuating the differential noise, and the CMC choke is filtering common mode noise. C8 Y-capacitor creates the path for the common mode noise to ground.

7 Conclusion

In this thesis work, conducted emissions and prevailing mode currents of the VSDs were measured. The measurements were compared against each other and how different motor cable length affected the results. Then the tested VSDs were disassembled and the electrical parts examined. After disassembling the devices, the common mode chokes were taken under further investigation and the impedance over the frequency spectrum was measured to characterize the performance. Extra testing with different lengths of motor cables were done but the results were left out this work to prevent singling out any specific manufacturer's absolute performance.

The devices were performing mostly as expected, and measuring results were meeting up with the expectations. The EMI designs in the AC side were quite similar almost identical with one another. Every device had overvoltage protection executed with varistors. IGBT and IPM power modules were used in every tested VSD except in VSD D which used discrete IGBTs and rectifier diodes. Similarities were noticed among the common mode choke designs but also differences such as different core materials.

Measurement of the conducted emissions point out to be a sensitive to the way the setup is assembled. Also, parametrization of the VSDs turn out to be much harder than expected.

The collected measurement data and analysis increased the understanding of the conducted emissions, common phenomenons and differences. This can be used in the future development of the design process. The collected information of the work also gave a good insight into the existing variable speed drive market.

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Main circuits and conducted emissions results of individual VSD used in the study

