Towards a First Time Right Design of the Common Mode Choke

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Abstract

There is a need for an analytical model of the EMI filter relating its designable parameters to its final performances in the circuit. The final goal of the model presented here is to support a first time right design of the common mode choke. A new equivalent circuit of the component is proposed where impedances are related to the designable parameters of the choke. This equivalent circuit is inserted in a global model of the output of the converter where the actual performances of the choke can be evaluated via a modification factor of the common mode current. All models introduced are validated with measurements. Sensitivities and deviation studies give additional insight on the behavior of the filter once it is placed in the practical system. The new common mode current flowing in the circuit after the insertion of the choke can then be evaluated without a 'cut and try' process.

1. Introduction

Common mode chokes (CMC) are a cornerstone component of the electromagnetic (EMI) filter. They are essential in power systems where switching devices contribute to a noise spectrum from a few kHz to several decades of MHz. Common mode currents are frequently referred as 'antenna-mode' currents and also are the predominant mechanism for producing radiated electric field in practical products and industrial electromagnetic environments [1, 2]. Common mode chokes are for instance used to eliminate part of the common mode current flowing in the cables of motor drive in order to comply to regulatory requirement and protect the drive from damages and overloads [3]. They are typically designed in a "cut and try" process with significant issues as size, cost and weight [4] .To avoid the construction of several prototypes, often oversized, designers need an analytical method to predict performances of filters linking the designable parameters of the choke to its performances in-situ.

In the first section of this paper a new electrical model of the common mode choke is presented. It links the designable parameters of the choke to the impedances of the model. A modification factor of the current is defined to characterized the modification of the common mode current due to the insertion of the common mode choke in the practical product. The validation of this modification factor by measurements is addressed. In the second section sensitivities and the deviations aspects of the modification factor are presented. They allowed an accurate optimization of the final performances of the EMI filter in the practical product.

2. Common mode choke modification factor

The main purpose of a CM choke is not for energy storage but it is for a transformation of this energy to heat and therefore to block the emission noise (electromagnetic interferences) while the lower frequency range of the signals are not affected. Figure 1 presents an equivalent electrical model of the common mode choke. Z_{cm} is the common mode impedance faced by the common mode current. L_{dm} is the leakage inductance faced by the differential mode current and C_{tt} and C_{int} are the turn to turn capacitance and the inter-winding capacitance respectively, also associated with the differential mode current. Figure 2 presents the equivalent common mode circuit of the output of a converter. Both models are detailed and validated in [5]. The TABLE 1 links the designable parameters of the common mode choke to the impedances of its equivalent electrical circuit. These designable parameters are the parameters that can be modified by the designer and will be the inputs of the model of the common mode choke. Each of the listed impedance can be calculated using the related designable parameters, formula can be found in [6-8]. The final performances of the common mode choke in situ are evaluated via a modification factor defines as follow:

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$$\mathrm{Att} = \frac{\mathrm{I_{cm2}}}{\mathrm{I_{cm1}}} = \frac{\mathrm{Z_a}}{\mathrm{Z_a} + \mathrm{Z_{cm}}} \quad (1)$$

Where I_{cm1} refers to the common mode initially flowing at the output of the converter, I_{cm2} is the common mode current flowing at the output of the converter after the introduction of the circuit. Z_a is the common mode impedance of the load and its feeder measured (or modeled) at the output of the converter, so that all parasitic to ground upstream of the converter are included . Z_{cm} is the common mode impedance of the common mode choke. This modification factor represent the factor by which the initial current I_{cm1} should be multiply to obtain the common mode current I_{cm2} once the choke is introduced in the circuit. If the factor is above 1, the current is amplified. If this factor is below 1, the current is attenuated. The measured impedances Z_a and Z_{cm} are presented in Figure 3. Two common mode chokes have been used: the CMC 1 has 15 turns and the CMC 2 has 30 turns. They are both build with the same toroid made of MnZn ferrite with the following dimensions: 21*5mm, 30mm of diameter. Their respective modification factors are both modeled and measured and can be found in Figure 4and Figure 5.

