LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
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A METHOD TO REDUCE COMMON MODE NOISE IN FREQUENY CONVERTER DRIVES

Examiners: D.Sc. Juhamatti Korhonen

Abstract

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When a line converter is connected to a grid without galvanic isolation, there can be problems with excessive leakage current and conducted emissions caused by common mode noise, especially when there is a battery pack with high stray capacitance connected to the DC link. In this thesis the methods for reducing common mode noise are discussed and a new method was tested in a laboratory.

It is very difficult or impossible to suppress the common mode noise with only adding Y-capacitors and common mode inductors if an isolating transformer or a different converter topology cannot be used. In this thesis a new solution that uses a bypass circuit was implemented. By adding a bypass circuit that consists of capacitors connected from the AC input to the DC link, some of the common mode noise is directed through this path and does not pass to the grid or through the batteries in the DC link.

The proposed solution was tested and it was found to be very effective in reducing the conducted emissions and the leakage current towards the grid. However, it was found that the solution does not help in the situation where there is a battery connected to the DC link, as the leakage current becomes too high.

Tiivistelmä

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Harri Matikainen

Menetelmä vähentää yhteismuotoisia häiriöitä taajuusmuuttajakäytössä

Kandidaatintyö
2020
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Työn tarkastajat: TkT Juhamatti Korhonen

Avainsanat: yhteismuotoinen, häiriö, invertteri

Verkkoon kytketty aktiivinen tasasuuntaja tuottaa paljon sekä ero- että yhteismuotoista häiriötä. Yhteismuotoinen häiriö kasvaa entisestään, kun tasasuuntaajaa käytetään järjestelmässä, jossa on suurihajakapasitanssinen akusto. Tässä kandidaatintyössä tutkittiin tapoja vähentää yhteismuotoista häiriötä ja uutta metodia kokeiltiin laboratoriossa.

Yhteismuotoista häiriötä on vaikeaa vähentää riittävästi passiivisilla suodinkomponenteilla, jos erotusmuuntajaa tai toisenlaista konvertterin topologiaa ei voida käyttää. Tässä työssä kokeiltiin käytännössä ohituspiirin käyttöä vähentämään verkon ja välipiirin vuotovirtaa ja yhteismuotoisia häiriöitä. Ohituspiiri koostuu kondensaattoreista, jotka ovat kytketty verkon vaiheista välipiiriin. Osa yhteismuotoisesta virrasta kulkee näiden kondensaattorien läpi ohittaen verkon ja välipiiriin kytketyn akuston.

Ehdotetun ratkaisun todettiin vähentävän tehokkaasti vuotovirtaa ja johtuvia häiriöitä verkkoon. Piiri ei kuitenkaan toiminut toivotulla tavalla lisättäessä välipiirin Y-kapasitanssia, sillä yhteismuotoiset häiriöt kasvoivat liian suuriksi.

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Nomenclature

AC	alternating current
CM	common mode
DC	direct current
DM	differential mode
EMC	electromagnetic compatibility
LISN	line impedance stabilized network
PE	protective earth
PWM	pulse-width modulation
TN	terre-neutral
TT	terre-terre
D	duty ratio
f_s	switching frequency
I_{CM}	common mode current
U_{CM}	common mode voltage
U_{DC}	direct voltage
U_{neg}	negative voltage
U_{pos}	positive voltage
T_s	switching cycle duration
U	voltage

1 Introduction

There is a huge and fast-growing market for mobile electric on-road and off-road vehicles, machinery and marine vessels. The mobility is often achieved with large batteries, which in turn requires high power chargers that are usually supplied from the largely available commercial alternating current (AC) grid. Sometimes the vehicle or vessel must be operated directly from the AC grid, which requires AC grid interfaces with even bigger current capacity. A line converter is often used to rectify the AC to direct current (DC) instead of a diode bridge to provide better voltage control, power factor and to enable power flow in both directions. The line converter causes electromagnetic compatibility (EMC) problems, especially when connected to large battery packs. Different kinds of line filters are used to pass the EMC regulations and designing an effective filter is crucial for getting the system perform well and within standards.

This thesis applies to common three phase pulse-width modulation (PWM) converters used as a motor drive, grid inverter or line converter.

