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MODELING AND OPTIMIZING A PASSIVE EMI FILTER TO ATTENUATE COMMON-MODE CURRENTS AT HIGH FREQUENCY IN A THREE-PHASE ADJUSTABLE-SPEED AC MOTOR DRIVE

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Abstract. *This paper proposes a novel optimization approach of a passive electromagnetic interference (EMI) filter using two-port network technique to reduce or minimize common-mode (CM) conducted noise emissions in a three-phase adjustable-speed AC motor drive. This parasitic current is generally generated by a Pulse Width Modulation (PWM) inverter, an essential part in adjustable-speed AC motor drive systems widely used in many industrial and/or avionic applications, and causes severe EMI problems, in particular at high frequencies (HF); this restricts power electronic drive's evolution. The proposed EMI filter is designed by optimizing its elements values by taking into account real impedances of each part of the considered system. This approach is contrary to commercial EMI filters typically designed by considering internal impedance of disturbance source and load, equal to 50 Ω/50 Ω, 0.1 Ω/100 Ω or 100 Ω/0.1 Ω. These do not represent the real impedances of the system; thus employing the latter EMI filter would make EMI minimization less effective. The efficiency of the proposed optimization method will be confirmed by comparing the minimized CM current spectra, in frequency domain, to an applied normative level such as EN55011 or DO-160D standards.*
Keywords: AC motor drive, Common mode current, Electromagnetic compatibility, Optimization, Passive EMI filter

1. **Introduction.** Electromagnetic interference (EMI) is an inevitable phenomenon occurring in electrical/electronic systems. In power electronic system, switched power converters or pulse width modulation (PWM) inverters broadly used in adjustable-speed AC motor drives to pilot electromechanical actuators in many industrial and/or avionic applications are the major source to generate both conducted noise emissions and radiated noise emissions. These electromagnetic disturbances may interrupt, obstruct, degrade or limit the effective performance of the electrical/electronic circuit or the system. EMI emissions occurring in an electrical/electronic production line could provide machine malfunction and/or catastrophic or latent damage to electrical/electronic product. Consequently, it is essential to apply an appropriate technique to minimizing or eliminating these EMI emissions.

In recent years, the switching frequency of voltage-source PWM inverters has been increased; this is due to the high progress of electric power and semiconductor elements (i.e., IGBT, MOSFET). This semiconductor evolution has brought great improvements of performances and characteristics of the converters and of the system; however, it has also generated progressively numerous EMI problems in electrical systems [1], in industrial applications, and in aircraft. These EMI problems 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 noise emissions (CM and differential mode (DM)) and/or radiated emissions.

Major EMI problems exceptionally caused [1-3] are such as:

(1) High-frequency leakage currents flowing to the ground through capacitive couplings in all parts of the drive system,
(2) Deterioration of motor winding insulation,
(3) Shaft voltage in motor bearing, and
(4) Radiation of power cables.

To ensure the reliability of functioning of the whole system in terms of Electromagnetic Compatibility (EMC), EMI minimization technique has to be applied.

Several traditional and innovative EMI reduction techniques have been proposed and applied for many years in order to minimize or overcome the mentioned EMI problems. These techniques are such as the use of passive and/or active EMI filter [4-10], the modification of converter structure [11,12], shielding, grounding, the use of soft switching converter and/or multilevel inverter [13,14], the modification of PWM strategy [15]. Each technique has different advantages. In this paper, the adding of a passive EMI filter is chosen due to its simplicity. 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 equipment connected to the same electrical source. If the EMI filter is located at the output of the inverter, the aim is for reducing parasitic HF currents mainly flowing through AC motor windings because these currents can cause shaft voltage and deterioration of motor winding. In this paper, only CM emissions will be focused and reduced due to their dominant effects in this kind of system. To be able 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 obtain an EMI filter with minimum volume, weight, and low cost. The effectiveness of the optimized EMI filter is simply deduced by comparing minimized CM current spectra to an applied EMC standard such as EN55011 (European standard), MIL-STD-461E (military standard), and DO-160D (aeronautical standard).