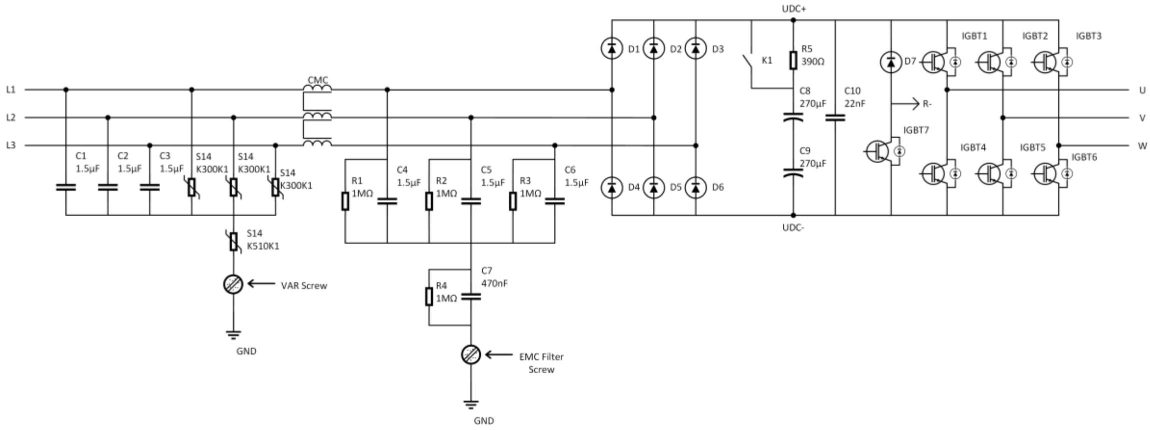

Figure 22 Schematic of the main circuit and EMI filter of VSD A

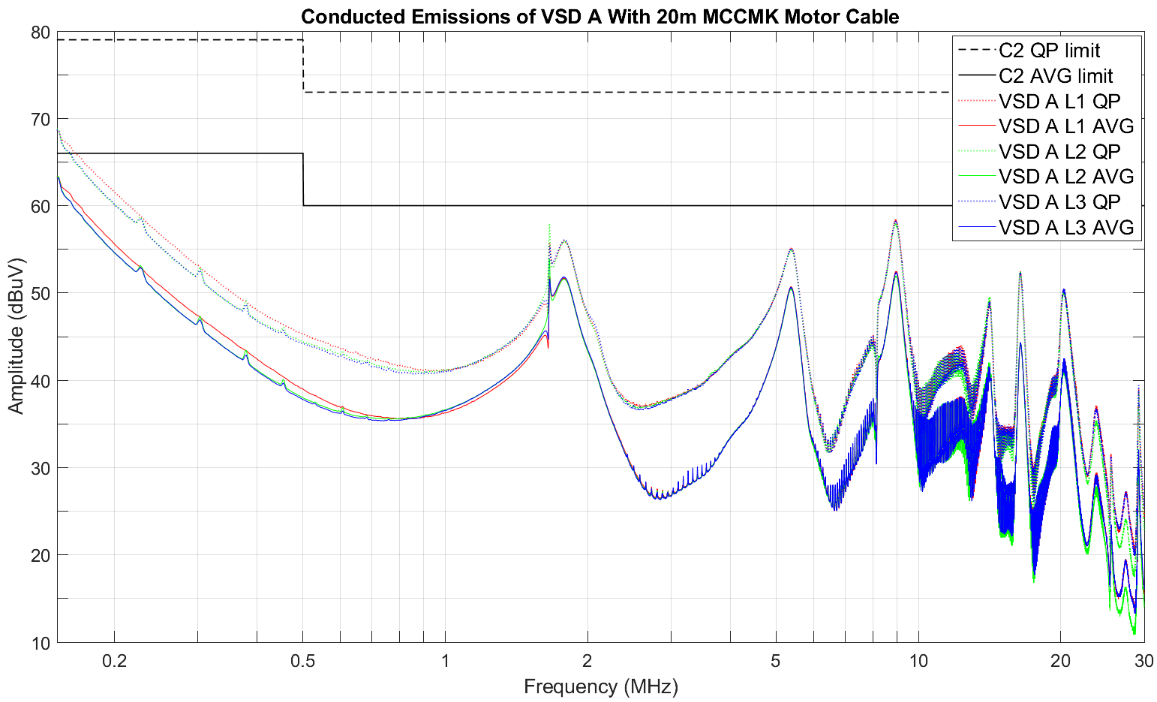

Figure 23 Conducted emissions results of VSD A with 20m MCCMK motor cable