1.1 Research problem

There have been problems with leakage current and conducted emissions when line converters are used in conjunction to battery packs and galvanic isolation between the converter and the grid is not possible. It is necessary to find solutions to reduce the leakage current flowing through the batteries and the AC grid.

1.2 Research methods

Most of the research was done by studying literature. Laboratory tests were conducted to verify the functionality of the proposed solutions.

2 Basics of inverter switching and common mode voltage generation

Power electronic inverters change DC to AC by switching rapidly between the DC voltage levels. By varying this switching pattern, the inverter can control the power flow from DC to AC and vice versa. The switching causes large differential and common mode (DM, CM) noise that can have serious negative effects for the functionality, lifetime and safety of the system.

2.1 Three phase PWM inverter switching

A typical three phase PWM inverter has six switches, two per phase. One switch connects the phase to the negative potential of the direct current (DC) bus and the other connects the phase to the positive potential. The positive and negative switches alternate constantly with the switching frequency f_s, usually under 50 kHz for insulated gate bipolar transistors (IGBTs). The output voltage is determined by the duty ratio D.

The inverter switches every phase once high and once low during a switching cycle T_s. The length of the on- state T_{on} and the off-state T_{off} is varied by the inverter control system. Duty ratio is the ratio between high and low state. When D=0.5 the total output voltage is 0 V, when D=1 the total output voltage is the positive DC-bus voltage and when D=0 the total output voltage is the negative DC-bus voltage. The sine wave and the PWM waveforms are shown in the figure 2.

2.2 Common mode voltage

Common mode (CM) voltage is the voltage between the live parts of a system and the ground level. Figure 1 is a simple graphic representation of the difference of common mode and differential mode voltages and currents. Common mode voltage U_{CM} in motor cables is the average of the phase voltages

$$U_{CM} = (U_1+U_2+U_3)/3,$$

where U_1, U_2 and U_3 are the phase voltages (Skibinski et. al., 1999). In the DC link it is defined as

$$U_{CM} = (U_{pos}+U_{neg})/2,$$

where U_{pos} is the positive DC voltage potential and U_{neg} is the negative DC voltage potential. The voltage sum of all three phases is never zero because the inverter has three higher switches and three lower switches. This causes an imbalance in the number of switches connected to each potential. However, the voltage sum averages to zero on longer time scale. Possible combinations for the switches are all phases high, all phases low, two phases high and one down or one phases high and two phases low. This means the common mode voltage U_{CM} can have a value of ±1/2U_{DC} or ±1/6 U_{DC}.

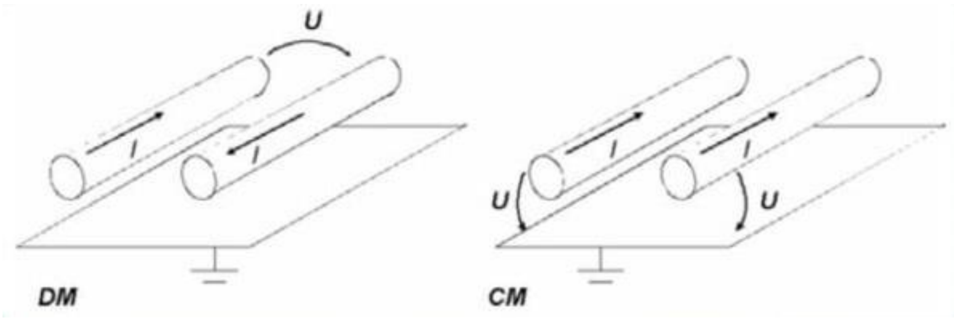

Figure 1. Differential mode voltage is the voltage between the main wires carrying signal or power. The common mode voltage is the voltage sum between the signal or power wires and the ground potential.

The variation in the voltage sum is common mode voltage ripple, which has an amplitude of U_{DC}. This voltage causes a common mode current I_{CM} to flow through the capacitances between the live parts and the ground. The amplitude of the current is dependent of the impedance of the current path.

