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Minimization of Common-Mode Conducted Noise in PWM Inverter-fed AC Motor Drive Systems using Optimized Passive EMI Filter

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***Abstract*—Conducted electromagnetic interference (EMI) generated by PWM inverter-fed induction motor drive systems, which are currently widely used in many industrial and/or avionic applications, causes severe parasitic current problems, especially at high frequencies (HF). These restrict power electronic drive's evolution. In order to reduce or minimize these problems, several techniques can be applied. In this paper, insertion of an optimized passive EMI filter is proposed. This filter is optimized by taking into account real impedances of each part of a considered AC motor drive system contrarily to commercial EMI filters designed by considering internal impedance of disturbance source and load, equal to 50Ω. Employing the latter EMI filter would make EMI minimization less effective. The proposed EMI filter optimization is mainly dedicated to minimize common mode (CM) currents due to its most dominant effects in this kind of system. The efficiency of the proposed optimization method using two-port network approach is deduced by comparing the minimized CM current spectra to an applied normative level (ex. DO-160D in aeronautics).**

***Index Terms*—AC motor drive, common mode conducted noise, optimization, passive EMI filter.**

I. Introduction

Pulse width modulation (PWM) inverters widely used in adjustable-speed AC motor drives to pilot electromechanical actuators in many applications cause many exceptional phenomena, especially in HF. Major EMI problems [1-3] are such as high-frequency leakage currents flowing to the ground through capacitive couplings in all parts of the drive system, deterioration of motor winding insulation, shaft voltage in motor, bearing currents, and radiation of power cables. These EMI problems are resulted from the increase of the carrier frequency of PWM and are principally related to significant magnetic or electrostatic coupling effects created by high dv/dt and high di/dt in the output voltage and current (faster switching rates of the power electronic switches [3]), leading to conducted emissions (CM and differential mode (DM)) and/or radiated emissions. To ensure the reliability of functioning of the full system in terms of Electromagnetic Compatibility (EMC), especially for the embedded electronics, which are very sensitive in aeronautics; it is necessary to apply an appropriate method to minimize EMI in the system.

Nowadays, the use of a passive EMI filter, which is a classical technique, is still a good method to minimize CM and/or DM currents in AC motor drive systems. This kind of filter can be added either at the input or at the output of the PWM inverter. Nevertheless, it is frequently placed at the input in order to restrict conducted noise emissions propagating to electrical network, which could damage other electric and/or electronic equipments connected to the same electrical source. Since one of the most difficult problem to resolve is related to high-frequency leakage currents flowing through stray capacitances in the system, which is a definition of CM; we will thus only investigate and focus on this mode. In order to efficiently diminish CM currents by using a low-pass CM filter, it had better to optimize its element values adapted to the considered system. The objective of this optimization is to acquire an EMI filter with minimum volume, weight, and cost. The effectiveness of the optimized filter is simply deduced by comparing minimized CM current spectra to an applied standard such as EN55011 (European standard), MIL-STD-461E (military standard), DO-160D (aeronautical standard).

In this paper, the considered AC motor drive system and some measured CM current spectra are first shown to reveal necessity of parasitic CM current minimization. Second, a known commercial EMI filter is added in the system to validate the proposed EMI filter design based on two-port network model [4]. Third, the optimization approach of EMI filter is presented with its numerical simulation results. These simulated results will be finally depicted and could be compared with those issued from the commercial EMI filter employed in this study to illustrate the optimized filter efficiency. Some simulated results issued from the system where an optimized EMI filter is placed at the output of the inverter are also shown to complete this study.

II. Studied AC Motor Drive System and Experimental Results

The studied system is a PWM inverter-fed AC motor drive system, which is mainly composed by an energy source, a power converter, and a motor. In this paper, the considered system is more complex; it is constituted of a three-phase transformer (400 V, 50 Hz, 4 kVA), a three-phase Line

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Impedance Stabilization Network (LISN), a three-phase diode rectifier, a three-phase IGBT inverter (adjustable switching frequency: 2 to 16 kHz), an asynchronous induction motor (Leroy Somer, 400 V, 3 kW, nominal speed: 1500 rpm), and shielded cables (four conductors, section = 5mm^2, shielding braid), and depicted in Fig. 1.