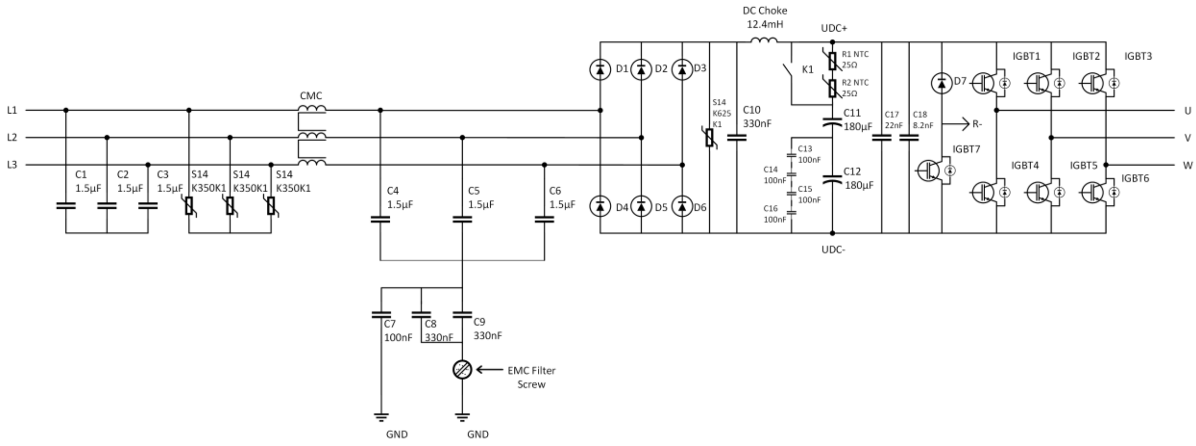

Figure 24 Schematic of the main circuit and EMI filter of VSD B

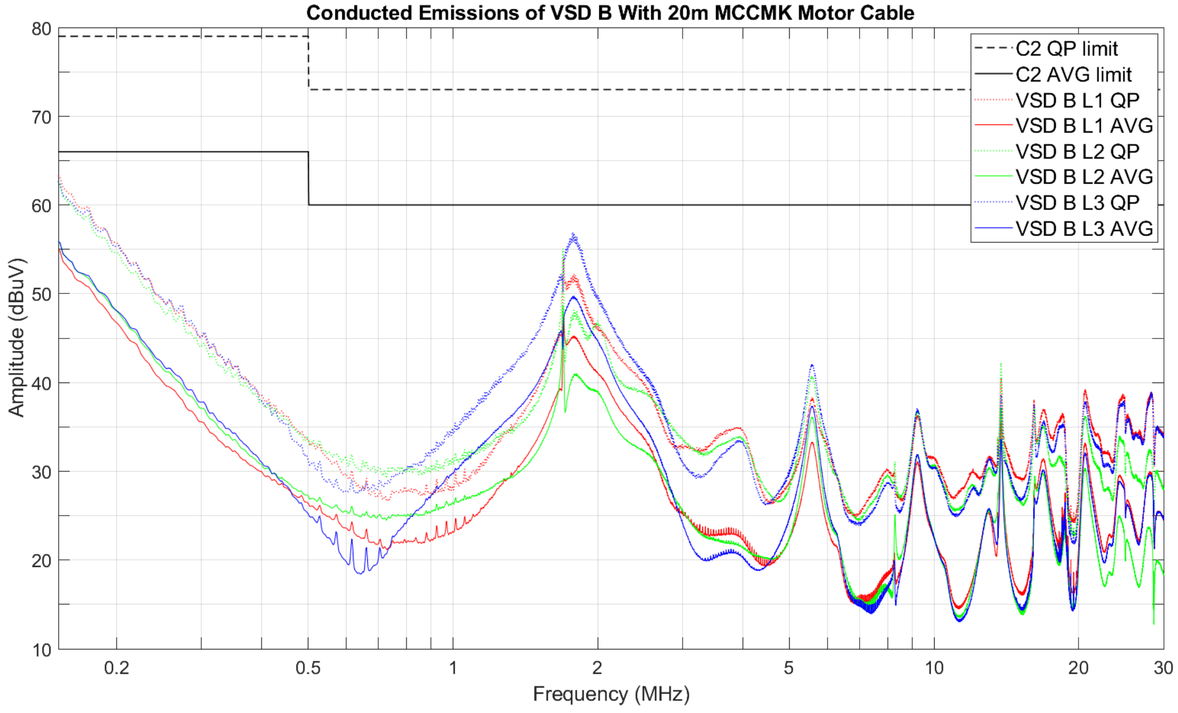

Figure 25 Conducted emissions results of VSD B with 20m MCCMK motor cable