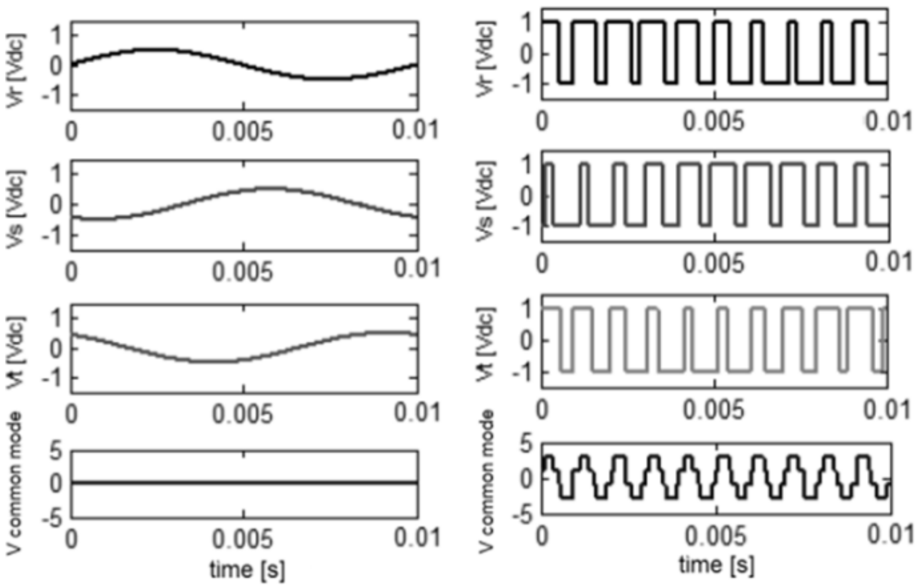

Figure 2. The common mode voltage is a sum of three phase voltages, *Vr*, *Vs* and *Vt* (Prieto et. al., 2011).

A simplified circuit of a three-phase inverter, a sinusoidal filter, electric grid and DC-link Y-capacitances is shown in figure 3. Switches *Z1…Z6* represent the inverter. The capacitors *C1…C3* and inductors *Lc1…Lc3* and *Lg4…Lg6* represent the sinusoidal filter. The electric grid is represented by three resistors *Rg1*, *Rg2* and *Rg3*. In terms of a common mode current path, the circuit can be reduced to an equivalent circuit shown in figure 4. The six switches are acting as a CM voltage source. The line filter inductance, grid impedance and DC link leakage capacitance together form an RLC circuit.

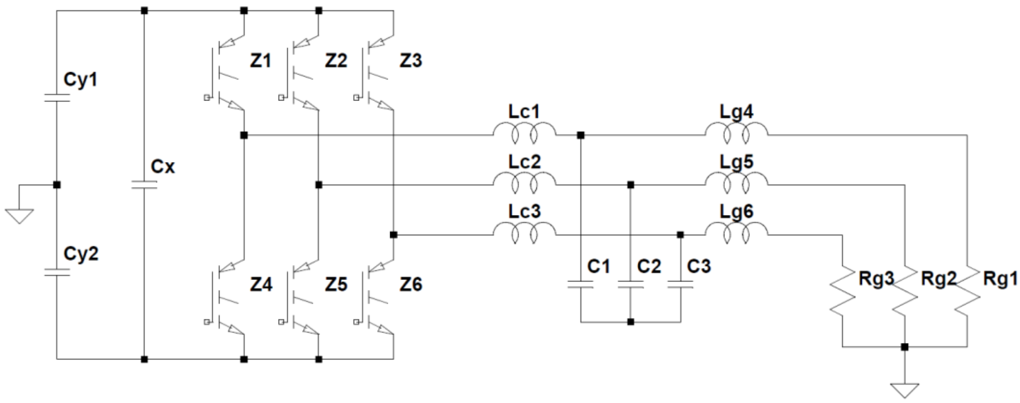

Figure 3. Three-phase inverter connected to a sinusoidal filter and a grid. DC-link Y-capacitance is drawn as two capacitors, *Cy1* and *Cy2*

