Nanocrystalline cores for common mode current suppression in electrical ship propulsion systems

Wulf Günther, Acal BFi Germany GmbH, Assar-Gabrielsson-Straße 1, D-63128 Dietzenbach, Germany, Wulf.Guenther@acalbfi.com

Zoran Malbasic, Alewijnse Marine Nijmegen B.V., Energieweg 46/g, 6541 CX Nijmegen, Netherlands, z.malbasic@alewijnse.com

Abstract

Electric ship propulsion system is a strong trend to increase efficiency under all operation conditions. In our specific case, however, the system of electric power generation, distribution and propulsion appeared to be non-conformal with all EMC requirements for ships – leakage currents (inclusive capacitive effect) exceeded limits defined by Lloyd’s rules – despite single components fulfilling specifications/requirements.

After analysis of electrical, mechanical and given dimensional requirements and conditions, we developed oval-shaped nanocrystalline cores for common mode suppression, being consistent with mechanical and thermal requirements in this certain environment. This article presents the requirements, the design of cores, and the results in terms of common mode currents.

1. Introduction

Electrical propulsion is being implemented to reduce both fuel use and space, as well as increasing reliability of the electrical power and propulsion systems. The reliability aspect is an essential requirement for a ship with Dynamic Positions (DP) notation like cable (pipe) layer vessel or offshore supplier vessel.

The system of electric power generation, distribution and propulsion is rather complex in terms of EMC because of the special situations in ships compared with common industrial or transportation applications. EMC requirements are defined by IEC 60533 and Lloyd’s rules.

In our specific case, the electrical components fulfilled IEC standards but the entire system appeared to not conform with Lloyd’s rules after finalisation of the electrical system. The challenge was to calculate and introduce supplementary common mode suppression within the given limited space.

2. System and problem description

The cable (pipe) layer vessel with electric propulsion system and with DP AA notation according to Lloyd’s Register Society is equipped with:

- 5 (6) diesel-generator sets, generating power at 690V, 60 (50)Hz (typical around 13MW)
- 2 propulsion azimuth thrusters (typical around 6MW)
- 3 bow thrusters (typical around 4MW)
- 1 stern thruster (typical around 1MW)

A part of the electrical power generation and distribution system and electrical propulsion system is shown in fig 1. The AC system is an IT power network system. The Variable Frequency Drive (VFD) with active rectifier (Active Front End, AFE) is directly connected to 690 VAC Main Switch Board (MSB) and 690 VAC electrical power distribution. Active Front End has some advantages than conventional 12-puls or 24-puls (Diode bridge) VFD systems: reduction of THD level, transformer is not obligated, smaller space, etc. In our case, the active rectifier is realised with IGBT switching elements of typical switching frequency of 1.5kHz.

Design of electrical power generation system and electrical propulsion system in relation to EMC aspect must comply with IEC 60533 and Lloyds rules (6.4 Protection against earth faults).

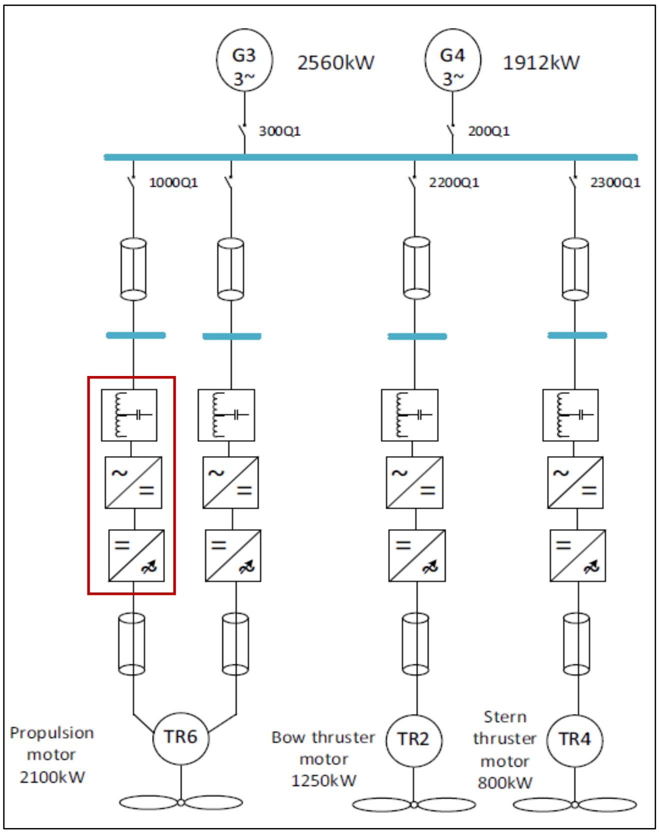

Fig. 1: Part of considered electrical power system.
The components in the red frame are shown in fig. 2.