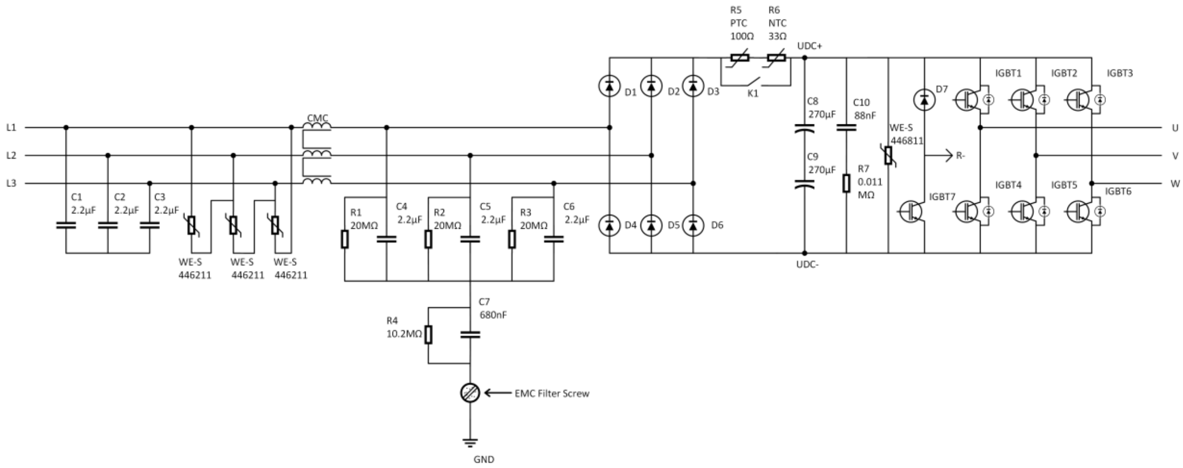

Figure 26 Schematic of the main circuit and EMI filter of VSD C

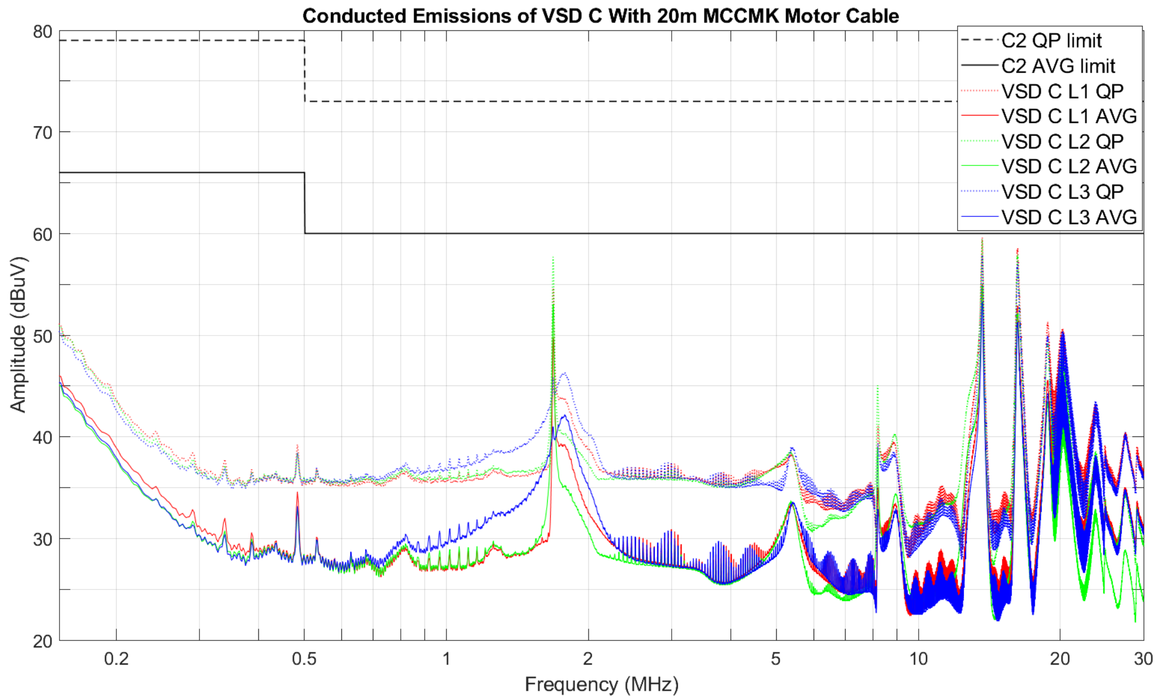

Figure 27 Conducted emissions results of VSD C with 20m MCCMK motor cable