In this paper, the experimental test bench of the considered adjustable-speed AC motor drive is first presented. Second, some measured CM current spectra in frequency domain are shown to reveal necessity of parasitic CM current minimization. Third, a known commercial EMI filter is added in the system to validate the proposed EMI filter design based on two-port network model [16]. Fourth, the optimization approach of common-mode EMI filter is presented with its numerical simulation results. Finally, the simulated results will be depicted and compared with DO-160D standard and also with those issued from the commercial EMI filter employed in this study to illustrate the optimized EMI filter efficiency.

2. **Adjustable-Speed AC Motor Drive Test Bench.** The studied system is a three-phase adjustable-speed AC motor drive, which is principally composed by an energy source, a power converter, and a motor. In this paper, the system is more complex; it is constituted of a three-phase transformer (400 V, 50 Hz, 4 kVA), a three-phase Line Impedance Stabilization Network (LISN), a three-phase diode rectifier, a three-phase IGBT inverter (adjustable switching frequency: 2 to 16 kHz), an asynchronous induction

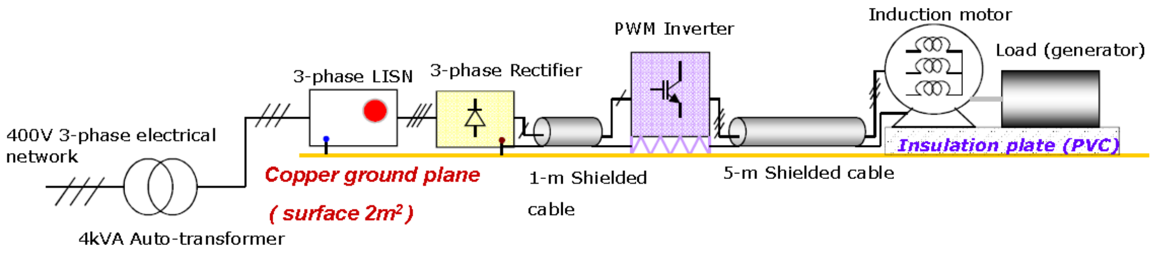

FIGURE 1. Experimental setup of the studied adjustable-speed AC motor drive

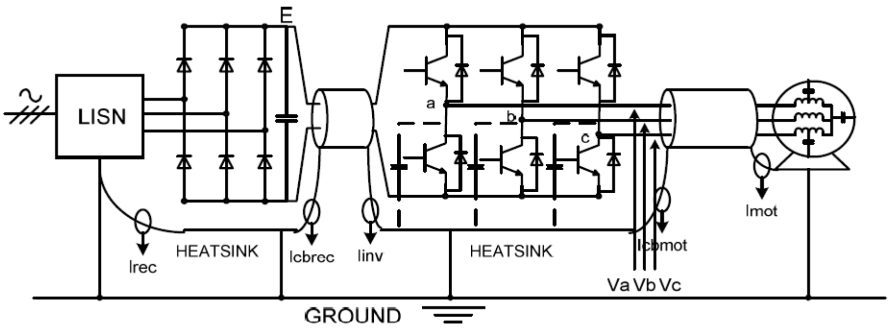

FIGURE 2. Schematic representation of the studied adjustable-speed AC motor drive

motor (Leroy Somer, 400 V, 3 kW, nominal speed: 1500 rpm), and power shielded cables (four conductors, section = 5 mm^2, shielding braid; 1-m cable is connected between the rectifier and the inverter and 5-m cable links up the inverter and the motor). The experimental test bench is depicted in Figure 1.

The schematic representation can be shown as in Figure 2.

In general, the PWM inverter is a major source of EMI because the design of its conversion structure is principally realized in a way of minimizing switching time. This approach will generate great abrupt variations of voltage and current. For example, a GTO semiconductor can switch at a rate of 500 A/μs and 1000 V/μs [17]. These variations of electric parameters are a main cause of EMI generation. Moreover, in the considered system (Figure 1), the three-phase power cable linking up the inverter and the motor is an important element to transport conducted electromagnetic disturbances to damage or degrade, for example, motor bearings.

The parasitic CM currents, which are the most disturbing in such a system, will be experimentally measured at the positions as indicated in Figure 2.

