Design of EMI filters for DC-DC converter

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***Abstract*- The subject of this paper is the design of EMI filters for the DC-DC converters. It is well known that the static converters used in electric traction systems are major sources 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, we propose a design method of the EMI filter based on the simulation of the filter in frequency domain. Thus, the high frequency models of the filter components are proposed. The obtained models have been tested and give good results on a large frequency range, from 9 kHz to 30 MHz.**

I. INTRODUCTION

The utilization of the static converter in the electric traction systems is very problematic for electromagnetic compatibility (EMC). Indeed, each power converter generates a lot of high frequency interferences causing a malfunction of the onboard electronic systems. The main solution to reduce these conducted emissions is based on the utilization of EMI filters [1] – [3]. It can also be combined with other solutions like: the slowing down the dv/dt during the transitions of the power semi-conductor components and/or by acting on the converter controls [4].

The EMI filters are made from coupled inductors combined with capacitors; the choice of the filter topology depends on network and load impedances. Generally, the Common Mode (CM) and Differential Mode (DM) filters are used for power converters. The passive components have a strong impact on filter efficiency [1]. 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 [5] – [6]. In order to design and optimized filter characteristics by simulation, a high frequency models, including parasitic elements of the passive components, must be used.

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.

II. EMI FILTER DESIGN

The EMI filters are used to reduce the common mode and differential mode emissions induced by the power converters. To design of EMC filter, it is necessary to separate conducted emission modes. 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. There are different methods which allow to separate these modes which are presented in literature [7] – [9]. 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. 1.

In this study, 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. 2. 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. Than, the conducted emissions are measured with a spectrum analyzer, in frequency band varying from 0.1 MHz to 30MHz, according to CISPR11/ EN55011 standard [10].

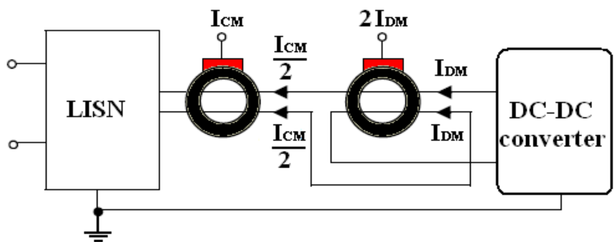

Fig. 1. Separation of CM and DM currents by using current probes

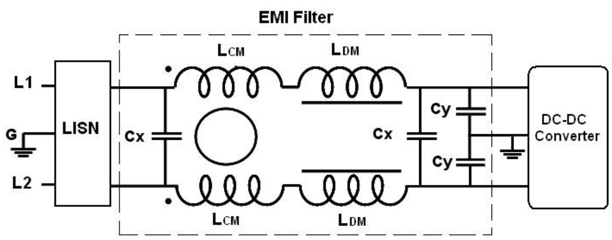

Fig. 2. EMI filter structure: common mode and differential mode

A. Common Mode Filter

The equivalent circuit of the common mode filter and 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). To meet the EMC standard, the EMC filter attenuation required is equal to the difference between the measured level of disturbance and the limits of the standard (Fig. 5). 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:

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

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.

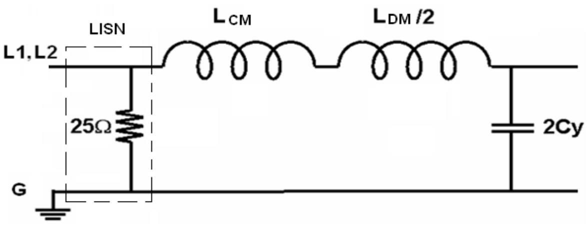

Fig. 3. Common mode filter equivalent circuit

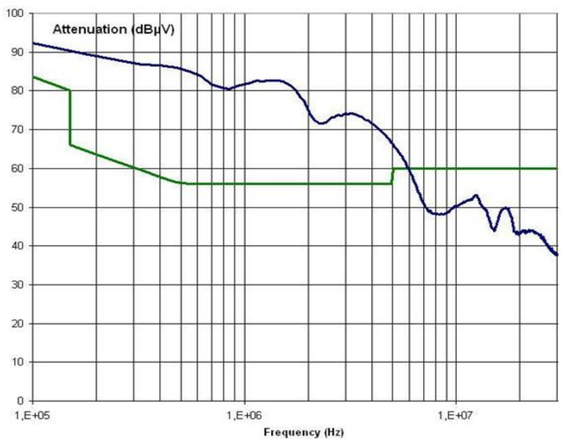

Fig. 4. Common mode noise without filter (Voltage under 25Ω)