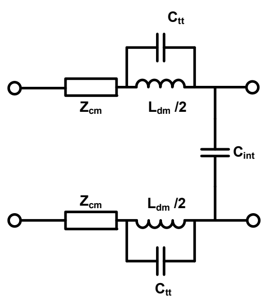

Figure 1: Equivalent electrical model of the CMC

TABLE 1 DESIGNABLE PARAMETERS OF THE COMMON MODE CHOKE

Impedance	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 the winding free section
Inter and Intra Winding capacitance	Number of turns Dimensions of the choke

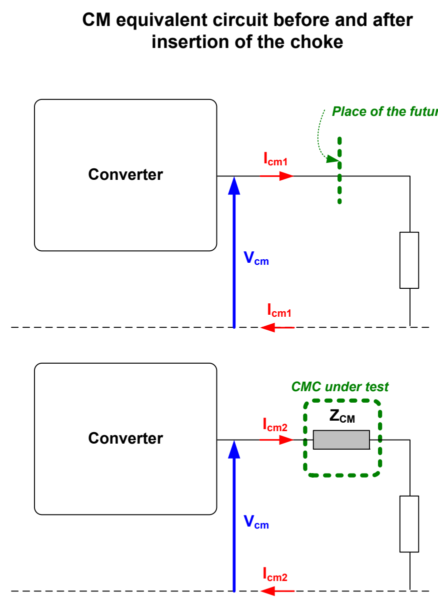

Figure 2: Equivalent common mode circuit of the output of the converter

2. Deviation and sensitivity aspects

Sensitivity studies provide additional insight into the behavior of the choke by understanding of how variations of parameters, for instance values of elements, influence the final performance. These studies are needed to take into account design variations.

Sensitivity studies can 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 for instance is mainly used to evaluate the effect of the error related to modeling or measurements of impedance. The normalized simplest sensitivity is used; it is the derivative function F with respect to any parameter h:

$$S_h^f = \frac{\partial \ln F}{\partial \ln h} = \frac{h}{F}\frac{\partial F}{\partial h} \quad (2)$$

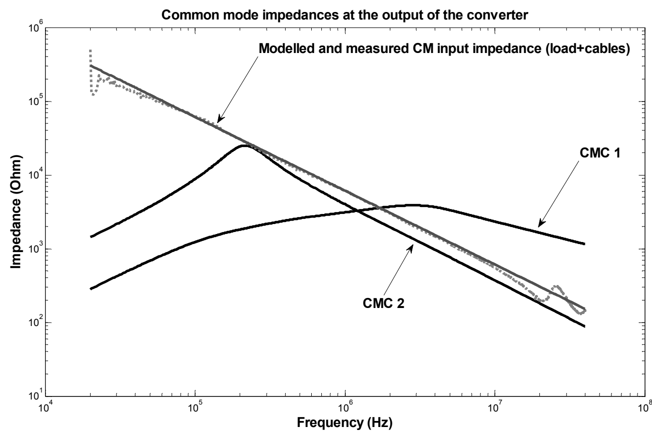

Figure 3: Common mode impedances at the output of the converter

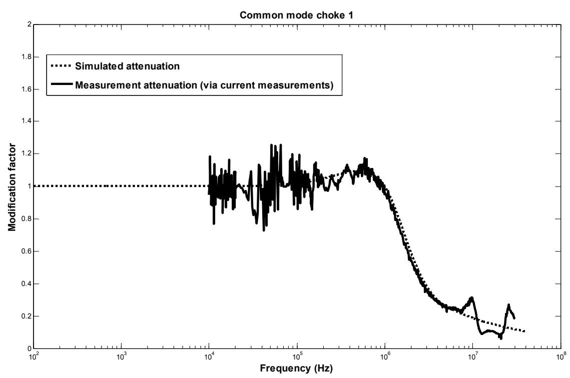

Figure 4: Measured and modeled modification factors for the common mode choke 1 (current measurements)

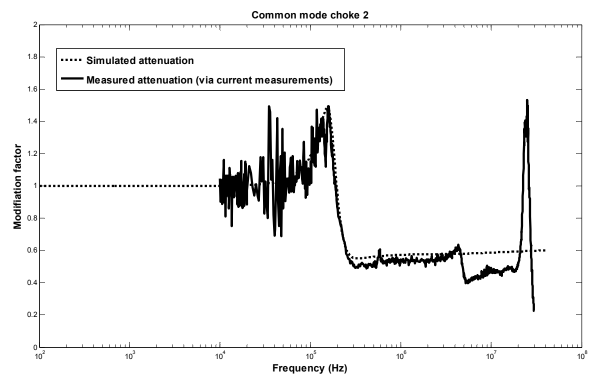

Figure 5: Measured and modeled modification factors for the common mode choke 1 (current measurements)