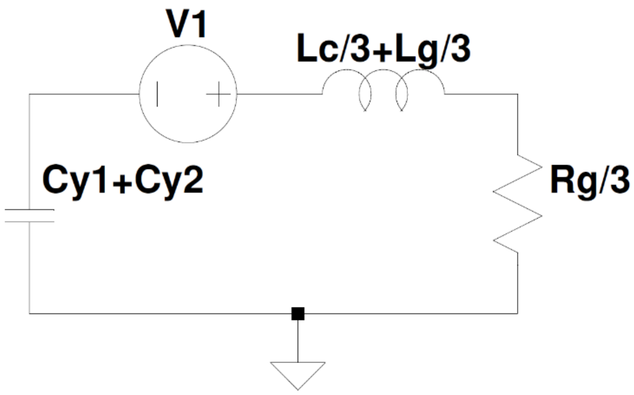

Figure 4. A common mode equivalent circuit. Capacitors C1…C3 do not appear in the equivalent circuit.

3 Problems caused by common mode noise

Common mode noise can cause problems in electric motors, in the electric grid and in the DC link. The noise can also get coupled to low voltage circuits.

3.1 Common mode noise in electric motor

Common mode current flowing through the electric motor's bearings causes wear and reduced lifetime (Erdman, 1996) (Busse et. al. 1997). The bearing currents are drawn in the figure 5. Common mode voltage and current in the motor cables cause radiating emissions, especially with longer motor cables. The cable type changes the emissions significantly, most notably an armored cable can solve most of the radiation problems. (Skibinski et. al., 1999).

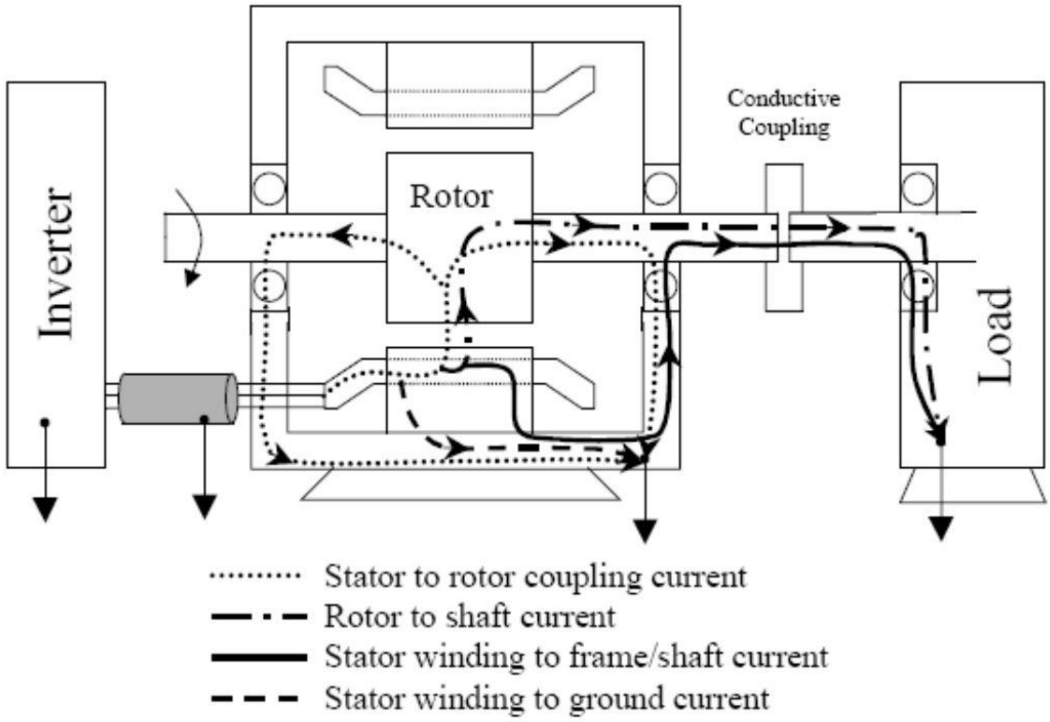

Figure 5. Leakage currents couple from the windings to the frame and rotor and can flow through bearings which causes wear to the bearings (Thakar et. al. 2015).

