EMI Filter design using high frequency models of the passive components

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EMI Filter design using high frequency model of the coupled inductors

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Abstract

The aim of this paper is to propose a new design method of EMI filters for the power converters using high frequency modeling. It is well known that the power converters are main source of conducted disturbances which are the common mode and differential mode. Often, the solution used to reduce conducted emissions consists to use the EMI filters. The design of these filters is very difficult because it requires complete mastery of the design process.

In this paper, a high frequency modeling method of the magnetic part of EMI filter is used. Coupled inductors and capacitor models have been introduced into complete EMI filters and simulations have been compared to a prototype for testing its reliability. A procedure for designing EMI filters will be presented in this study. It is based on the analysis of conducted EMI induce by the DC-DC converter.

1 Introduction

The static converters are very problematic for electromagnetic compatibility (EMC). Indeed, each power converter generates a lot of high frequency interferences causing a malfunction of the electronic systems [1]. The main solution to reduce these conducted emissions consists to use the EMI filters. These filters are made from coupled inductors combined with capacitors. The passive components have a strong impact on filter efficiency [2]. Parasitic elements of these components such as equivalent series inductor (ESL) of the capacitors and equivalent parallel capacitances (EPC) of the coupled inductors have a negative influence on the EMI filter performances [2]. In order to design and optimized filter characteristics by simulation, a high frequency models, including parasitic elements of the passive components, must be used.

2 EMI Filter Design

In order to reduce the conducted emissions induced by the DC-DC converter, common mode and differential mode filters are used as shown in Fig. 1. The common mode filter uses a coupled inductors L_{CM} and two capacitors C_Y connected to the ground. However, the differential mode filter uses two separate inductors L_{DM} and two capacitors C_X. The measurement method, according to EMC standard, is based on the utilization of an LISN in frequency band varying from 0.15 MHz to 30MHz, according to CISPR11 standard [4]. It is well known that the utilization of the Line Impedance Stabilizing Network (LISN) does not allow to separate the common mode and differential mode disturbances.

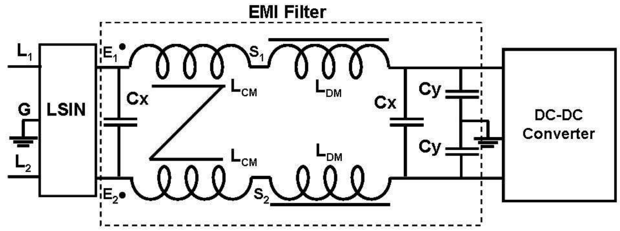

Fig. 1. EMI filter structure

There are different methods which allow to separate these modes which are presented in [5]. In this study, we used the current probes (FCC – FC52): 10 kHz to 500 MHz to measure the common mode current I_{CM} and the differential mode current I_{DM} at the output side of the LISN as shown in Fig. 2.

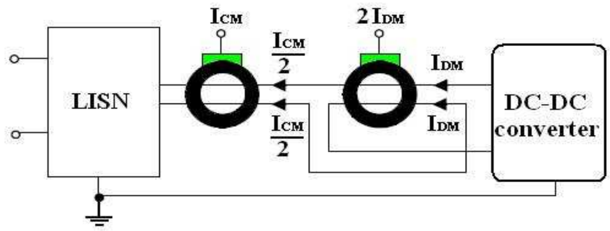

Fig. 2. Measurement method of the common mode and differential mode currents

A. Common Mode Filter

The equivalent circuit of the common mode filter with LISN is shown in Fig. 3.The common mode emissions, measured (without EMI filter) using current probes, allow to calculate the voltage under the resistor of the LISN using the following relation $V_{CM} = 25\Omega * I_{CM}$. The result of the calculation shows that the level of conducted emissions is over the EMC standard limit up to 6 MHz (Fig. 4).