The following EMC zones are specified according to IEC 60533:

- Deck and bridge zone
- Accommodation zone
- General power distribution zone
- Special power distribution zones

Electrical propulsion systems including VFD are placed in the Special Distribution zone. Here, no maximal level of the radiated and conducted emission is specified like in the other three zones. Therefore the supplier of Active Front End has no obligation to reduce the maximal level of the radiated and conducted emission. In particular, the VFD has no common mode filter as standard component. Usually this situation is specified in contracts as responsibility of the system integrator.

According to Lloyd's rules (6.4 Protection against earth faults), on the other hand, every distribution system having an intentional connection to earth is to be provided with a means to continuously monitor and indicate the current flowing in the earth connection which is limited to $5A_{rms}$. Insulated neutral systems with harmonic distortion of the voltage waveform, which may result in earth fault currents exceeding this level because of capacitive effects, are to be provided with arrangements to isolate the faulty circuit(s).

In the design of electrical installation in a ship, the aspects as cable routing, cable selection and cable segregation are essential in relation to above requirements. In the design of VFD cabinets for the electrical propulsion system, additional components acting as a high frequency earthing system, such as EMC rail, commode mode filter etc. must be implemented in relation to above mentioned requirement. In electrical design, however, it is not possible to cover all risks in relation to common mode phenomena. Therefore during commissioning it is necessary to measure level and frequency spectrum of common mode currents.

The switching process in IGBT generates via DC link (as source) common mode voltage (noise) typically between 20kHz and 1MHz, in our case mainly between 50 and 200kHz. The corresponding current mainly flows through the PE rail and back to the DC link. However, a part of the common mode current is following a parasitic path via the hull back to the generator via MSB back to the drive terminals. Besides the general problem regarding Lloyd's rule, generators suffer from this current which reduces lifetime. All common mode currents mentioned in this article were measured at the generator cables close to the generator (see fig. 1).

During installation of VFD cabinet, additional common mode filters (see fig. 2, it is not standard component in VFD), are implemented at the input of the AFE. They consist of capacitors only and are connected via the star point to the PE rail of the drive cabinet to route the common mode back into the DC link (red path in fig. 2, I_{CMC2} in fig. 3). The lower the impedance path of the filter, the less is flowing to the main distribution (I_{CMC1} in fig. 3). The installation aspects of the filter have high influence on the efficiency of the filter.

In this project, the common mode filter was built into the drive cabinet. It resulted in expected reduction of common mode currents, but it was still higher than $5A_{rms}$ in some operational configurations (see table 1). Additional measures (components) were needed to reduce common mode to acceptable level according to class requirements.