3.2 Common mode noise in electric grids

Household electrical device safety standards like IEC 60335 (2010) set a limit for leakage current that varies from 0.25 mA to 3.5 mA depending on the type of the device (IEC 60335, 2010). Electrical safety standards for medical devices and other specialized devices have much more stringent limits for the leakage current. Following the current limits set in the safety standards ensure that the user is not in a danger of electrical shock even if the ground connection is lost and the leakage current passes through the user as the user gets in contact with the enclosure.

There are separate safety standards for different industrial applications. IEC 61800-5-1 (2007) applies to adjustable speed electrical power drive systems and it allows a leakage current greater than 3.5 mA with some requirements such as using correct connectors or fixed connections and a stiff connection between the enclosure and the earth to prevent an electrical shock (IEC 61800-5-1, 2007).

To protect the users from dangerous touch voltages, residual current devices (RCD) are often used. RCD measures the sum of the phase currents. The sum is the leakage current to the ground. If the sum exceeds 30 mA the device trips, although the limit increases with frequency, typically up to 300 mA at 1 kHz (ABB, 2013). A typical inverter can easily cause much larger ground current which trips the RCD already in normal use without any ground fault.

The safety standards of many countries require RCD’s in the electrical outlets. Finnish standards, among many others, require all electrical outlets of 32 A or less to be equipped with an RCD and occasionally an RCD is used also in larger outlets (SFS 6000-4-41, 2017). As many properties do not provide a larger electrical outlet than 32 A and thus no outlet without an RCD is available, it is necessary for the converter system to work within the leakage current limits dictated by the RCD. Also, in terre-terre (TT) earthing systems an RCD must be used also in larger outlets to provide electrical safety as line-to-earth faults cannot always be detected with normal circuit breakers.

Common mode noise causes disturbance to other equipment connected to the same AC grid. The CM noise can also break sensitive devices. EMC standards define limits for the emitted common mode noise for most devices and defines the minimum noise levels that the devices must withstand. Some deviation from the standards is often allowed when connected to industrial grids. (IEC 61000-4-16, 2015) (IEC 61000-6-2, 2019)

In the widely used terre-neutral (TN) and TT earthing systems the impedance from the grid phases to the ground is very low as the star points of generators and transformers is connected to the earth. This provides an excellent path for common mode current to flow. Teodorescu et. al. (2007) gives values for the grid impedance from 0.003 Ω in stiff industrial grid to 2.7 Ω in weak consumer grid (Teodorescu et. al., 2007). ANSI/IEEE Standard 142-2007 (2007) recommends keeping grounding resistances under 5 Ω, a typical value for a good ground connection being 2 Ω (ANSI/IEEE Standard 142-2007, 2007).

3.3 Common mode noise in DC link

Common mode voltage in the DC bus can disturb or break devices that are connected to the same DC bus. Some of the common failures are input filter failures due to overvoltage or overcurrent. Common mode noise in the DC link causes also unexpected behavior of connected devices and for example tripping of auxiliary drives.

Some batteries and supercapacitors have a large stray capacitance because of their internal construction. If an inverter is supplied from a battery, a common mode current has a low impedance path to earth through the battery. This becomes a problem especially when the converter is used to connect the battery to a grid. The batteries and supercapacitors also have a lot of measurement, balancing and protection electronics in them, which are susceptible to common mode disturbance.

Most DC supplied auxiliary devices, for example power supplies and smaller inverters used to drive auxiliary devices have internal EMI filters to prevent the device causing noise in the DC bus. These filters usually have Y-capacitors to clamp the common mode noise to the ground. All these Y-capacitors add up in the system and provide a path for the common mode current.

3.4 Coupling to low voltage circuits

Common mode noise in high voltage systems can easily get coupled to the low voltage signal systems such as temperature sensors and low voltage power supplies and control wires. This can cause significant problems in reading the signal, especially if the sensor input is not properly isolated. The coupling can be galvanic, inductive and capacitive. For example, battery or capacitor cell voltage measurements are galvanically connected to the cells, so the common mode noise can disturb the measurement directly. Long signal cables are susceptible to the noise coupled from adjacent high voltage cables.