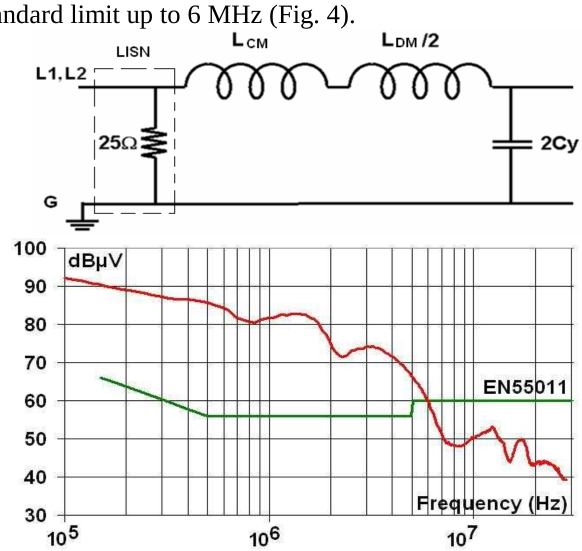

Fig. 3. Equivalent circuit of the common mode filter

Fig. 4. Common mode noise without filter (Voltage under 25Ω)

In order to meet the EMC standard, the filter attenuation required is equal to the difference between the measured level of disturbance and the limit of the EMC standard (Fig. 5).

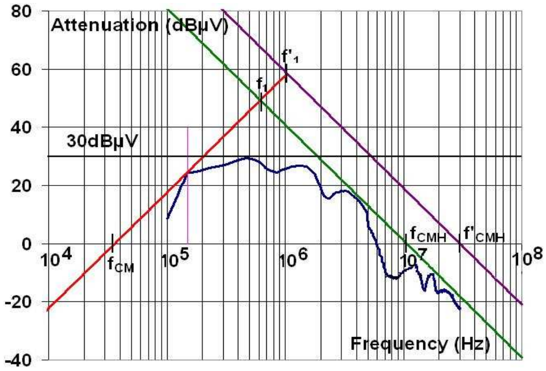

Fig. 5. Common mode attenuation requirement

By drawing a line with slope 40dB/dec tangent to the attenuation curve, we obtain successively the cut-off frequencies where the tangent cuts the frequencies axis. The elements "L_{CM} and C_Y" are determined from the frequency cut-off "f_{CM}" as shown in Fig. 5. In the case of common mode, and in order to limit the leakage currents to ground, the chosen value of capacitor C_Y is 4.7nF. Thus, from this value and the cut-off frequency, we calculate the value of the common mode inductor L_{CM} using the following relation:

$$L_{CM} = (\frac{1}{2\pi . f_{CM}})^2 . \frac{1}{2.C_Y} \qquad (1)$$

Using the results of Fig. 5, we can determine the first cut-off frequency that is equal to f_{CM} =36 kHz. Thus, we deduce the value of the CM inductor which equal to L_{CM} = 2mH. The second cut-off frequency f_{CMH} equal to 10.5 MHz is obtained from the curve shown in Fig. 5. It will allow us thereafter, with f_{CM}, to calculate the stray elements of the common mode filter. From Fig. 5, it is possible to determine the frequency f_1 corresponding to the intersection between two lines. The CM filter will reduce the disturbances from f_{CM} to f_1 then decreases until f_{CMH}. With a simple model, one can simulate (with SPICE software) the high-frequency behavior of filter in order to obtain the required attenuation for various frequency bands (f_{CM} until f_1) then (f_1 until f_{CMH}). The simulation diagram is given in Fig. 6. It includes a coupled inductor with L_{CM}=2mH and its parallel resistance of 10KΩ and a stray capacitance Cf. Two capacitors C_Y are represented by their high frequency equivalent series circuit measured using the impedance bridge: C_Y=4.9nF, R_Y= 200mΩ and L_Y= 6.2nH. The inductance Lf corresponds to the wiring inductance of the filter. The generator impedance of 50Ω feeds the filter loaded with a resistance of 50Ω.

The calculation of f_1 is given by:

$$\log f_1 = 1/2\,(\log(f_{CM}) + \log(f_{CMH})) \qquad (2)$$

Let f_1 = 615kHz, which provides the maximum value of the wiring inductance Lf.

$$\boldsymbol{Lf = (\frac{1}{2\pi . f_1})^2 . \frac{1}{2.C_Y} - L_Y / 2 = 6{,}83\mu H} \qquad (3)$$

With frequency f_{MCH} = 10.5 MHz, we can calculate the maximum capacity cf with the following formula:

$$\boldsymbol{Cf = (\frac{1}{2\pi . f_{CMH}})^2 . \frac{1}{(Lf + L_Y / 2)} = 33{,}6pF} \qquad (4)$$

