Performance Optimization Aspects of Common Mode Chokes

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Abstract—**Optimization aspects of common mode chokes are presented. These are based on a behavioural model for common mode chokes and its sensitivity study. Results are used to show the influence of the designable parameters on the final performance of the choke placed in a circuit.**

I. INTRODUCTION

A proper filtering of the frequency converter is a key aspect in the management of the EMI in the overall motor drives. Frequency converter (FC) components generate a high level of electromagnetic interferences on the power lines, motor cables and via radiated electromagnetic field. It is necessary to provide a proper filtering of the main supply and cables to reduce their radiation which constitutes the main source of interferences. Traditionally filters are designed after the construction of the FC. The EMI emission phenomenon is complex, and in the case of passive filtering [1], chokes are designed in a "cut and try" process with significant issues as size, cost and weight [2], [3] .To avoid the construction of several prototypes, often oversized, designers need an analytical method to predict performances of filters. In this paper some sensitivity aspects of designable parameters of the common choke are presented.

In the following section, the designable parameters and the behavioural model used as a basis for the sensitivity analysis is presented, this is followed by focuses on the sensitivity analysis. In the last section theoretical results are compared to measurements. A toroid core with 2 windings as illustrated in Figure 1 is considered for the studies.

II. BEHAVIOURAL MODEL AND DESIGNABLE PARAMETERS

In this section the designable parameters of the common mode choke (CMC) are identified. A behavioural model is used to determine the influence of these parameters in the 'in-situ' performances of the CMC under consideration.

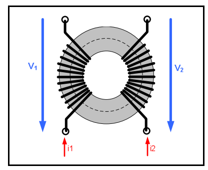

Figure 1: Typical CMC under consideration

A. Designable parameters and modelling

The designable parameters of the common mode choke are presented in table 1. The impedances of the CMC can be modelled via several formulae available in the literature. The modelling of the turn to turn capacitance and the inter-winding capacitance is detailed in [4], [5].

The value of the CM impedance is strongly related to the value of the permeability of the core. As detailed in [6] the ferrite core introduces frequency variable impedance in the circuit. The core will not affect the lower frequency operating signals but does block the conduction of EMI. The permeability of a ferrite is a complex parameter consisting of a real part and an imaginary part. The real component represents the reactive component and the imaginary part represents the losses. The CM impedance of a CMC can be represented by the series equivalent circuit of a ferrite suppression core: the loss free inductor (L_s) is in series with the equivalent loss resistor (R_s). The flowing equation relates the series impedance and the complex permeability.

$$Z = R_s + j.w.L_s = j.w.L_o(\mu_s' - j.\mu_s'')$$

where

$$L_o = \mu_0 . \frac{A_e}{l_e} . N^2$$

N: Number of turns

A_e and l_e: Respectively the effective area and length of the current under consideration

This impedance is usually measured and an approach by polynomial approximation. In [7] a model is proposed of frequency dispersion of complex permeability in ferrites. Figure 2 presents the simulated CM impedance of a sintered MnZn ferrite core.

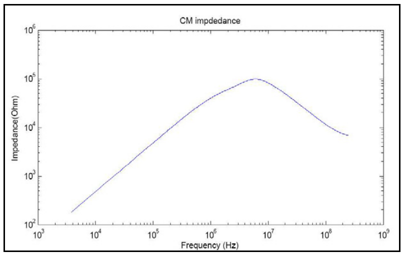

Figure 2: Simulated complex CM impedance of a MnZn sintered core (Dimension: 25*10*5 mm, N=20)

The value of the DM impedance is related to leakage inductances, and hence to spaces within the wiring system. For a more accurate estimation, formulae are available in literature [8].

An overview of the topology of the model in consideration is presented in Figure 3.