4 Reducing the leakage current and common mode noise

The difficulty in suppressing the common mode current is mostly due to the inverter acting as a CM voltage source (Dai et. al. 2018). Large series impedance (inductance) must be used in conjunction to capacitance, because using only capacitance to suppress the common mode noise would just make the common mode current larger without reducing the voltage.

A lot of devices use Y-capacitors to reduce CM noise. Y-capacitors are connected between the live parts and earth to provide a path for earth current. X-capacitors are connected between the phases or DC link positive and negative buses to filter DM noise. An example connection of the X-capacitors and the Y-capacitors are shown in figure 6. X-capacitors do not have an effect on CM noise. Small Y-capacitors can be effective in suppressing high frequency noise in both the DC link and the AC phases. However, adding Y-capacitors increases the leakage current by providing a path to the earth. The Y-capacitors and stray capacitances in the DC link are the main paths for the common mode current.

In addition to the current flowing through the capacitors at switching frequency and its harmonics, there is also current flowing through the AC side Y-capacitors at line frequency. It can be calculated that each added nF of capacitance increases the leakage current by 79 µA at 250 V_{AC} and 50 Hz. The current path is through the capacitors to the earth and through the grid impedance back to the line phases.

With a grid inverter or an active front end the obvious solution for the problem would be obstructing the common mode current path with an isolating transformer. However, a traditional 50 Hz transformer is large, heavy and expensive even with relatively low current ratings. The other solution, that also works with motor inverters, is to use a galvanically isolated DC/DC converter between the DC power supply and the inverter's DC input. This method also requires a transformer, but the size of the transformer can be smaller due to the higher frequency used. The problem with these is that they increase the complexity and the price of the system. Also, there are few commercial products with higher power ratings.

Most commercially available passive CM filter solutions use a combination of a common mode inductor and capacitors and some damping resistors. The filters work best at relatively high frequencies, starting from 0.1 MHz, which does little for suppressing the noise at switching frequency. (KEMET, 2017)

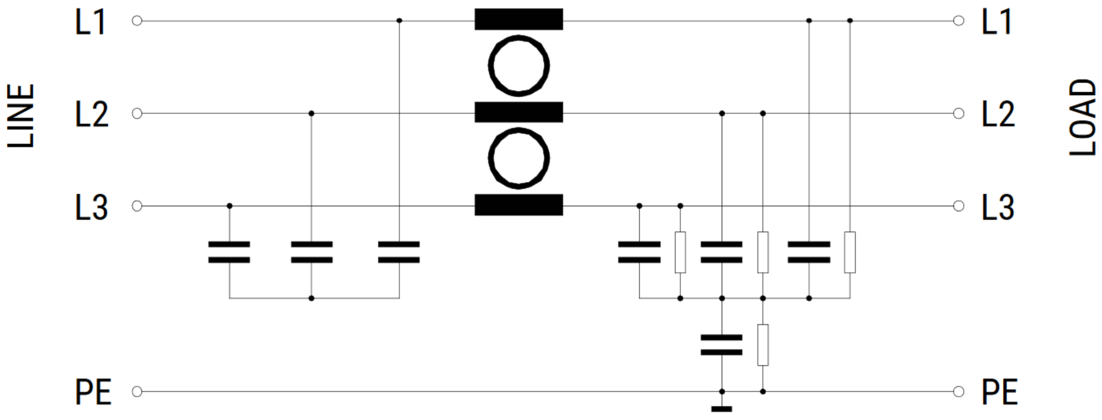

Figure 6. A typical commercially available AC filter circuit. Between the line input and the CM inductor, there are X-capacitors connected between the phases in Y-configuration. Between the CM inductor and the load output there are X-capacitors with a Y-capacitor connected from Y-point to the protective earth (PE). Resistors are connected in parallel to the load side capacitors to adjust the damping ratio. (KEMET, 2017)

5 Bypass capacitors

As previously stated, CM disturbance is not wanted in neither the DC system or the AC system and avoiding or isolating it without using a different inverter topology or an isolating transformer is difficult. The figure 7 shows an alternative path for the leakage current that can be created by adding bypass capacitors between the AC phases and DC-link (Chen et. al., 2016). This way the leakage current does not pass through the AC grid or the devices connected to the DC link. The CM equivalent circuit is shown in figure 8. The proposed solution is very promising, as the leakage current in the AC grid can be greatly reduced. However, the bypass route requires large series capacitors for the bypass circuit to have a significant effect in reducing leakage currents. When combined with large leakage capacitances in the DC link, a new leakage current path is created, as the current passes through the bypass capacitors and DC link capacitances to the earth.