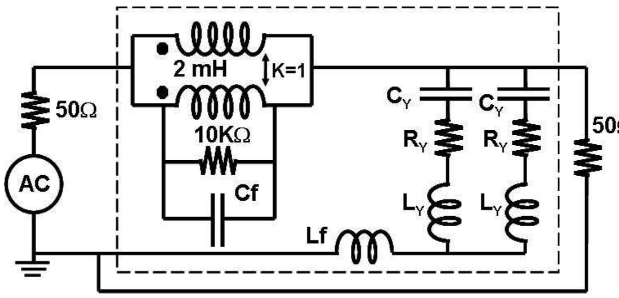

Figure 6: simulation diagram of the common mode filter

The simulation results shown in Fig. 7 gives the filter attenuation obtained with calculated values of Lf and Cf. this result is not satisfactory in high frequency band. For this raison and according to the EMC standard, the maximum frequency of the conducted disturbances is equal to 30MHz. To design the filter, we take the maximum frequency equal to f'_{CMH} = 30MHz, as shown in Fig. 7

The same relationships (2), (3), (4) allow to calculate the values of f'_1= 1.04MHz and the maximum values of Lf=2.39µH and Cf =11.8pF.

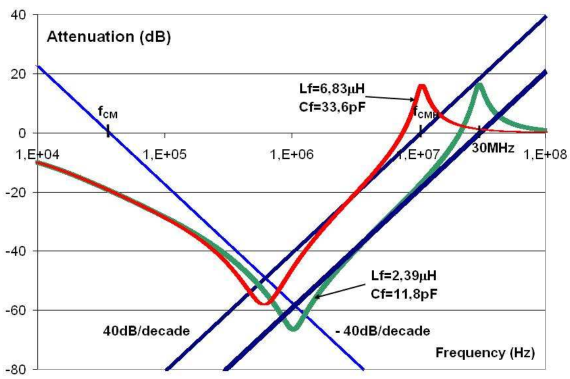

Figure 7: influence of stray elements of the filter

B. Differential Mode Filter

The equivalent circuit of the differential mode filter with LISN is shown in Fig. 8. The differential mode emissions, measured (without EMI filter) using current probes, allow to calculate the voltage under the LISN resistor using the following relation V_{DM} = 100Ω * I_{DM}. The same method is applied to calculate the differential mode filter. However, in differential mode, the knowledge of the cut-off frequency f_{DM}

gives a degree of freedom, since only the product $L_{DM} * C_X$ is known. For the differential mode, cut-off frequency of the filter is equal to f_{DM} = 115 KHz and f_{DMH} = 4.4MHz as shown in Fig. 9. We can chosen the value of the capacitor C_X = 1.5nF. The calculation, using the relation (1), gives the value of L_{DM}. From Fig. 8, if we taking into account the common mode capacitors, the differential mode equivalent capacitance is equal to: $C_{DM}=C_X + C_Y / 2$= 3.85nF. Thus, we deduce $2*L_{DM}$ = 0.5mH. Since, the differential mode filter include two inductors (Fig. 1), then, the differential mode inductor is equal to L_{DM} = 0.25mH. The equivalent circuit used for C_X is a series circuit: C_X = 1.4nF, R_X= 130mΩ and L_X = 10nH