The local sensitivity of the common mode impedance S_Zcm and the local sensitivity of the impedance to ground S_Za are expressed as:

$$S\_Zcm = \frac{Za}{Att_{cm}} * \frac{\partial Att_{cm}}{\partial Za} = \frac{Z_{cm}}{(Z_a + Z_{cm})}$$
$$S\_Za = \frac{Z_{cm}}{Att_{cm}} * \frac{\partial Att_{cm}}{\partial Za} = -\frac{Z_{cm}}{(Z_a + Z_{cm})} \quad (3)$$

Figure 6 presents the curves of local sensitivity of the common mode impedance and the impedance to ground for the common choke 1 and 2 presented in the previous section. The common mode modification factor, with a impedance to ground chosen between 0.5nF and 2nF, presents a peak of sensitivity at the resonance between 20 kHz and 200 kHz. A slight modification of the value of the common mode impedance and/or the impedance to ground will have as predominant effect to shift the resonance frequency of the attenuation and to change its amplitude. The amplitude can be multiplied up to 10 times at the resonant frequency. This graph gives insight to engineers on how stable is the design of a particular choke around the frequency of resonance. It can be critical if this resonance is close by a peak of common mode current in the initial set-up without choke.

Deviation studies are used to evaluate the consequences of an error in the initial designable parameters and/or measurements on the final modification factor . A percentage of error is used to evaluate two first upper and lower limits of the modification factors. Figure 7 illustrates the upper and lower limits of the modification factor for a tolerance set between 10 and 30 percent. The final result is an additional tool allowing engineers to evaluate a best and a worst case scenario.

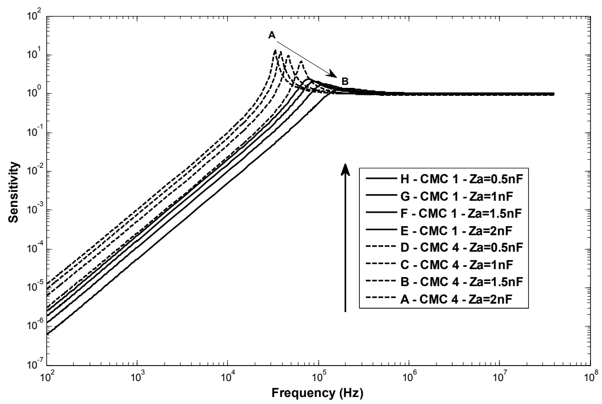

Figure 6: Local sensitivity of the impedance related to the common mode current attenuation

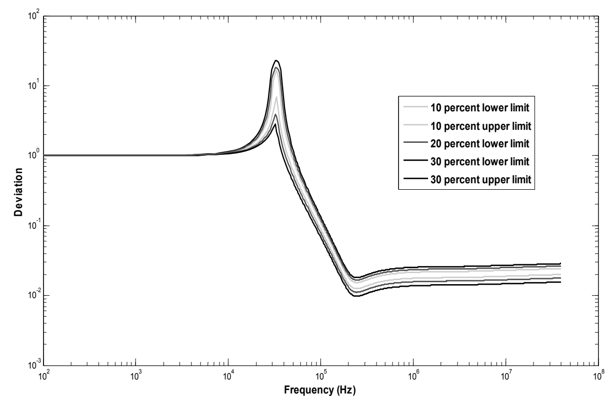

Figure 7: Upper and lower limits of the modification factor (Incertitude from 10 to 30 percent)

3. Conclusion

Electromagnetic interferences filters and especially its common mode choke are a cornerstone in the management of the emission noise in power system. A new equivalent circuit of the common mode choke has been introduced and inserted in a global model of the output of a converter . This global structure links the designable parameters to the final performances of the common mode choke in the actual system. All models have been validated by measurements. The output of the model is a modification factor of the common mode current allowing the prediction of the common mode current flowing in the circuit after the insertion of the choke. Sensitivities and deviation aspects of the design gives further insights on the behavior of the filter once it is placed in the actual system. The final goal of this model is to support designers in a first time right design of the electromagnetic filter without a 'cut and try' process.

4. References

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