To measure CM currents flowing through the system via conductors and ground, the system is positioned on a 2-m^2 copper ground plane, except a dc generator loaded by a bulk resistor used as the load of the system and the motor are placed on a thick PVC plate to insulate them from the ground. The PVC plate introduces its own parasitic capacitance in series with former capacitance between the motor frame and the ground; consequently, the equivalent stray capacitance becomes much lower than parasitic capacitance of the cable. Therefore, all parasitic CM currents flowing through the motor only return to the CM source by the cable shield. This allows us to easily measure CM currents in the motor (I_{mot}) as indicated in Figure 1 because CM current measurement in ground plane is difficult to carry out. Besides, every part of the system can be separately connected to ground in order to independently estimate or measure the parasitic CM current issued from each part of the whole system.

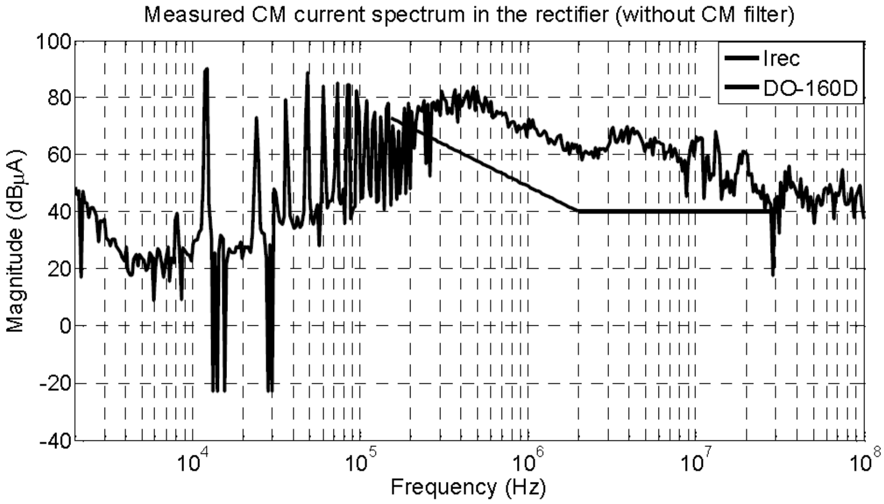

FIGURE 3. Common-mode current spectrum measured at electrical network side

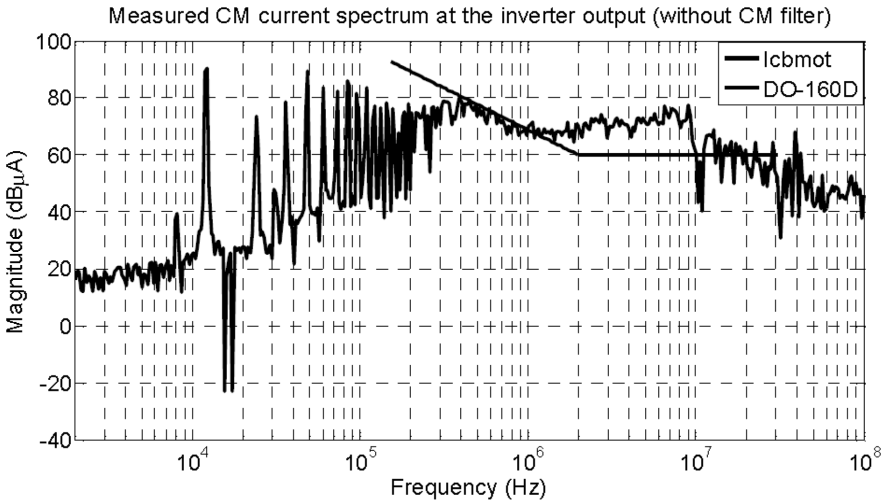

FIGURE 4. Common-mode current spectrum measured in the power shielded cable feeding the motor

3. **Common-Mode Current Spectra Measured in the System.** CM current spectrum is measured at every part of the system as illustrated in Figure 2 (in the rectifier (I_{rec}), in the cable (I_{cbrec} and I_{cbmot}), in the inverter (I_{inv}), and in the motor (I_{mot})) in the frequency range of 2 kHz to 100 MHz. The measured CM current spectra in the rectifier (I_{rec}) (the part connected to electrical network) and in the power shielded cable feeding the motor (I_{cbmot}) are illustrated in Figure 3 and Figure 4, respectively.

