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HIGH DENSITY EMI FILTER DESIGN FOR DC-FED MOTOR DRIVES

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ABSTRACT —This paper presents strategies to reduce both differential-mode (DM) and common-mode (CM) noise using a passive filter in a dc-fed motor drive. The paper concentrates on the type of grounding and the components to optimize filter size and performance. Grounding schemes, material comparison between ferrite and nano crystalline cores, and a new integrated filter structure are presented. The integrated structure maximizes the core window area and increases the leakage inductance by integrating both CM and DM inductances onto one core. Small-signal and large-signal experiments validate the structure, showing it to have reduced filter size and good filtering performance when compared with standard filters at both low and high frequencies.

Keywords: Common mode (CM), differential mode(DM), electromagnetic interference (EMI), EMI filter, grounding.

I. INTRODUCTION

Electromagnetic interference (EMI) is one of the major design challenges in motor drive systems, especially in applications where stringent standards need to be followed. EMI noise is usually defined as common-mode (CM) and differentialmode (DM) noise. CM noise is defined as the noise flows between the power circuit and the ground, while DM noise is defined as the current following the same path as the power delivery. Even though EMI standards only restrict the total noise, the noise is usually separated into CM and DM noise with a noise separator [1]. An understanding of the propagation of the noise facilitates filter design, since each filter mode can be considered separately [2].The design of these filters is very complex, and trial-and-error is often needed to achieve a filter that can meet the specifications.

An inadequate filter design can result in poor performance, high cost, and a larger size than required. The last aspect is of utmost importance for high-power-density applications, since EMI filters usually account for as much as 30% of the total converter weight [1The un-predictable behavior at HFs is mainly due to the parasitic of the filter components such as the CM choke or the coupling between components, as well as their interaction with the noise source. These HF effects are usually worse when the size is reduced and the components are close together.

II. EMI STANDARDS

The issues of safety and 'electromagnetic compliance' (EMC) are usually clubbed together in most countries. The CE mark (i.e. European Conformity mark) is one such example. Another is the CCC mark (China Compulsory Certification — required by the People's Republic of China, i.e. mainland China). Generally speaking, designated product categories must carry such marks in their respective market regions, and are then assumed to comply with both the applicable safety and EMC standards. In the United States, though, the issues of safety and EMC are taken up separately.

The "UL mark indicates compliance to product safety standards, whereas "FCC reflects compliance with electromagnetic interference (EMI) standards [3]. But EMI is only one note in the gamut of EMC. In the United States, unlike Europe, the 'susceptibility' aspect of EMC has been left to the dictate of market forces rather than to the force of law. In Japan, the situation is that though EMC specifications exist, they are stated specifically only for IT equipment in addition, the decision to actually affix the relevant mark is completely voluntary.

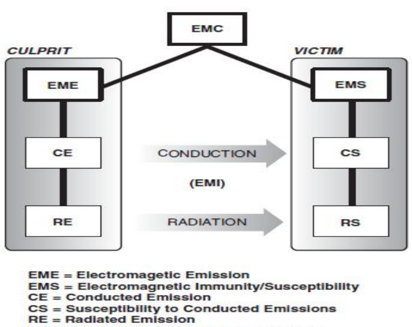

Figure 1Electromagnetic Compliance

III. PROPOSED SYSTEM

A.BASELINE EMI FILTER DESIGN

The system used for study is a commercial motor drive used as a dc-fed inverter connected to a fan load via a 10 m shielded cable. The cable has three phase conductors, one ground conductor, and a shield. The inverter is configured at 2.5 kW, 300 V, and has a switching frequency of 12 kHz. The experimental schematic representation is shown in Fig. 2