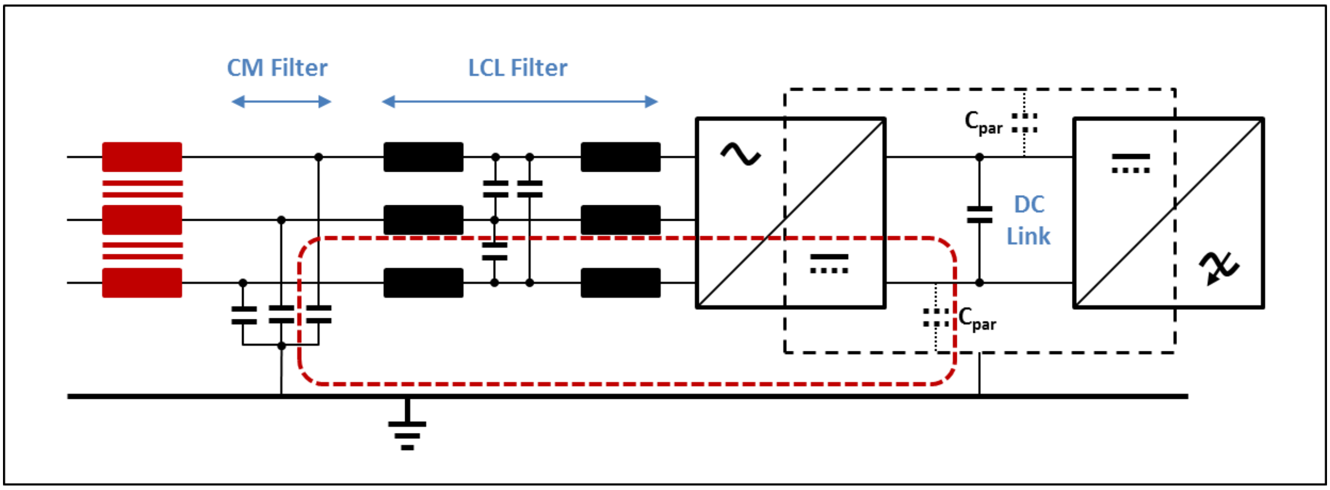

Fig. 2: Detail of fig. 1: Configuration of Active Front End with different filters and desired common mode current (red dash)

3. Technical solution

Implementation of cores around power supply cables between Main Switch board and drive cabinet of Active Front End (AFE) was obviously one of the considered technical solutions. The goal is to increase high frequency impedance (inductive resistance X_L) of the path to MSB, and to keep the common mode currents inside the VFD cabinet. The cores around the cables form a common mode choke with 1 turn per phase. Principally a low pass filter towards the MSB is to be formed by the existing common mode filter and the core.

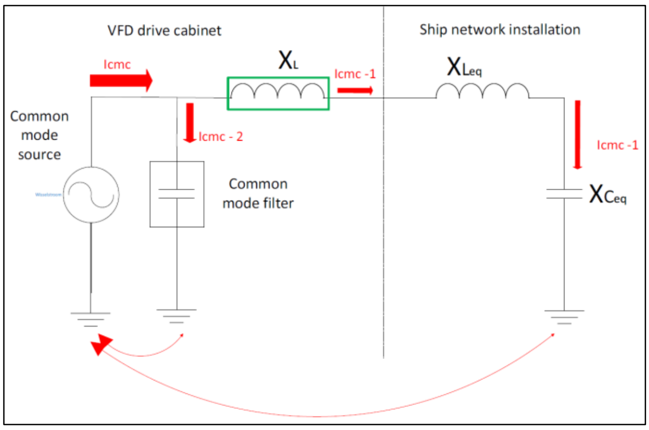

Fig. 3: Principal schema of common mode currents in the system

To select the right cores, analysis of current situation and simulation of different options are essential. A very important aspect of this solution is the measurement of the common mode level and frequency spectrum by different configurations of the electrical plant (selected results in table 1). The measuring plan and definition of measuring points are part of this process. The results have been used as inputs for the technical specifications of cores.

For this specification, the following aspects have been considered:

- Available mechanical space in drive cabinet
- Common mode level and frequency spectrum
- Relation between inductance and frequency L(f)
- Relation between inductance and bias current, $L(I_{DC})$
- Ship electrical power network impedance
- Ship power network resonance frequency

Some parameters of the cores were defined using MathLab Simulink tool. The same model, using test results of actual cores, was used to estimate the influence of the cores on the common mode level. Test results of sample cores included L(f) and $L(I_{DC})$ measurements.

4. Properties of cores

Cores for suppression of these common mode currents must fulfil a couple of requirements:

- Because of limited space (fig. 5), high impedance in small volume, i.e. high permeability
- Due to rather high common mode current, and limited space (resulting in maximum magnetic path length), an upper limit of permeability / saturation induction ratio to avoid saturation
- Due to high flux swing, resulting from the previous considerations, and medium frequencies with higher harmonics: low losses
- High resilience against mechanical influences like vibrations and pressure due to assembling
- Thermal resilience and low ageing

Nanocrystalline cores appeared to be the optimum solution.

Fe-based amorphous cores have higher saturation induction (B_S = 1.56T), but are not appropriate for high impedance in the used frequency range. When impregnated (see below), the permeability decreases to a few 1,000 due to high magnetostriction, and losses become too high. Finally, the high saturation induction can't be used, and impedance is small.

Ferrites, although being the optimum solution for many CMC-applications, provide too low saturation induction (B_S = 0.3-0.45T), leading to huge size in our case which cannot be produced or accommodated in the available space (fig. 5). Moreover, ferrite or even powder cores have been expected not resilient enough against mechanical strain considering the core size.

Powder cores or laminated steel do not provide enough impedance in the given volume.