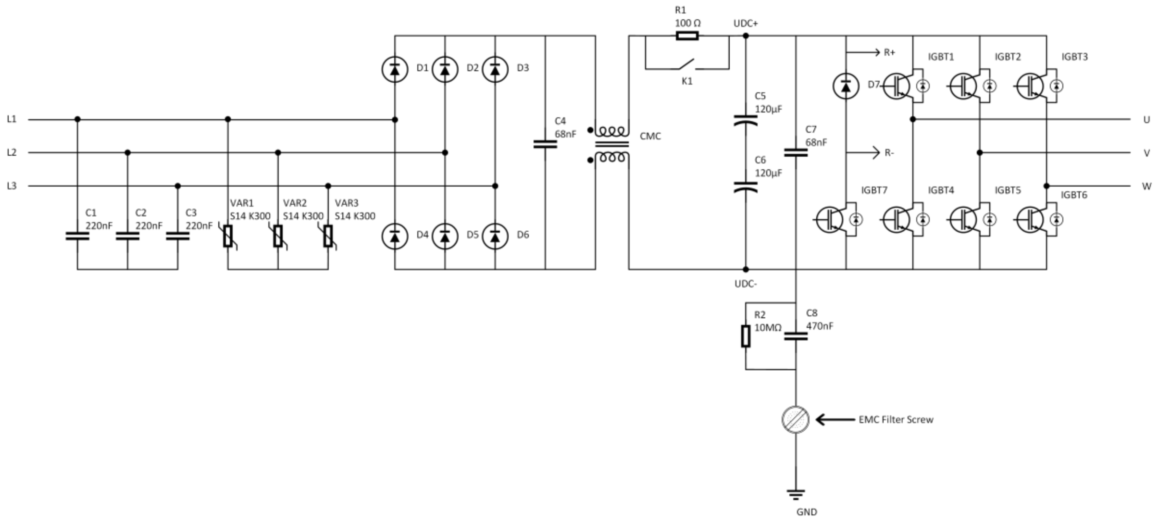

Figure 28 Schematic of the main circuit and EMI filter of VSD D

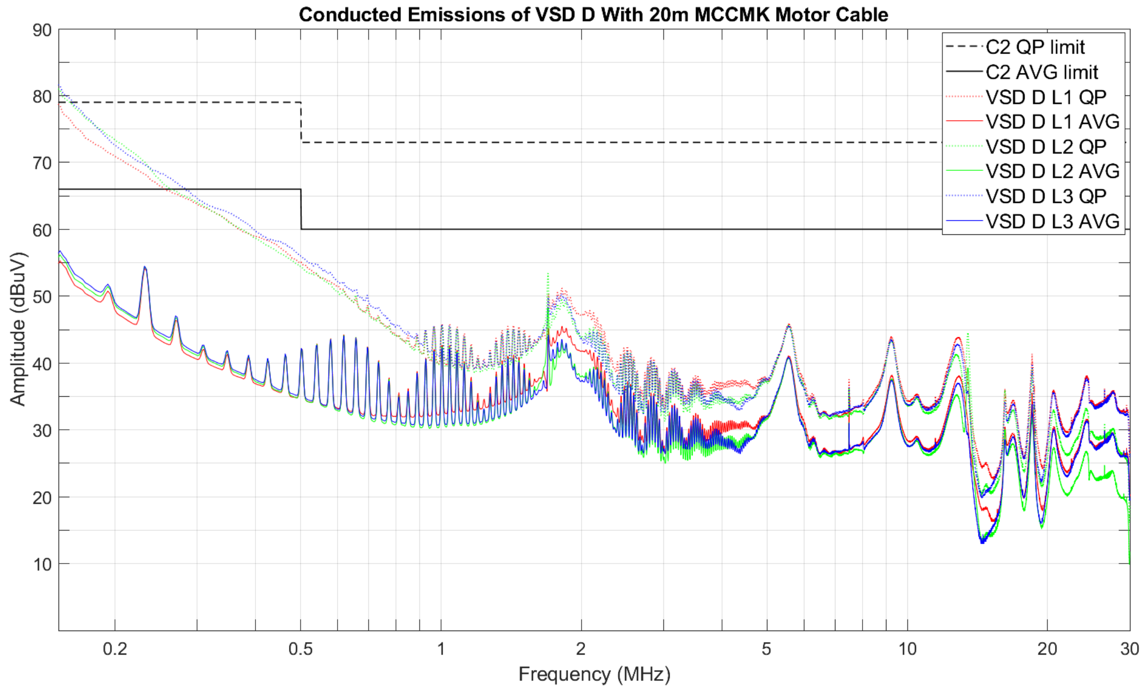

Figure 29 Conducted emissions results of VSD D with 20m MCCMK motor cable