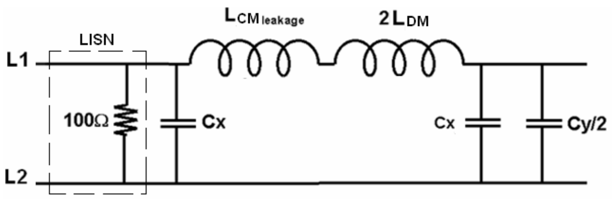

Fig. 8. Equivalent circuit of the differential mode filter

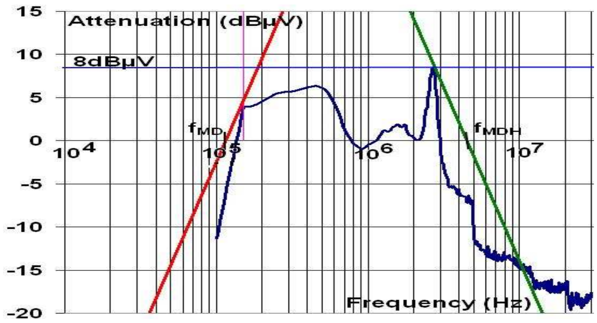

Fig. 9. Differential mode attenuation requirement

2 Realization of the EMI filter

In order to realize the common mode inductor L_{CM} = 2mH, we used a coupled inductances obtained with two winding and copper wire (diameter 0.8mm) rolled up on a ferrite core N30 from EPCOS manufacturer. The specific inductance of this material is A_L = 4260nH, since we have $A_L. n_s^2$ = 2mH, one deducts the number of turns n_s = 22. The choice of the magnetic circuit and the number of turns allow to calculate the value of the stray capacity Cf of the coupled inductors [6]. The calculated value is equal to Cf = 4.1 pF, this value is well below the maximum value calculated above of 11.8 pF. The cut-off frequency f_{CMH} for the common mode filter will determine the choice of the characteristics of the capacitor C_Y. Indeed, the equivalent circuit (RLC) of this capacitor must have a resonant frequency higher than f_{CMH}. It is interesting to take a low value of the capacitor because the parasitic inductance L_{CM} shifts the resonance frequency to lower frequencies. In our case, le value of this capacitor is fixed to C_Y = 4.7nF. The stray elements of this capacitor, measured with the impedance analyzer, give a cut-off frequency equal to 28.9 MHz. On the fig. 5, the second cut-off frequency f_{CMH} is equal to 10.5MHz. In order to have attenuation allows to meet the EMC standard, it is necessary to have a coupled inductance with a very low stray capacitance Cf .

3 Common mode filter modelling

High frequency model of the coupled inductors, obtained in the previous study [7] and shown in Fig. 10 is used. The coupling coefficient of two windings is assumed equal to K = 1.To determine the various elements of this model some experimental tests are necessary [7].

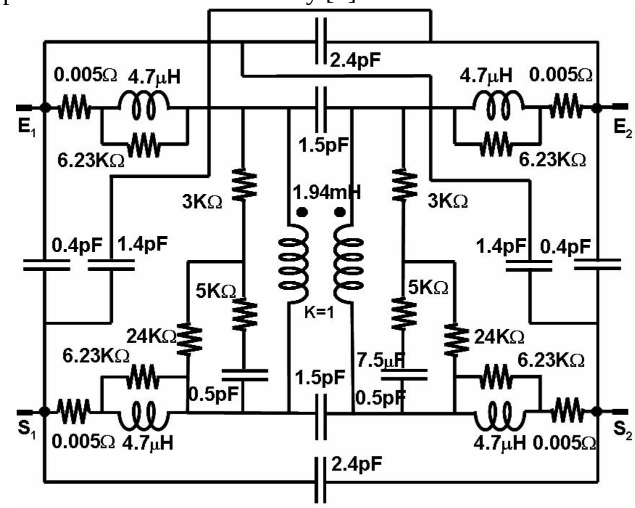

Fig.10. High frequency model of the common mode coupled inductors

We can check that the value of the capacitance Cf previously calculated (4.1 pF) is nearly equal to that obtained with the coupled inductor model: Cf = 2*(1.4 + 0.4) = 3.6 pF

To validate the model of the filter, we use the experimental set-up shown in Fig. 11. Thus, the measurement of the filter attenuation is carried out with a spectrum analyzer (HP ESA-L1500A). Figure 11 shows the principle of measuring the attenuation of the filter. The resistive divider is used to distribute power on each input of the filter.

The common mode and differential mode capacitors have been characterized using an impedance analyzer. Connecting the high frequency models of the common mode chokes and capacitors C_X, C_Y, the obtained filter model is simulated with SPICE.

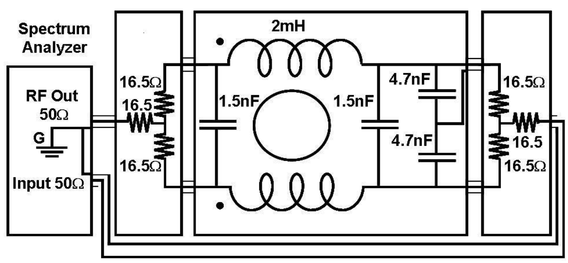

Fig. 11. Measurement of the CM filter attenuation

Figure 12 gives the results of the comparison of the attenuation measured and simulated with the high frequency model. This comparison confirms the validity of the proposed model which can be used to study the various structures of EMI filters. However, these curves show that the reduction of the attenuation depends not only of the ferrite characteristics and capacitors but also of parasitic elements of these components (the position of L and C elements, positions and configuration of the PCB, the length of connections between the elements ...). All these parameters reduce the efficiency of the filter. The wiring inductance measured is equal to Lf =

39nH, well below the maximum calculated value of 2.39 µF. In conclusion, the quality of the EMI filters depends on the characteristics of the used passive components. However, the realization of the filter requires a rigorous design which allows to reduce a maximum the parasitic effects.