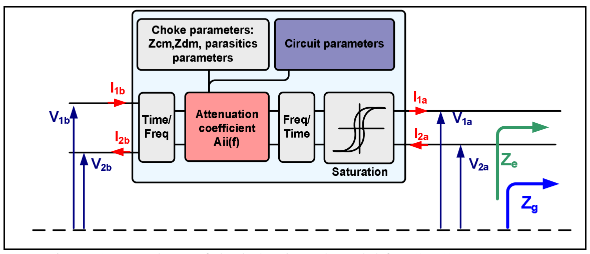

Figure 3: Topology of the behavioural model for CMC

TABLE 1
DESIGNABLE PARAMETERS FOR COMMON MODE CHOKE

Impedances of the CMC	Designable parameters
Z_{cm}	Material (complex permeability) Dimension of the choke Number of turns Effective length
Z_{dm}	Number of turns Dimensions of the choke Angle of leakage inductance
Intra Winding Capacitance And Turn to Turn Capacitance	Number of turns Dimensions of the choke Wire dimensions and materials(isolation and diameter) Length of turns

B. Topology of the behavioural model

The behavioural model for common mode chokes meets some major requirements: the frequency dependence of the parameters is taken into account to provide accurate results even at higher frequencies.

It is also assumed that designers do not have access to a prototype and to experimental values. However other electrical information like voltages, currents and other parameters provided by the manufacturer or common knowledge available in literature is provided to the designer. Small values of parasitics can be integrated in the simulation. The final model is a 'black box' for designers. It requires several tested parameters as inputs and provides output needed in graphs and tables. The software Matlab and Simulink have been chosen to develop the presented study.

The topology of the model is based on a translation of the common choke in its electrical equivalent circuit 'in situ'. Impedances included are: common mode and differential mode impedances, parasitics capacitances (turn to turn and intra-windings). The impedances seen from the future place of the choke between the two phases and between one phase and the ground are also included in the network. The designer will have to provide values of currents and voltages, measured or simulated, where the CMC will be placed later.

These values in addition of the characteristics of the common mode choke allow evaluation of performances of the CMC with 4 attenuation coefficients. Figure 4 presents the electrical setups in the case of a frequency converter with voltage regulation. The equivalent circuit of the common mode choke is represented: Z3, Z4 and Z5 are the parasitic capacitances discussed before. Z1 and Z2 are a combination of the common mode impedance Z_{cm} and the differential mode impedance Z_{dm}:

$$Z_1 = Z_{cm} + Z_{dm}$$

$$Z_2 = Z_{cm} - Z_{dm}$$

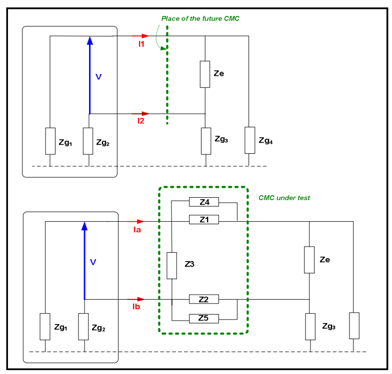

Figure 4: Electrical setups in case of a voltage regulation of the frequency controller

Currents i_1 and i_2 are the current initially flowing at the output of the frequency converter. Currents i_a and i_b represent the current flowing at the output of the frequency converter when the common mode choke is placed in the circuit. These currents can be predicted from the initial setup and the known impedances of the common mode choke with the following relations. The current i_a and i_b are predicted via four attenuation coefficient parameters depending on the common mode choke and the circuit configuration. The new common mode current flowing in the circuit can be expressed function of the former current flowing in the circuit i_1 and i_2:

$$Zeq_1 = \frac{Z_1 * Z_4}{Z_1 + Z_4}$$
$$Zeq_2 = \frac{Z_2 * Z_5}{Z_2 + Z_5}$$
$$Pg_4 = \frac{Zg_4}{Zg_4 + Zg_3 + Z_e}$$
$$Pg_3 = \frac{Zg_3}{Zg_4 + Zg_3 + Z_e}$$
$$a = Zeq_1.(1 + \frac{Zg_1}{Z_3}) + Z_e.P_a + Zeq_2.\frac{Zg_1}{Z_3}$$
$$b = -Zeq_2.(1 + \frac{Zg_1}{Z_3}) + Z_e.P_b + Zeq_1.\frac{Zg_2}{Z_3}$$
$$P_b = \frac{Zg_3 + \frac{Zg_2}{Z_3}(Zg_3 + Zg_4)}{Zg_4 + Zg_3 + Zg_4}$$
$$P_a = \frac{Zg_4 + \frac{Zg_1}{Z_3}(Zg_3 + Zg_4)}{Zg_4 + Zg_3 + Zg_4}$$
$$A_{11} = -Zg_1$$
$$A_{12} = Zg_2$$
$$A_{21} = Z_e.P_4$$
$$A_{22} = -Z_e.P_3$$
$$B_{11} = -Zg_1$$
$$B_{12} = Zg_2$$
$$B_{21} = a$$
$$B_{22} = -b$$
$$\begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}\begin{pmatrix} i_a \\ i_b \end{pmatrix} = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}\begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$$
$$\begin{pmatrix} i_a \\ i_b \end{pmatrix} = \frac{1}{\det(A)}\begin{pmatrix} -A_{12}B_{21} + A_{22}B_{11} & A_{22}B_{12} - A_{12}B_{22} \\ -A_{21}B_{11} + A_{11}B_{21} & -A_{21}B_{12} + B_{22}A_{11} \end{pmatrix}\begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$$
$$\det(A) = A_{22}A_{11} - A_{12}A_{21}$$

C. *Sensitivity aspect*

Sensitivity studies provide additional insight into the behaviour of the choke by understanding of how variations of parameters, for instance of elements values, influence the final performance [9], [10].

Sensitivity studies will be performed at two levels. The local approach is based on a first order approximation and is not suitable for large variations. The local approach will be mainly used to evaluate for instance the effect of the error related to modelling or measurements of impedances. The normalized simplest sensitivity will be used; it is the derivative function F with respect to any parameter h:

$$S_h^f = \frac{\partial \ln F}{\partial \ln h} = \frac{h}{F}\frac{\partial F}{\partial h}$$

When a large change occurs in the system, large change sensitivity will be considered. This study is especially relevant when the designer wants to try designs drastically different from each other (change of material, size of choke or number of turns). The large change sensitivity is based on a modification of the original system (the attenuation coefficients) by a low rank matrix. Assuming that *m* elements are subject to change, an (m+1)*(m+1) matrix, by means of which all the information can be obtained, is formed.

III. RESULTS

A. *Impedances*

Measurements have been performed on a common mode choke presented in Figure 5. Its characteristics have been measured with an Impedance/Gain-Phase Analyser (HP 4194A) between 100Hz and 40 MHz. Results are presented in Figure 6.

The core is made of iron powder material (Fe). It may be used as pure inductor up to approximately 200 kHz. The resistive losses dominate thereafter up to approximately 3 MHz as presented in Figure 6. The core is no longer effective in the frequency range above approximately 10 MHz.

The core is bonded with a copper wire with a diameter of 0.99 mm. Its insulation in polyurethane has a thickness of 12 m. The rated current is 5A and nominal voltage 250Vac.

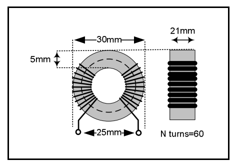

Figure 5: CMC under test

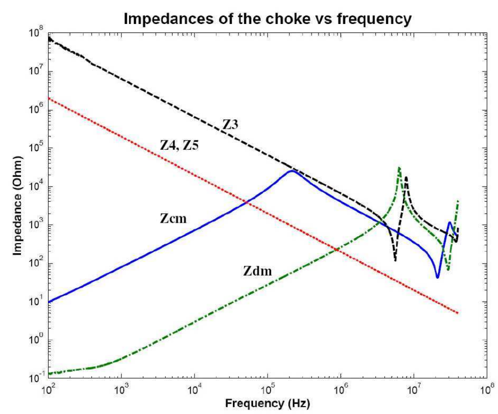

Figure 6: Impedances of the choke vs. frequency

TABLE 2: PARAMETERS OF THE CHOKE UNDER TEST

Impedances	Theoretical values	Practical value
CMC inductance	10mH	9.9mH
Leakage inductance	41μH	40uH
Cap. inter windings	Nan	16pF
Cap. Turn to turn	71pF	49pF