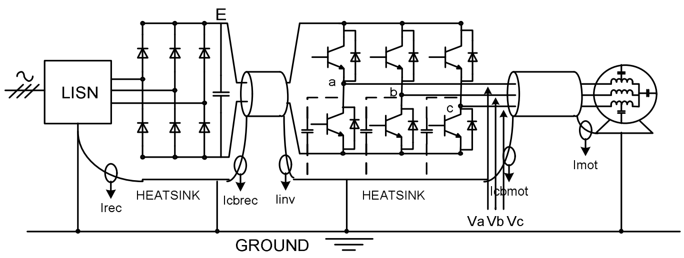


Fig. 1 Representation of the studied AC motor drive system

CM current spectrum is measured at every part of the system as shown in Fig. 1 (in the rectifier (I_{rec}), the cable (I_{cbrec} and I_{cbmot}), the inverter (I_{inv}), and the motor (I_{mot})) in the frequency range of 2 kHz to 100 MHz.

An example of measured CM current spectrum in the rectifier (I_{rec}) (the part connected to electrical network) is illustrated in Fig. 2.

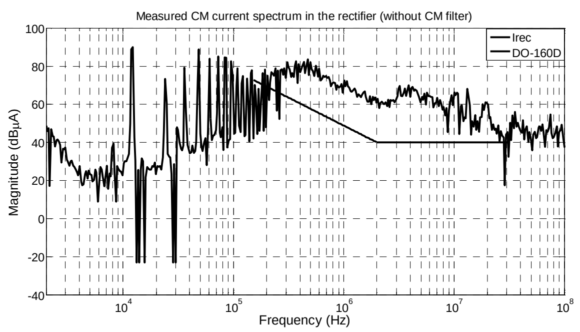


Fig. 2 CM current spectrum measured at electrical network side

According to the result, the parasitic CM current spectrum does not respect an applied EMC standard (DO-160D) on all the considered frequency range (150 kHz – 30 MHz). Hence, an EMI minimization approach will be used to minimize CM conducted noise emissions in the system. The technique proposed herein is the insertion of a passive EMI filter.

III. COMMERCIAL PASSIVE EMI FILTER USED IN THIS STUDY

In order to minimize or eliminate CM currents at the electrical source side in the considered system, we tried first with a known commercial passive EMI filter. This filter was inserted at the input of the rectifier as represented in Fig. 3.

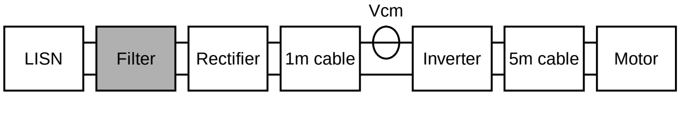
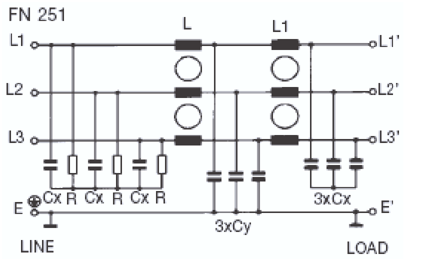


Fig. 3 Representation of the system with an EMI filter at CM standpoint by two-port networks in cascade

The principal role of a passive filter is generation of an impedance mismatch, minimizing disturbing energy transfer between the disturbance source and the load of the system on the considered frequency range. To minimize EMI at HF, 3 structures can be created: Π, T or L in single stage or several stages with different cut-off frequencies.

Theoretically, the structure of CM filter should be in a form of inductors in series in each phase followed by capacitors in parallel. The inductor windings are built in opposition of phase in order to cancel flux generated by DM current. The effectiveness of this kind of filter is often restricted by parasitic element effects throughout the windings, and by the performance of magnetic materials restricted by frequency, in particular at HF.

The commercial EMI filter employed in this study has characteristics as shown below (Fig.4).



Nominal current = 4A,
L = 7mH,
L1 = 1,5mH,
Cx = 1μF,
Cy = 15nF,
R = 470kΩ

Fig. 4 Commercial EMI filter used in this study

When the commercial EMI filter is located at the position as indicated in Fig. 3, reduced CM current spectrum at the input of the filter is illustrated in Fig. 5. The minimized CM current spectrum still exceeds the applied standard level (from 2 MHz to 30 MHz). Consequently, optimization of this kind of filter is necessary in order to acquire CM current spectrum below the normative level on all frequency range.