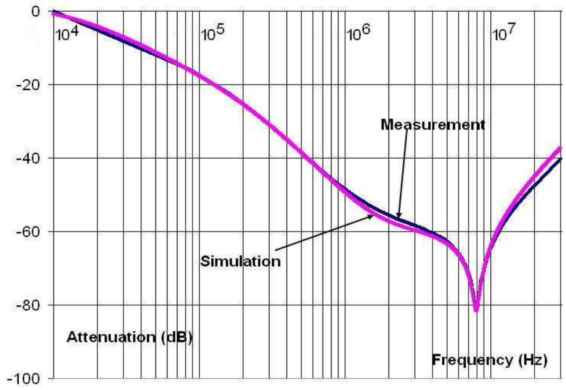

Fig.12. Filter attenuation (measurement and simulation)

4 Experimental validations

To validate the high frequency model of the EMI filter, we used the experimental setup shown in Fig. 13. It consists of a buck converter which feeds through 4-wire shielded cable an electrical machine. The choice of this cable and the AC motor will allow in the future to study a PWM voltage inverter.

The coupled inductors have been realized using EPCOS ferrite magnetic material: N30. Core shape for CM is a ring R25.3/14.8/10 and windings are made of 2*22 turns of copper wire (diameter 0.8mm). Core shape for DM is a ring R27/14/11.5 and windings are made of 57 turns of copper wire (diameter 0.6mm). The coupled inductors have then been associated with capacitors for achieving a complete EMI filter. They have been connected together on a PCB circuit as shown in Fig. 14. The high frequency models of the coupled inductors proposed is used to simulate the EMI filter.

The comparison of measurement data and simulation results of the conducted emissions without and with EMI filter shows a good agreement because the gap is less than 10dBµV in all frequency band. The spectra shown in Fig. 15 represent the conducted emissions measured with a spectrum analyzer and an LISN with and without EMI filter.

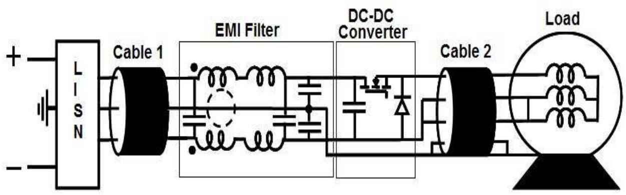

Fig.13. Experimental setup

These results show the efficiency of the filter, since the level of the conducted emissions induced by the power converter towards the DC supply is lower than the limit of EMC standard.

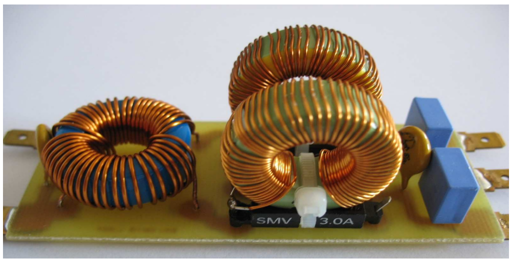

Fig. 14. Common mode and differential mode filters

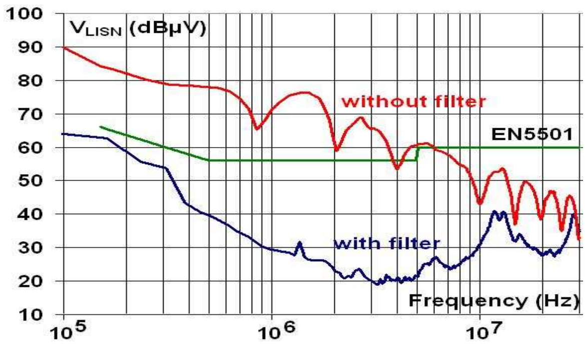

Fig. 15. Conducted emissions measured with LISN

Conclusions

In this paper, a design method of EMI filters based on the high frequency simulation of the common mode and differential mode filters is presented. The high frequency model of inductors used in EMI filter made it possible to study, by simulation, the influence of the parasitic elements of the passive components on the efficiency of the EMI filter. The utilization of the EMI filter models is very useful for investigating the effects of parasitic couplings on their performances, and they therefore offer guides for EMI filter design. The objective is to use the high frequency model of the filter associated at the high frequency model of power converter to optimize the design of the EMI filter. The next step is to use these passive components models to study the 3-phase EMI filters in the adjustable speed drives.

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