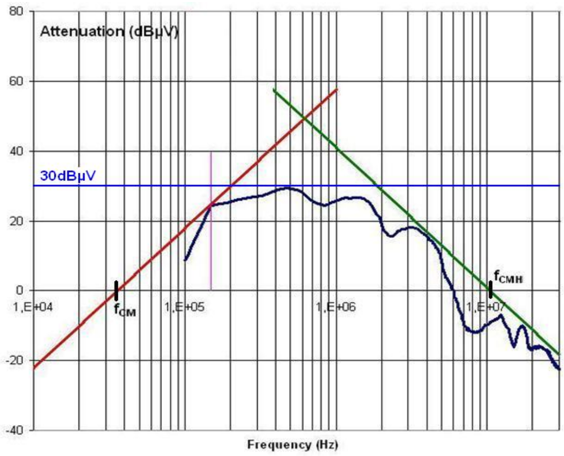

Fig. 5. Common mode attenuation requirement

B. Differential Mode Filter

As previously, the equivalent circuit of the differential mode filter and LISN is shown in Fig. 6. The differential mode emissions, measured (without EMI filter) using current probes, allow to calculate the voltage under the resistor of the LISN using the following relation $V_{DM} = 100\Omega * I_{DM}$. The result of the calculation shows that the level of conducted emissions is over the EMC standard limit up to 3 MHz (Fig. 7). 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 as shown in Fig. 8.

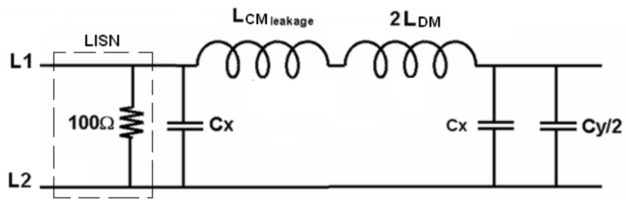

Fig. 6. Differential mode filter noise equivalent circuit

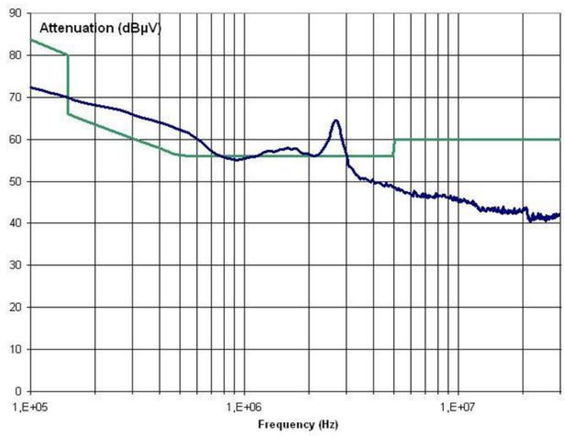

Fig. 7. Differential mode noise without filter (Voltage under 100Ω)

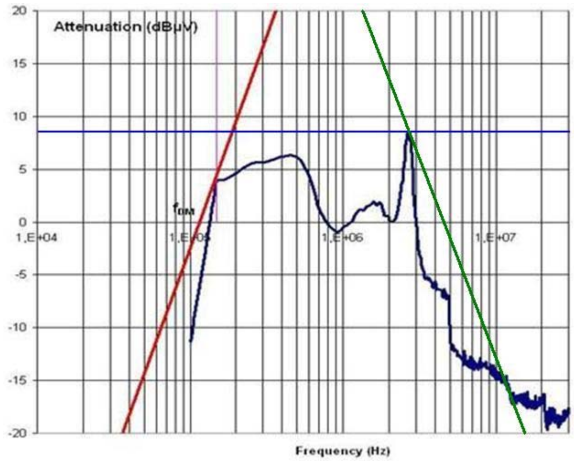

Fig. 8. Differential mode Attenuation requirement

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. 6, if we taking into account the common mode capacitors, the differential mode equivalent capacitance is equal to: $C_{DM} = C_X + C_Y / 2 = 3.85$nF. Thus, we deduce $2L_{DM}$ = 0.5mH. Since, the differential mode filter include two inductors (Fig. 2), then, the differential mode inductor is equal to L_{DM} = 0.25mH. In the next section, we study the high-frequency model of the EMI filter.