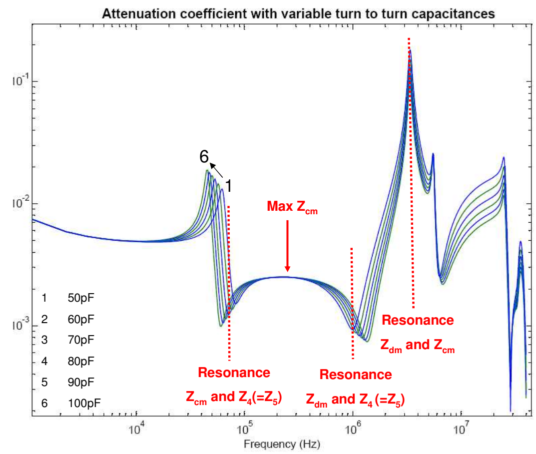

Figure 7: Attenuation coefficient with variable turn to turn capacitances

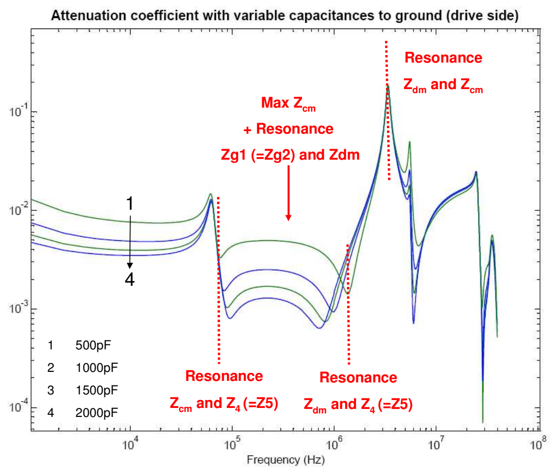

Figure 8: Attenuation coefficient with variable capacitances to ground

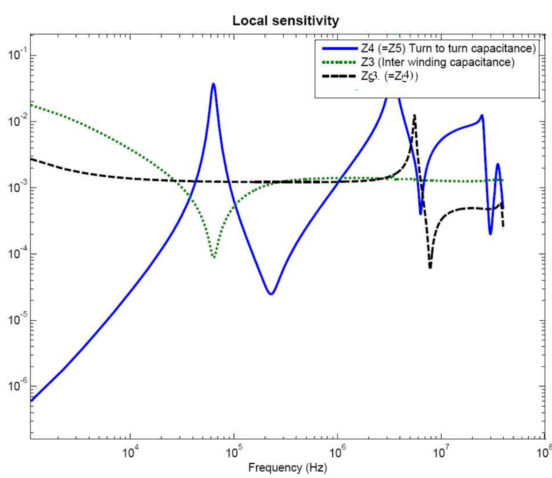

Figure 9: Local sensitivity

The figure 7 and 8 present the attenuation coefficients with respectively a variable turn to turn capacitance and a variable capacitance to ground. The behaviour of these coefficients is mainly driven by three resonances between the three impedances: common mode impedance, turn to turn impedances and differential mode impedances. While the increasing value of the turn to turn is widening the area of maximum attenuation in the figure 7, the increasing value of capacitance to ground is affecting the level of attenuation itself in figure 8.

The local sensitivity presented in figure 9 is helpful in predicting where the sensitivity is the highest and can be for instance used to design a filter whose attenuation coefficients are more independent of environment of the filter.

A toolbox has been developed in Simulink. The designer provides as input the value of the designable parameters detailed in the table 1 and get as output the sensitivity curve as well as the attenuation coefficient.

Some work is carried on large change sensitivity to allow the designer to test designs presenting designable parameters with a wider range of values (different size of chokes, material…)

CONCLUSION

Optimization aspects of common mode chokes are presented. There are based on a behavioural model for common mode chokes which model accurately the impedances of the choke using its designable parameters. Sensitivity studies are carried on. Results are used to evaluate the influence of the designable parameters on the final performance of the choke placed in a circuit.

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