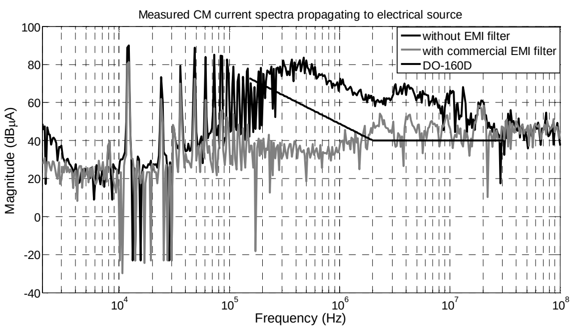


Fig. 5 CM current spectra in the system with/without the commercial EMI filter

IV. MODELING OF SYSTEM INCLUDING EMI FILTER BY TWO-PORT NETWORK TECHNIQUE

The CM conducted noise emissions generated in such system without an EMI filter is already modeled by two-port network approach and validated up to 10MHz approximately in [4]. In order to reliably optimize a CM filter using two-port network approach, a known passive EMI filter has to be first inserted in the system to make sure the validity of the modeling approach when the system becomes more complex (Fig. 3).

The modeling principle is described in [4]. Briefly, to acquire simulated results based on this modeling approach, it consists of determining, by specific experimental characterizations, equivalent CM impedances of each element

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in the impedance matrix coefficient form (Z_{11}, Z_{12}, Z_{21}, and Z_{22}) by an Impedance Analyzer, and CM voltage generated by PWM inverter. Matrix [Z] is then transformed into matrix [T] using (1) to simplify CM current computation.

$$\begin{bmatrix} T_{11} = \dfrac{Z_{11}}{Z_{21}} & T_{12} = \dfrac{Z_{11}Z_{22}}{Z_{21}} - Z_{12} \\ T_{21} = \dfrac{1}{Z_{21}} & T_{22} = \dfrac{Z_{22}}{Z_{21}} \end{bmatrix} \qquad (1)$$

At CM point of view, a sub-system (i.e. inverter, cable, motor) can be represented by Fig. 6. The simulated CM currents and/or CM voltages, computed in Matlab, are simply obtained by using transfer matrix [T] relations defined by (2).

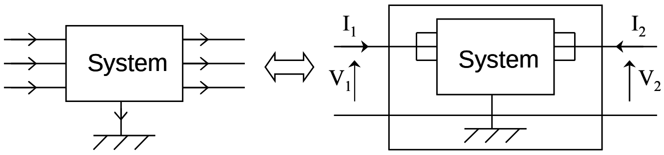

Fig. 6 Representation of a sub-system at CM standpoint, associated to electrical parameters

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = [\mathbf{T}].\begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \qquad (2)$$

Some examples of comparison between measured and calculated CM current spectra in the filter and in the inverter are illustrated in Fig. 7 and Fig. 8.

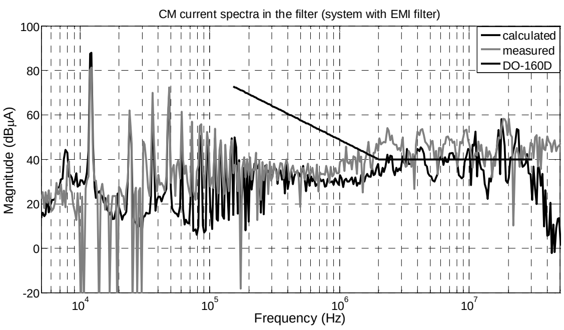

Fig. 7 CM current spectra in the EMI filter

The results show that the CM current model based on two-port network approach can efficiently predict or estimate CM currents in the system. This model can be now used to design EMI filter adapted to the considered system in order to respect an applied EMC standard.