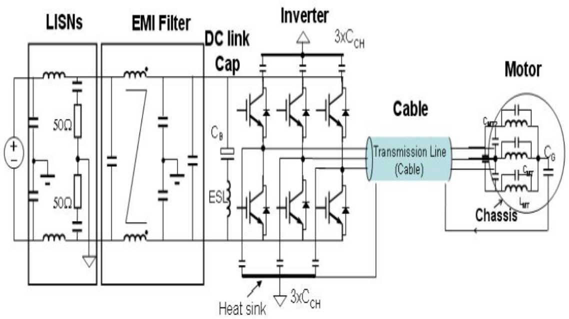

Figure 2 DC-fed motor drive system under study schematics

Depending on the application, different standards might be required, necessitating different experimental setups, noise-level requirements, and frequency ranges [6]. Additionally, there may be some constraints on the maximum CM capacitance due to leakage current safety standards. This paper uses the section of Military Standard 461E that defines the EMI noise limit for frequencies from 10 kHz to 10 MHz.

B.DESIGN PROCEDURE

The typical approach used in was used to design a baseline EMI filter for the experiment shown previously. A basic network filter topology shown in Fig 3, is used to attenuate both CM and DM noise. It is composed of elements that affect CM noise or DM noise only, and others that affect both CM and DM noise [5]. The capacitors Cy which is generally in the nano farad range, in theory attenuates both CM and DM noise; however, its value is very small compared to Cx1 and Cx2 which are in the micro farad range so its effect on the DM noise is almost negligible. Cx between the power lines attenuates the DM noise only. The main component of the filter is LCM which ideally suppresses only the CM noise; nevertheless its leakage inductance between the two windings is used to eliminate the DM noise.

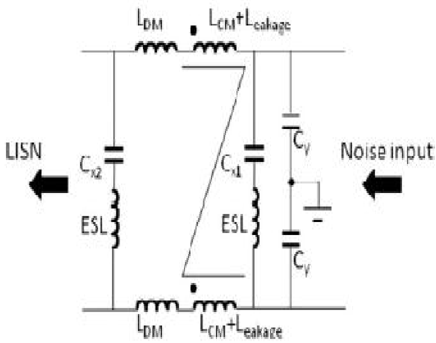

Figure 3commonly used single-stage EMI filter

The equivalent circuit of the filter for each mode is represented for the CM and DM sections, respectively. The network topology for the CM filter is an "LC" type filter while the topology for the DM is a "π" type with two Cx capacitors [7]. The common rule is to obtain the maximum impedance mismatch between the filter and the outside system. The analysis below illustrates the concept with a specific example. Note that the LISN is characterized for each line by a 50 Ω resistor and is approximated by a 25 Ω or 100 Ω resistor for CM and DM correspondingly, using two resistors in parallel or in series.The equivalent CM noise source of the system could be represented by the average collector voltage of the IGBT device in series with equivalent impedance Zg. The choke is usually made of a high-permeability core such as ferrite, and mainly reduces the CM noise; nevertheless, its leakage is used as DM inductance. The leakage can be approximated using (1). The number of turns N and winding angle θ are identified to be the main parameters [7] [8]. Ae is the effective cross-sectional area of the core in centimeters square, and le is the effective length of the core in centimeters. µDM effective is the effective relative permeability of the DM flux.

$$L_{DM} = \mu_{DM\ effective} \frac{0.4\pi N^2 A_e}{l_e \sqrt{[(\theta/360) + (\sin(\theta/2)/\pi)]}} \times 10^{-8}\ \text{(in Henry)}. \qquad (1)$$

These factors are set during the design of the CM choke and cannot be easily changed without an impact on the CM choke size. For some applications, it is appropriate to add small DM inductors in series with the CM choke to increase the total DM inductance, thereby reducing the size of the DM capacitor[11]. The structure presented at the end of this paper makes use of this idea by integrating these two cores into a single core, which has the desirable effect of significantly increasing the DM inductance. The total DM inductance increases threefold when compared to the leakage obtained by the CM choke alone.