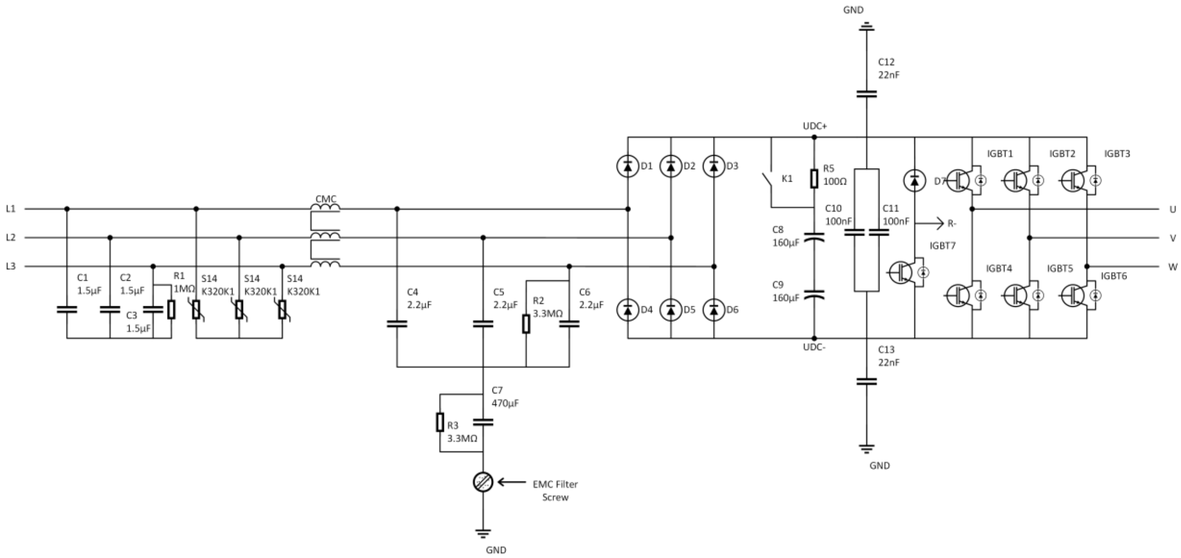

Figure 30 Schematic of the main circuit and EMI filter of VSD E

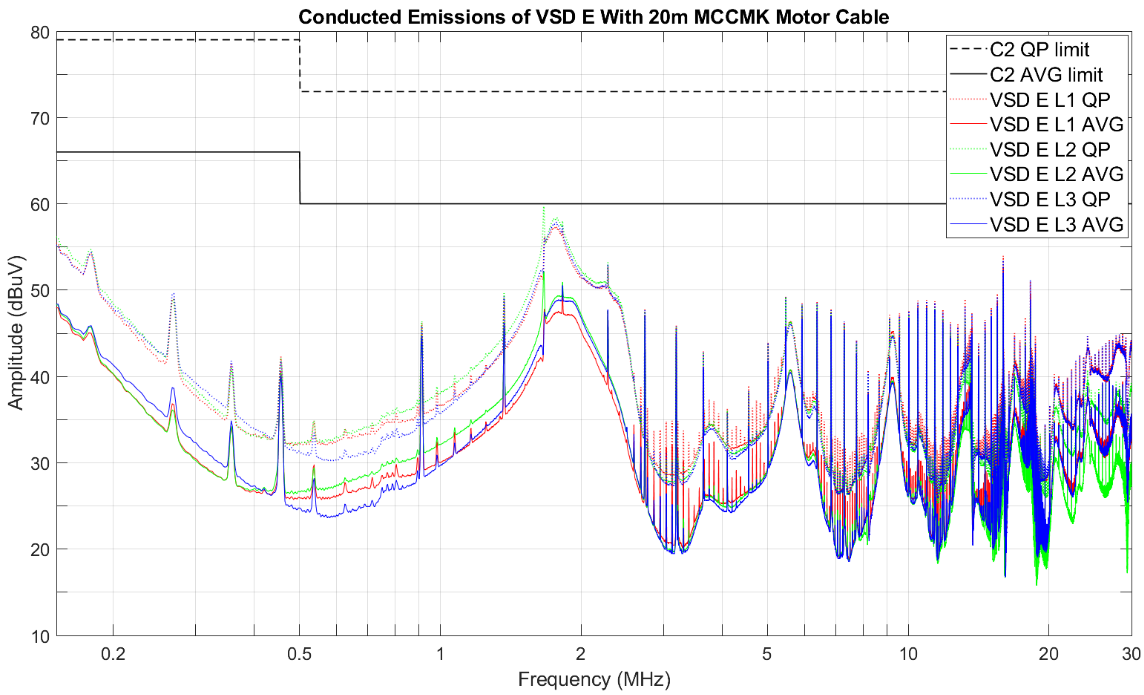

Figure 31 Conducted emissions results of VSD E with 20m MCCMK motor cable