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

4. **Commercial Passive EMI Filter.** The filtering technique, which is a classical method to reduce EMI emissions, is still applied in many applications. The functioning principle of passive EMI filter is generation of an impedance mismatch, minimizing

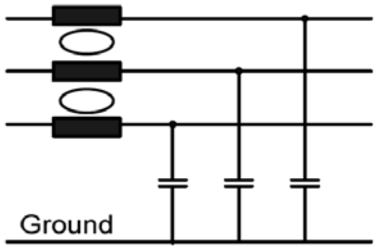

FIGURE 5. Classical structure of passive EMI filter in L

disturbing energy transfer between the disturbance source and the load of the system on the considered frequency range. Since high-frequency (HF) electromagnetic disturbances are dominant and must be eliminated, three structures of low-pass EMI filter can be applied. These types of filter are in structure of Π, T and 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 as shown in Figure 5. 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. Hence, if these parameters can be controlled in phase of realization, the EMI filter performance will be increased.

Normally, during design phase, a commercial EMI filter is carried out by considering that the system, which is designed for, comprises the impedances of source and load equivalent to 50 Ω and 50 Ω or 0.1 Ω and 100 Ω or 100 Ω and 0.1 Ω. Then, the insertion loss (IL) is calculated for each type of filter. We notice that these impedances do not represent the real impedances of the system; consequently, insertion of this filter is less effective, in particular at HF. However, the element values of EMI filter can be determined using some simulation software such as PSpice, PSIM, and Saber. The designer will try with some values of each element (L and C), and then visualize the results whether the parasitic currents are minimized and respects the standard. This method can be called "cut-and-try method", which is used in most research papers concerning EMI filter. By this reason, the optimization is necessary in order to save time and increase design performance. Several research papers have been proposed about EMI filter optimization techniques [18,19]. These are more or less complex. In this paper, an algorithm of EMI filter optimization is also proposed in order to acquire optimized values of each element of filter, adapted to the considered system. The proposed technique is different from the others.

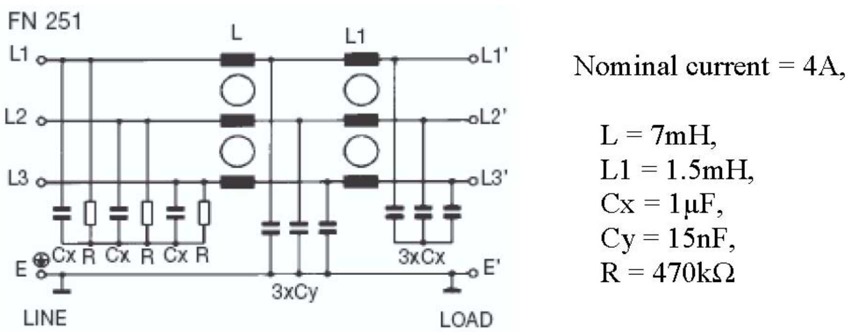

FIGURE 6. Commercial passive EMI filter used in this study

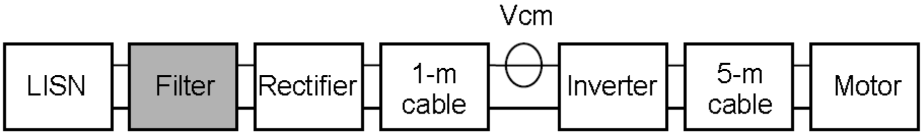

FIGURE 7. Studied system including an EMI filter represented at CM standpoint by two-port networks in cascade