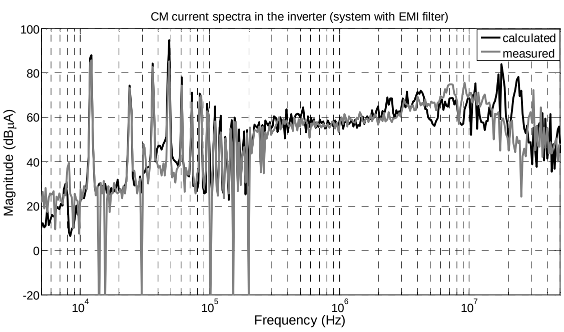

Fig. 8 CM current spectra in the inverter

V. OPTIMIZATION OF PASSIVE EMI FILTER BASED ON TWO-PORT NETWORK MODEL

The main object is to obtain a passive EMI filter with low weight, volume and cost, and providing CM current spectra respecting a normative level at the electrical source side. Therefore, LC structure is chosen in this study, and added at the input of the rectifier as presented in Fig. 9. The values of equivalent parasitic CM capacitances at low frequencies (LF) are: $C_{rcr} \approx 595$ pF and $C_{icmm} \approx 8.5$ nF.

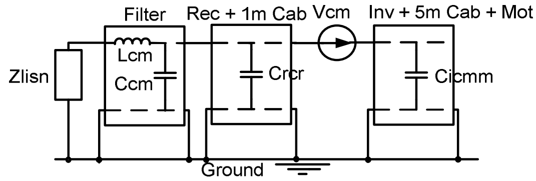

Fig. 9 Studied system with insertion of an EMI filter

A. Principle of optimization

The optimization programming is carried out in Matlab environment. Its principle consists of bringing CM current spectra to be under a normative level on all considered frequency range. The considered standard DO-160D is defined from 150 kHz to 30 MHz.

The algorithm process used to optimize passive EMI filter is described by the flowchart in Fig. 10.

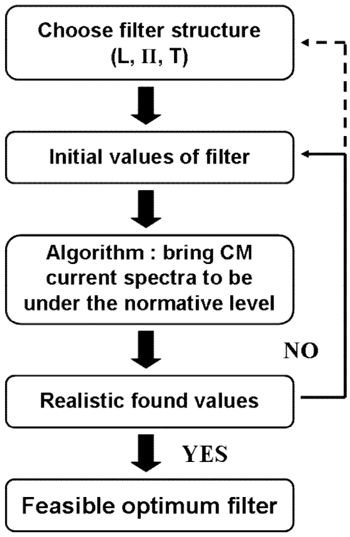

Fig. 10 Flowchart for optimization algorithm

To reduce CM currents propagating to electrical network, the element values of optimized EMI filter given by optimization algorithm are: $L_{cm} = 1.12$mH, and $C_{cm} = 0.72$pF.

L_{cm} represents equivalent CM inductor and C_{cm} represents equivalent CM capacitor as indicated in Fig. 11.

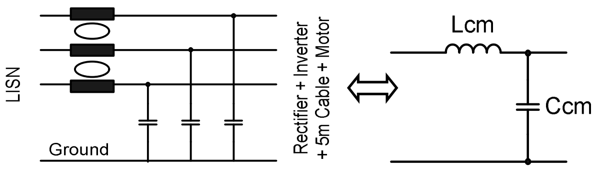

Fig. 11 Single-phase representation of optimized CM filter structure

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B. CM current spectra issued from system including optimized filter

The result obtained by the ideal EMI filter is represented in Fig. 12. We notice that CM current is well minimized.

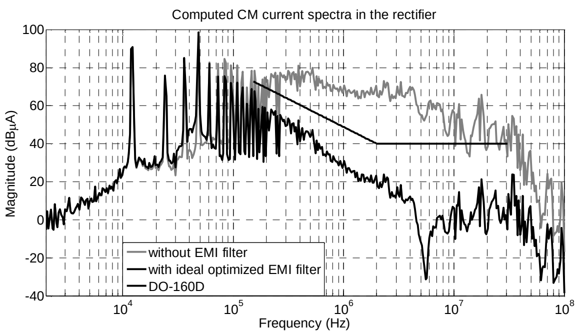

Fig. 12 CM current spectra in the rectifier without/with ideal optimized EMI filter

Normally, each element (L_{cm}, C_{cm}) has parasitic elements that play important part, in particular at HF. Thus, in order to efficiently predict the optimized EMI filter effectiveness, their parasitic elements should be taken into account in the optimization programming.