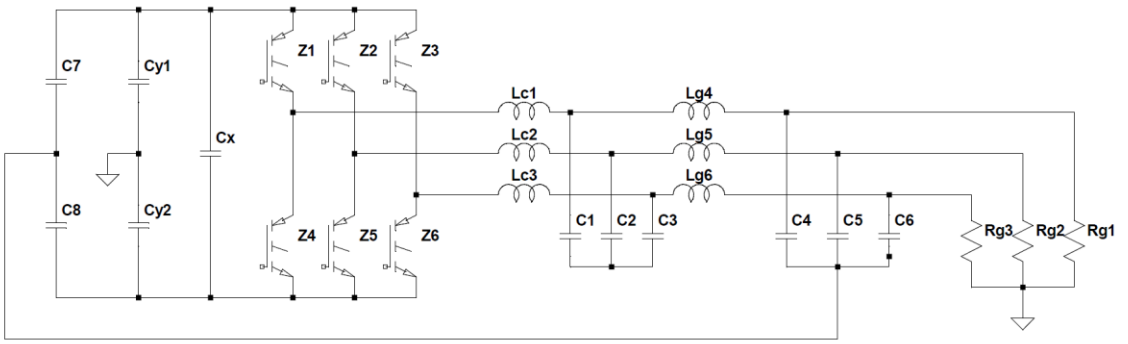

Figure 7. Bypass capacitors C4…C8 connected from the AC phases to the DC-link.

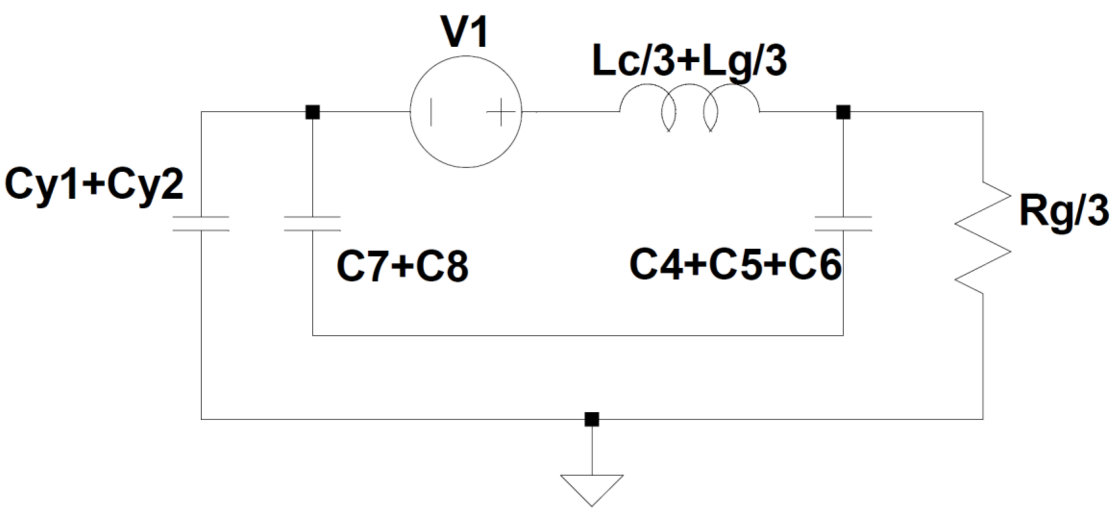

Figure 8. Equivalent circuit with the bypass capacitors.

5.1 Laboratory experiments

The proposed bypass circuit was tested in a laboratory. The filter and converter were connected to a Rohde & Schwarz ENV-4200 line impedance stabilization network (LISN). Conducted emissions ranging from 150 kHz to 30 MHz were measured by Rohde & Schwarz ESR 7 EMI test receiver. Leakage currents at low frequency were estimated by connecting the input to an RCD, where the tripping of the RCD was an indication of too high leakage currents. After some experiments, two CM inductors were added between the filter and the grid input.