The baseline filter is designed by determining the corner frequency required to attenuate LF CM and DM noise, and then determining the values of the filter components [8]. The margin is needed since we are looking at each mode independently and not the total EMI noise. Finally, the theoretical attenuation slope is applied to the most stringent harmonic, and the corner frequency is obtained by (3). In (2) and (3), V stands for the noise signal (voltage) and f stands for corner frequency.

$$(V_{attenuation\_required})_{dB} = (V_{original})_{dB} - (V_{standard})_{dB} + \text{margin} \qquad (2)$$

$$F_{CM\ or\ DM} = \frac{F\ \text{for stringent harmonic}}{10^{(V_{attenuation\ required})_{dB} / (\text{Filters attenuation})_{dB/dec}}} \qquad (3)$$

C.BASIC APPROACH TO CHOOSE FILTER STRUCTURE

The load impedance represented by the LISN is well known. The source impedance for CM noise is the parasitic capacitance in the motor, cable, and the motor drive. For the system under study, the measured parasitic capacitance is around 5nF, most of which is contributed by the motor. Therefore, the CM filter should use topology 2, and DM the filter should use topology 1 from Table I. For the CM filter, the CM capacitance should be much larger than parasitic capacitance so that the impedance mismatch rule is met. For the DM filter, the dc-link capacitor is part of the "π"-type filter in topology "1." The filter is an integration of CM and DM filters that has been tested and proven to provide the best attenuation and size reduction for both CM and DM noise.

TABLE I
Selection of Emi Filter Topologies Based On Noise Source and Load Impedances

Z_{load} / Z_{source}	High	Low
High	1 (C–L–C: Z_{source}, C, L, C, Z_{load})	2 (C–L: Z_{source}, C, L, Z_{load})
Low	3 (L–C: Z_{source}, L, C, Z_{load})	4 (L–C–L: Z_{source}, L, C, L, Z_{load})

The use of a multistage filter to further increase the attenuation and reduce the size of the filter could be useful in certain applications. However, when following the MIL461E standard specifications, this is not true for frequencies starting at 10 kHz, as the benefits of using more stages is very limited in this case and may not lead to a smaller filter size. This is because the required attenuation at LFs is relatively small. According to (3), the corner frequency of the EMI filter is very close to the frequency of the first noise peak regardless of the number of filter stages used.

IV. GROUNDING EFFECT

A.GROUND IMPEDANCE

For the simple "LC" filter shown in Fig. 4, the purpose of the Cy capacitor is to bypass the high-frequency CM noise. However, the high-frequency performance of the 61 capacitors is a function of the grounding impedance. In real applications, the EMI filter is directly built into the MD so the CM ground inductance is small and doesn't affect the high-frequency behavior too much [9]. On the other hand, if the design of the EMI filters occurs after the completion of the drive, appropriate measures need to be applied during the testing. In this research, so the EMI filter had to be interconnected between the MD and LISN.

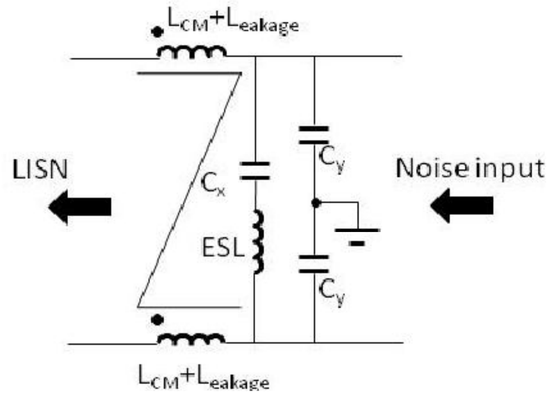

Figure 4 One stage EMI filter "LC" type

For a typical EMI filter PCB layout, the CM capacitors are directly soldered on the copper plane of the filter. The filter ground is then connected to the MD ground as shown in Fig 5. The following experiments show that the length and the type of connection are important.