III. High frequency model of the EMI filter

To calculate the EMI filter, it is necessary to separate the CM and DM disturbances. The values of the EMI filter components previously calculated are summarized in the following table:

Common mode Filter		Differential mode filter	
L_{MC} = 2mH	C_Y = 4.7nF	L_{DM}= 0.25mH	C_X = 1.5nF

A. Common Mode 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.

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 Lc 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 .

1) Calculation of the Inductor Stray Capacitance

The calculation of the stray capacitances of the coupled inductors Cf is based on the geometrical dimensions of the ferrite core, the numbers of turns of inductor windings and the position of windings compared to the core as shown in Fig. 9. These calculations are detailed in [11], [12]. Dimensions of the ferrite core are following:

$d_e = 2.r_e = 26$ mm, $d_i = 2.r_i = 14.8$ mm, $h_e = 10.6$ mm,
$d_c = 2.r_c = 1$ mm, $n_s = 22$, $b_f = 1$ mm,
$m_e = 2$ mm, $\varepsilon_0 = 1/36.\pi.10^9$.

The calculation of d_t and α is given:

$$d_t = 2.(r_t).\sin(\alpha/2) \qquad (2)$$

$$\alpha = 2.\arcsin\left(\frac{(r_c + m_e/2)}{r_e + r_c + b_f}\right) \qquad (3)$$

One can then calculate surface a_s equivalent at to 2 planar plates distant of dt which correspond to 2 winding turns as shown in Fig. 10. The value of a_s is given by the following relation:

$$a_s = 2.d_c.(h_e + 2.b_f + r_c + \frac{(d_e - d_i)}{2} + 2.b_f + r_c) \qquad (4)$$

The calculation of the stray capacitances of the coupled inductors is given by:

$$Cf = \varepsilon_0\, n_s\, a_s/d_t = 4.1\text{pF} \qquad (5)$$

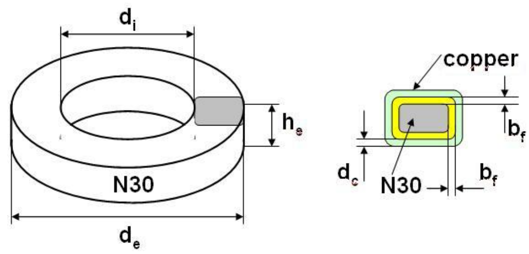

Fig.9. Geometrical dimension of the core and conductor

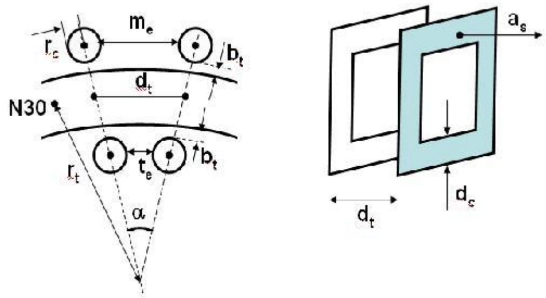

Fig.10. Stray capacitance between two turns of the inductor winding

Knowing the stray capacitance of the coupled inductors, and starting from a simple model of this inductance, one can make the simulation of the EMI filter using the equivalent circuit shown in Fig. 11. One can see on figure 12 the attenuation variation that corresponds to the common mode filter obtained with the simplified model. This filter uses a coupled inductors L_{CM} = 2mH, a stray capacitance Cf = 4.1pF and resistance R = 10 KΩ. The value of this resistance has not the influence on the resonance frequency of the filter. We have also added external inductors Lc which correspond to the connection of the filter.