After experimenting with various component values the leakage current and conducted emissions were suppressed under the required level, the result is shown in the figure 9. The focus was to find a solution that will provide compatibility with a 30 mA RCD type B. With the bypass circuit, the RCD did not trip like it instantly does when the bypass circuit is not in place. However, when the DC link Y-capacitors were increased from to 330 nF the RCD tripped instantly at the start.

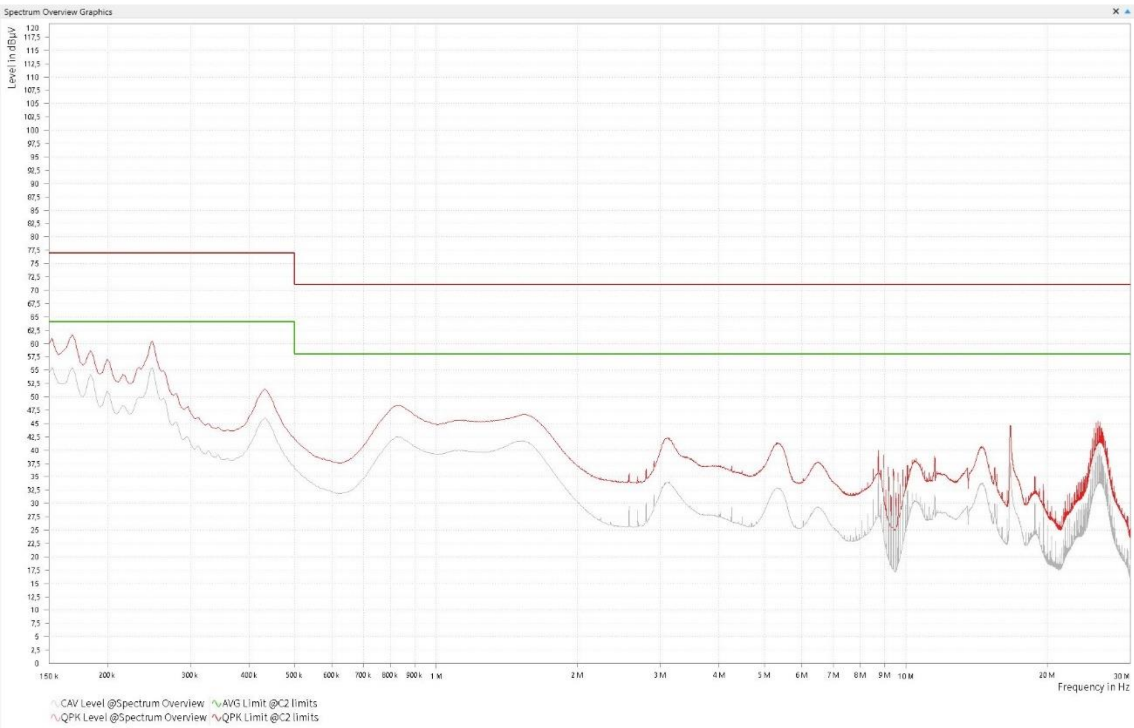

Figure 9. The conducted emissions with bypass circuit, added CM inductors and 33 nF Y-capacitors in the DC link. The emissions are under the required level (green line).

6 Conclusions

There are multiple ways to mitigate CM noise and leakage current in inverter systems and there are tradeoffs in each solution. The easiest and cheapest solution of adding Y-capacitors increase the leakage current and transformers are usually too expensive and large for most applications.

The proposed bypass circuit was very promising as it effectively reduces the leakage current to grid. The circuit was tested in various configurations and a working solution was found. The proposed bypass circuit required large common mode inductors between the grid and the bypass capacitors to ultimately get the conducted emissions under the required level.

However, it was found that the bypass does not help in the situation where there is a battery connected to the DC link, because the setup does not work with even moderate Y-capacitance in the DC link.

There are numerous ways to vary the total filter circuit so that both low and high frequency noise could be mitigated. Further study is certainly needed to find a possible solution that allows the use of larger Y-capacitance in the DC link.

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