B.MINIMIZING SIZE AND IMPROVING PERFORMANCE OF EMI FILTER

Now that the baseline design, topology and guidelines for grounding the system have been revised, it is essential to look at the optimization of the EMI filter and especially at the size reduction of the CM choke to achieve a high-density EMI filter. The first part of this section deals with the material technology available that could help to reduce the volume of the filter, such as the nano crystalline core [10]. Later on, the key parameters of the CM choke, such as the leakage, the EPC and the saturation, are calculated, analyzed and pushed to their limits. The multi-layer winding technique is then analyzed and tested with a large signal to prove its integrity and benefit [9]. Moreover, a new structure is proposed to integrate a CM and DM inductor in the same core to increase the total DM inductance and reduce the total volume. Lastly, a small study on capacitors is performed to determine the effect of voltage rating and the benefit of a ceramic capacitor for DM mode for use with large signals.

C.CM CHOKE CORE MATERIAL

The type of material used for the CM choke is very important. It will set the maximum saturation flux density, the number of turns needed to achieve the given CM inductance, and its behavior depending on the temperature. It is usual to use a toroidal ferrite-type material, which is cheap and performs well from low to high frequencies [11]. On the other hand, ferrite material has a small saturation flux density (≈0.4 T) which is dependant on the temperature, as shown in Fig. 5. When the core reaches a temperature of 100 ºC the saturation is almost halved, and achieves 0.24 T instead of the 0.42 T seen at 20 ºC. The change in saturation flux density could lead to the saturation of the core when the temperature increases.

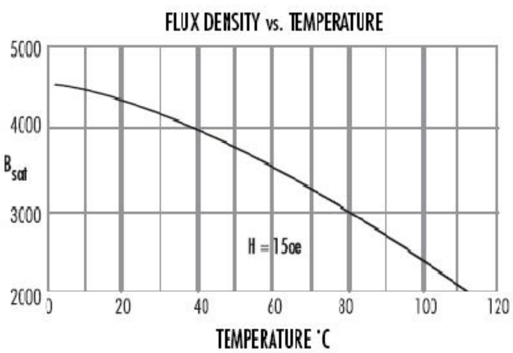

Figure 5 Flux density in function of temperature for ferrite core

The ferrite "J" type material is often used and has a permeability of 5000. Nevertheless, when a really high CM inductance and small size is needed, the ferrite technology is lacking. A better material choice will be the nano crystalline core, which has a initial permeability of >70,000 with a saturation flux density three times higher than ferrite (1.3T) that is almost independent of the temperature [11]. Furthermore, its curie temperature is much higher than ferrite (570ºC compared to 150ºC for ferrite).

The nano-crystalline core therefore seems to be the best suitable technology; however, some precautions need to be taken when designing the other parameters of the filter. First, since the permeability of the nano-crystalline material is much higher, the number of turns required to obtain the same CM inductance is lower than for ferrite [6]. The size of 77 the CM filter is consequently decreased greatly. On the other hand, the leakage inductance provided by the CM choke is reduced. A tradeoff occurs between the reduction of the DM capacitor and the addition of an extra inductor.

Figure 6 CM choke representation using ferrite and nano-crystalline core

VSOFTWARE SIMULATION

SIMULINK/MATLAB Software is used.