The simulation results of the attenuation, carried out with SPICE, using a simplified model of the filter are shown in Fig. 12. The ideal case corresponds to Cf = 4pF and Lc=0, the maximum attenuation A = 82dB is obtained at 33MHz. In fact, we cannot avoid the filter connection corresponds to the external inductance, which is in our case measured using the impedance bridge, and its value is equal to Lc = 39nF. The simulation results show that the maximum attenuation value is equal to A = 90dB at 8MHz. Thus, the attenuation decreases but remains significant and equal to A = 45dB at 30MHz. The third curve corresponds to Cf = 14pF and Lc = 39nF. This last curve shows that the attenuation is equal to A = 78dB at 8 MHz. These results show that in order to increase the attenuation of the EMI filter, it's necessary to reduce the stray elements.

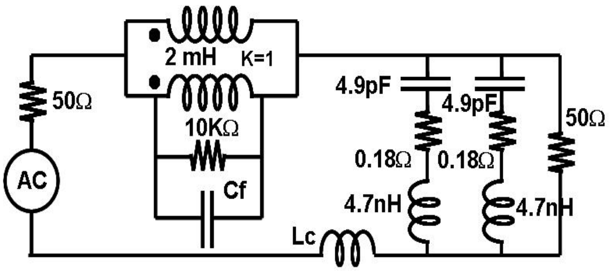

Fig.11. Simplified diagram of simulation of the Common Mode filter

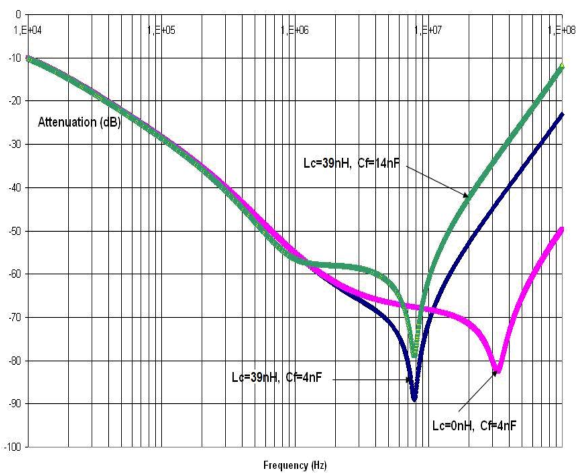

Fig.12. Influence of stray elements on the filter attenuation

2) High Frequency Model of the Coupled Inductors

High frequency model of the coupled inductors, obtained in the previous study, shown in figure 13 will be used [13]. The coupling coefficient of two windings is assumed equal to K = 1. The different impedances Z_1 and Z_2 are used to model the high frequency behavior of the coupled inductors. Thus, the impedances Z_1 correspond to the leakage inductances are symmetrically distributed. However, the impedance Z_2 allows to model the effect of the magnetizing inductance. The various capacitances represent the capacitive effects in the coupled inductors in high frequencies band.

To determine the values of the resistances, inductances and capacitances, various tests are needed [13]. These tests are done with impedance analyzer (Agilent 4294A) in a frequency band between 1 kHz to 30 MHz. The necessary tests are: the load test, short circuit test and when the windings are in parallel with additive and subtractive flux. The test when one winding of the coupled inductors is in open circuit, with additive and subtractive flux, is used to determine the elements of the impedances Z1 and Z2. To determine the values of stray capacitances, two tests, when two winding of coupled inductors are in short circuit, are needed. These calculations are detailed in [13].

We can check the value of the stray capacity which we have already calculated. According to the high frequency model (Fig. 13), the capacitance is equal to Cf = 2. (1.4 + 0.4) = 3.6 pF and the calculated value with (5) is equal to 4.1pF. These results validate the method of calculation of the stray capacitances.

We can realize now the prototype of the filter by using the common mode coupled inductors with the capacitors C_Y and C_X, but in the first time, without differential mode chokes.