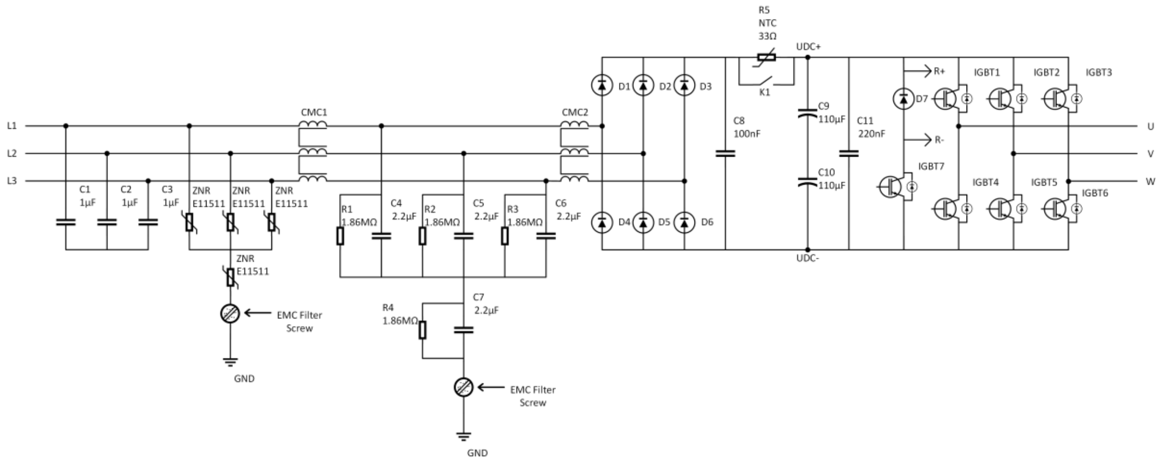

Figure 32 Schematic of the main circuit and EMI filter of VSD F

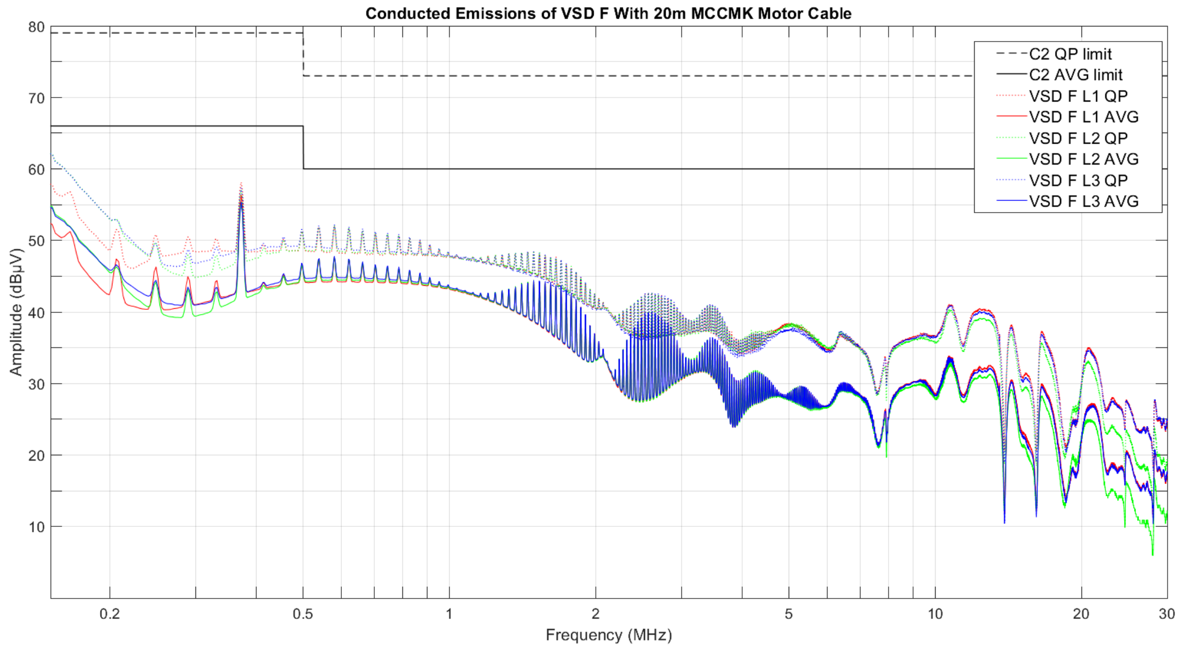

Figure 33 Conducted emissions results of VSD F with 20m MCCMK motor cable