The core size was designed according to the space and assembling conditions. Finally we used three types of extreme oval cores with total length of about 350-400mm and total widths of 100-170mm, matching the cabinets being already mounted in the ship. The upper permeability to avoid saturation considering this core size was calculated to be around 50,000, which was also an appropriate value for materials permeability under these conditions.

For the cores we used VP500 material of VACUUMSCHMELZE® (B_S = 1.2T, μ_i adjustable between 20.000 and 150.00 for linear B-H-behaviour). Cores have been manufactured by us according to desired initial permeability of about 30,000. Thereafter, they were wrapped with glass fibre tape and impregnated with Epoxy resin to achieve sufficient mechanical and thermal robustness.

After impregnation, initial permeability decreased to about 15.000 - 20.000 due to non-zero magnetostriction, which is not achievable exactly for this big core volume. On the other hand, this certain degradation of linear hysteresis loop results in softer transition into saturation which helps to suppress also non-expected common mode current peaks: as shown in fig. 4, the A_L value is still about 40% of initial value at highest observed common mode currents (around 15A peak) without suppression cores, which is acceptable/within reasonable limits (see below).

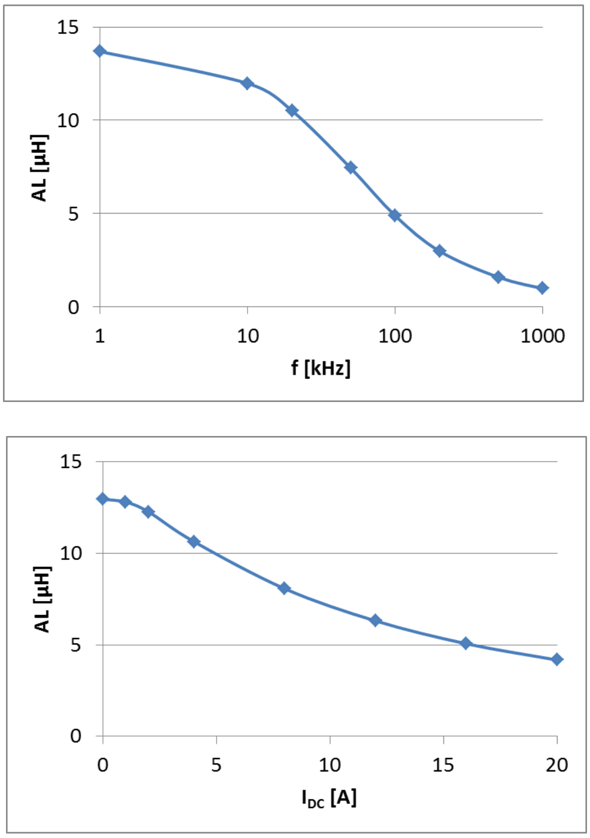

Fig. 4: A_L-Value of a typical core (mean magnetic path length = 810mm, magnetic cross section = 560mm^2, weight 3.4kg) depending on frequency (top) and DC-bias current (bottom, f = 5kHz) showing the saturation behaviour.

5. Results

Cores in different sizes according to spatial conditions have been manufactured and assembled into the drive cabinets (fig. 5). In table 1, values of the common mode currents towards generator before and after the implementation of the cores are shown. The table shows only three specific configurations of the electrical plant. Generally, the analysis of common mode was done for all 44 different configurations.

Fig. 5: two assembled cores in the cabinet

No. of AFE drives online	Without cores		With cores	
	Frequency [kHz]	Max. I_{CM1} [A_{rms}]	Frequency [kHz]	Max. I_{CM1} [A_{rms}]
0	60 - 180	0.035	0 - 212	0.315
2	70 - 100	6.2	0 - 212	2.94
4	80 - 110	8.2	0 - 212	2.84
6	80 - 110	9.2	0 - 212	2.26

Table 1: Measurement results before and after implementation of the cores. Frequency indicates the range with significant excitation; common mode current has been measured in this range.

After implementing the cores, the maximum level of common mode measured in one specific configuration is 3.1 A_{rms}. All common mode values, which were measured during the last measuring campaign, satisfy class requirements for all 44 different configurations.

6. Conclusion

Implementation of Active Front End in Electrical Propulsion system requires more attention in electrical design and commissioning process in relation to EMC requirements. Therefore, electrical cable installation, measuring of common mode levels (including frequency spectrum), power network analysis and, if possible, simulation of the entire system is necessary before commissioning.

Supplementary implementation of cores for suppression of common mode currents is possible and has been successfully demonstrated. It is, however, a complex process considering different operational configurations and limited space.