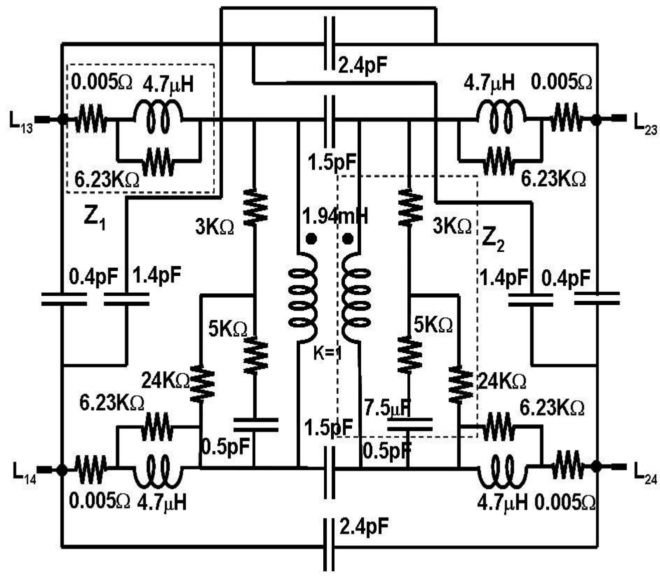

Fig.13. High frequency model of the CM coupled inductors

3) Validation

To validate the model of the filter, we use the structure shown in Fig. 14. Thus, the measurement of the filter attenuation is carried out with a spectrum analyzer (HP ESA-L1500A). It injects (output RF OUT) a signal in the frequency band between 10 KHz to 30 MHz at the filter input. The filter is connected to the receiver of the analyzer (Input impedance is 50 Ω). Figure 14 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. The equivalent circuit used for C_Y is a series circuit: C_Y = 4.9nF, R_Y = 200mΩ and L_Y = 6.2nH. The equivalent circuit used for C_X is a series circuit: C_X = 1.4nF, R_X= 130mΩ and L_X = 10nH. Connecting the high frequency models of the common mode chokes and capacitors C_X , C_Y, the obtained filter model is simulated with SPICE.

Figure 15 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.

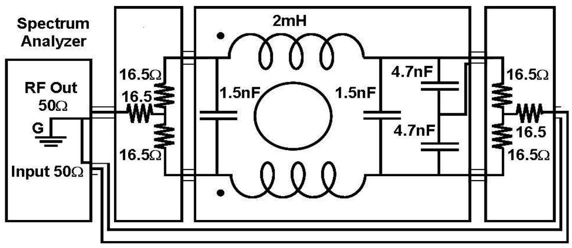

Fig.14. Measurement setup of the filter attenuation

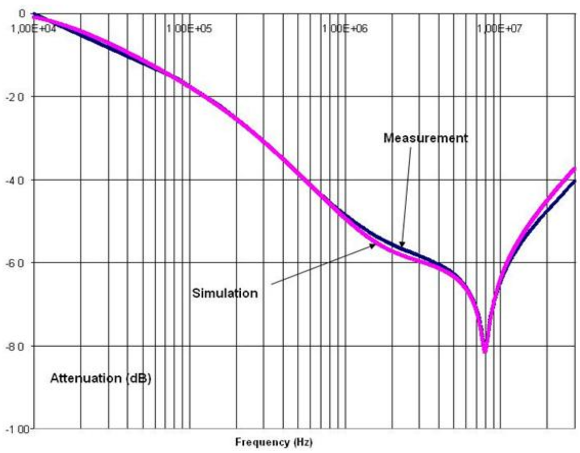

Fig.15. Filter attenuation (measurement and simulation)

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.

B. *Differential Mode Filter*

Differential mode filter uses two inductances and of two capacitors Cx. The characteristics are: 2 coils independent of 57 turns for each one with a copper section of 0.6mm. Thus, the DM mode choke value is equal to L_{DM} = 0.26mH. The main characteristic of the magnetic material "ferrite", used to realize the DM chokes, is the saturation current which appears for the higher values. Thus, inductors saturate from 3A.

IV. Experimental validation

To validate the high frequency model of the EMI filter, we used the experimental setup shown in Fig. 15. 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. 16. 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. 17 represent the conducted emissions measured with a spectrum analyzer and an LISN with and without EMI filter.