A.OPEN LOOP CIRCUIT

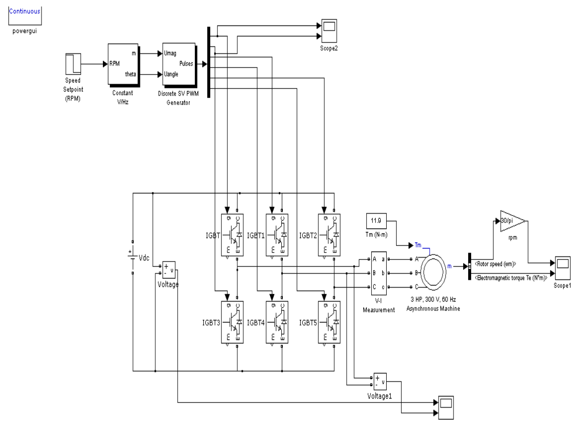

Figure 7 Simulation Diagram

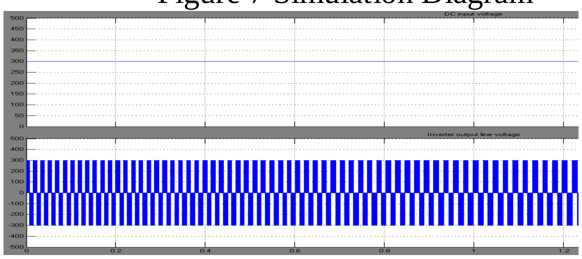

Figure 8Input and output voltage waveform

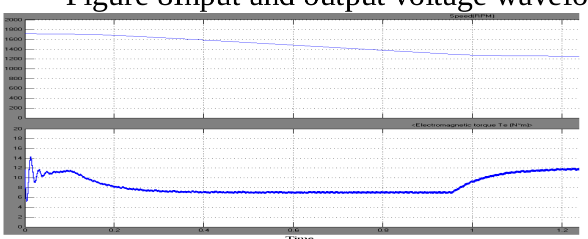

Figure 9 Electromagnetic torque and speed

B. CLOSED LOOP CIRCUIT

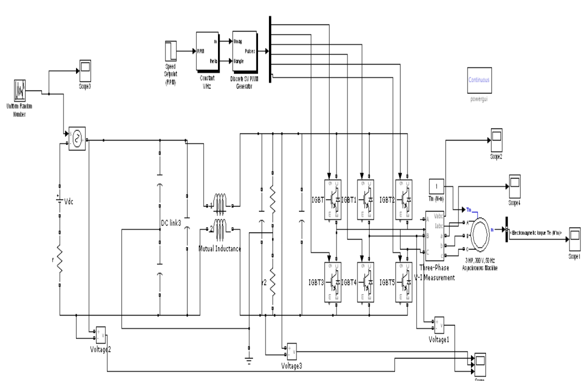

Figure 10 Simulation Diagram

The closed loop circuit is implemented in MATLAB simulink version 7.9. Then its connected to the block where the Volt/Hz control is processed. Then the result is fed to the SVPWM (Space Vector Pulse Width Modulation) block where the pulses are driven to the 6 switches of the inverter bridge after the connected EMI filter in parallel to the inverter. The input voltage is 400V DC and the output is 200V AC. The speed controlof induction motor is done using the uniform random number by setting value from -1 to 1.

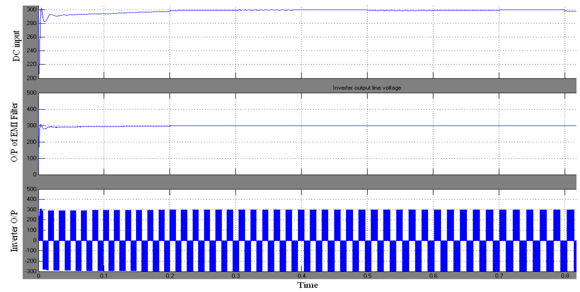

Figure 11 Input and output voltage waveform

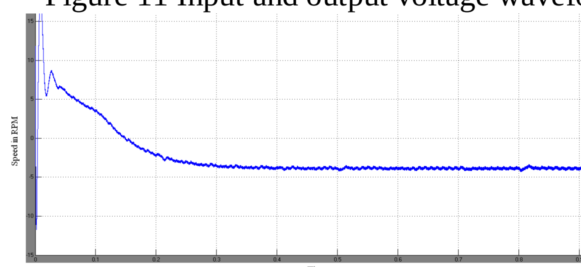

Figure 12 Electromagnetic torque and speed

VI. CONCLUSION

This project has been used as a starting prototype to understand and analyze EMI problems in large signals measurements. Its main contribution is on the grounding scheme guidelines that have been derived from the tremendous number of tests done. Finally, optimization solution have been suggested and studied to achieve a smaller filter size. Consequently, the final size of the filter has been reduced and its performances improved. It has been made possible by the combination of new material technologies and the novel integrated structure proposed.

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