In our case, the real inductor model is constituted of a resistance R_s in series with L_{cm} and a capacitance C_p in parallel. The parasitic elements of C_{cm} could be neglected because C_{cm} (0.72pF) is negligible before C_{rcr} (595pF); this signifies that it is not necessary to put C_{cm} in the circuit. It is sufficient to only place CM inductor (L_{cm}) at the input of the rectifier; this will reduce more the filter volume.

To determine parasitic elements of CM inductance (L_{cm}) using optimization algorithm, the optimized values of L_{cm} and C_{cm} given by the first algorithm is fixed in the second one where the maximum parasitic element values are always controlled by respect of minimized CM current spectrum to the normative level. The optimization programming provides finally the parasitic elements of L_{cm} as follows: $R_s = 0.325\Omega$, and $C_p = 7.4$pF. The simulated CM current spectrum while including all parasitic elements in the model of the optimized filter is depicted in Fig. 13.

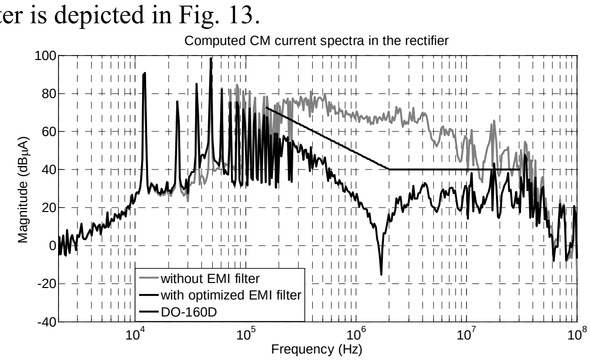

Fig. 13 CM currents in the rectifier without/with optimized EMI filter including its parasitic elements

According to Fig. 12 and Fig. 13, we agree that parasitic elements of EMI filter play the part very importantly on its effectiveness, especially at HF. In practice, to realize this EMI filter, it has to control its parasitic elements.

C. Simulated results for optimized filter located at the output of the inverter

As the DO-160D standard concerns EMI level in the LISN (electrical source side) and in the connecting power cable. In this part, we will use the same algorithm programmed in Matlab to optimize element values of EMI filter positioned at the output of the inverter. The LC structure including parasitic elements is still used in this case. After optimization, the obtained values are $L_{cm} = 0.123$mH, $C_{cm} = 23.44$pF, $R_s = 1.03\Omega$, and $C_p = 28.56$pF (negligible before equivalent CM impedance of motor cable and motor ($C_{cmm} \approx 8$nF)). The simulated CM current spectrum is shown in Fig. 14.

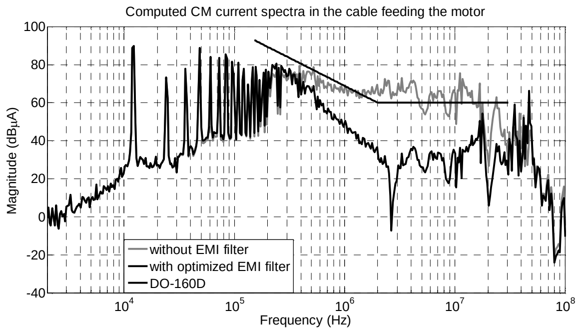

Fig. 14 CM current spectra in the power cable feeding the motor in the system without/with optimized EMI filter located at the output of the inverter

VI. CONCLUSION

The two-port network model predicts or estimates CM currents in the system with insertion of an EMI filter fairly well up to 10 MHz. This confirms that the filter optimization can be carried out from this model. The results show that the optimized CM filter reduces CM conducted noise emissions better than the commercial filter used in this study. The reason is that the first one is determined from the true values of CM impedances of the system contrarily to the second one designed for generic propagation impedance of 50Ω. Furthermore, the optimization method can be applied for various filter structures (L, T or Π; a single stage or more) positioned at the input or the output of the converter as presented in this paper, and effectively used in other systems. The effectiveness of the filter depends on the objective. In this paper, the normative level DO-160D was chosen to design the optimal filter and to demonstrate its effectiveness. In practice, the parasitic elements of the filter should be controlled so as not to degrade its effectiveness, especially in HF.

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