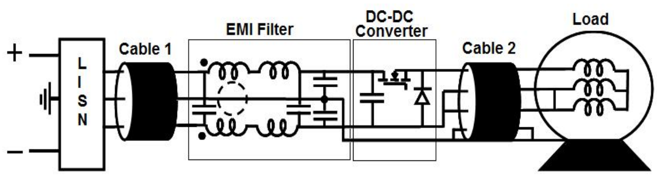

Fig.15. Experimental setup

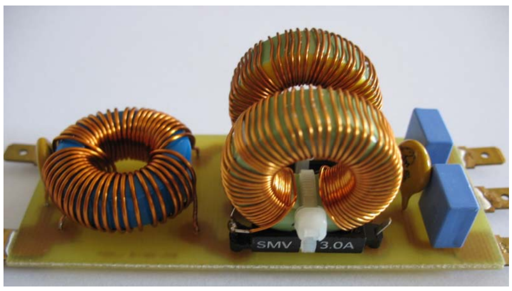

Fig. 16. Common mode and differential mode filters

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. To study separately the attenuation of each filter (CM, DM), we calculated, from the measured currents (I_{CM} and I_{DM}), the common mode voltage ($V_{CM} = 25\Omega * I_{CM}$) and differential mode voltage ($V_{DM}=100\Omega * I_{DM}$) as shown in Fig. 18 and Fig. 19.

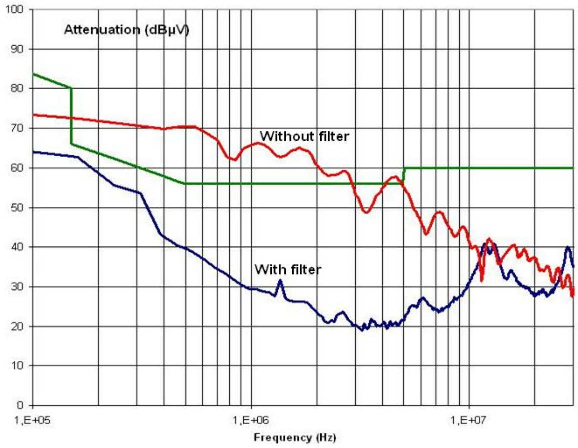

Fig. 17. Conducted emissions measured with LISN (with and without filter)

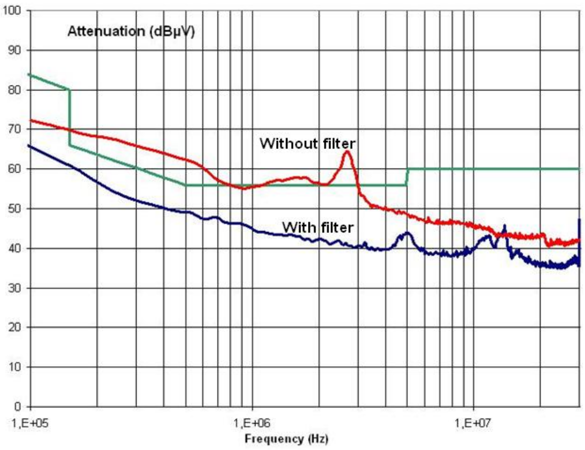

Fig. 18. Differential mode emissions with and without EMI filter

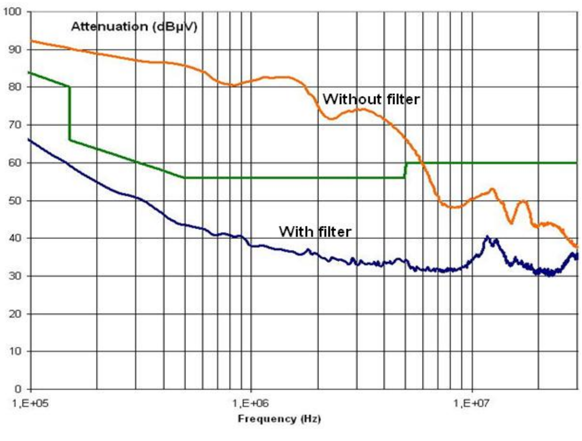

Fig. 19. Common mode emissions with and without EMI filter

These curves give a comparison of the common mode and differential mode emissions with and without EMI filter. These results show that for the DM filter attenuation is higher at 10dBµV up to 5 MHz. However, for the CM filter, the attenuation is importance and reached 40dBµV in all frequency band.

V. Conclusion

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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