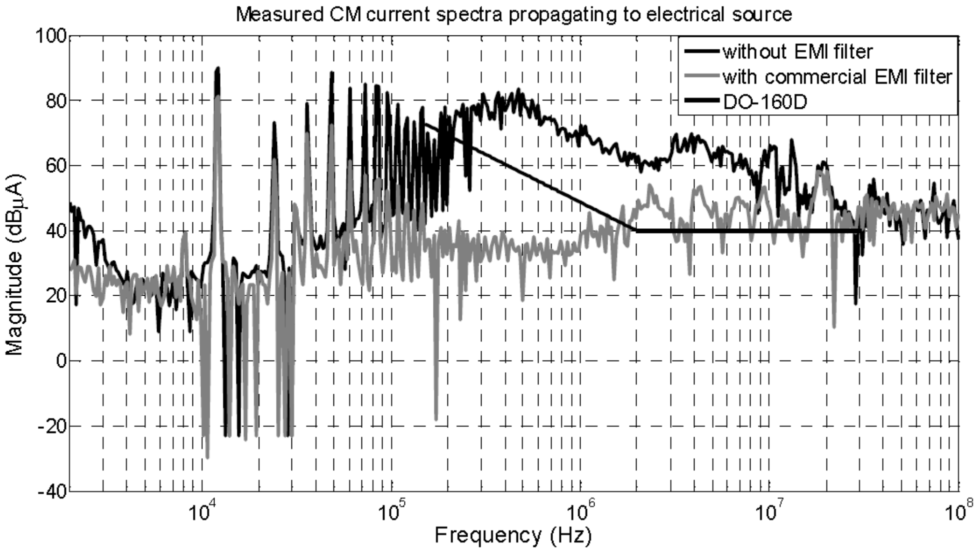

FIGURE 8. Common-mode current spectra in the system with/without the commercial EMI filter

In this study, the employed commercial passive EMI filter has characteristics as illustrated in Figure 6.

If we focus on minimization or elimination of CM currents at the electrical source side in the considered system, we can try by adding a known commercial passive EMI filter at the input of the rectifier as depicted in Figure 7.

When the commercial EMI filter is inserted in the system at the position as indicated in Figure 7, minimized CM current spectrum at the input of the filter is illustrated in Figure 8. The minimized CM current spectrum still exceeds the applied standard level (from 2 MHz to 30 MHz). As a result, elements values of this kind of filter should be optimized in order to obtain CM current spectrum below the normative level on all frequency range.

5. **Modeling of System with Insertion of EMI Filter Using Two-Port Network Technique.** The CM conducted noise emissions generated in such a system without an EMI filter is already modeled by two-port network approach and validated up to 10 MHz approximately in [16]. In order to reliably optimize a passive CM filter using two-port network technique, a known passive EMI filter has to be first inserted in the system to ensure and confirm the validity of the modeling approach when the system becomes more complex (Figure 7).

The modeling principle is described in [16]. Briefly, to acquire simulated results based on this modeling approach, it consists of determining, by specific experimental characterizations, equivalent CM impedances of each element 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.

$$\begin{bmatrix} T_{11} = \frac{Z_{11}}{Z_{21}} & T_{12} = \frac{Z_{11}Z_{22}}{Z_{21}} - Z_{12} \\ T_{21} = \frac{1}{Z_{21}} & T_{22} = \frac{Z_{22}}{Z_{21}} \end{bmatrix} \tag{1}$$

To apply the two-port network model to the studied system, the equivalent CM impedances of each part have to be determined. The input and the output of the considered part (i.e., inverter, power cable, and motor) must be short-circuited, and then the impedance is measured between conductors short-circuited and the ground of that part as represented by Figure 9.

For the commercial EMI filter shown in Figure 6, its CM impedances are depicted in Figure 10.

The results show that there are effectively parasitic elements of the filter; this fact can be noticed from the resonances of this filter. That is why, in phase of design, most engineers must be aware of these self-resonant effects of the parasitic winding capacitance of an inductor and the parasitic inductance of a capacitor in order to increase the EMI filter performance [20].

Next, the simulated CM currents and/or CM voltages are computed in Matlab by using transfer matrix [T] relations defined by (2).

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = [\mathbf{T}] \cdot \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \tag{2}$$

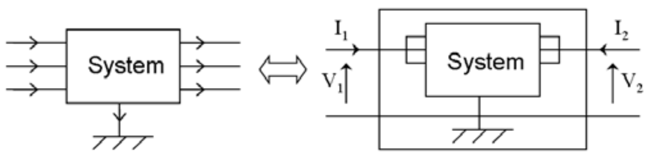

FIGURE 9. Representation of a sub-system at CM standpoint, associated to electrical parameters

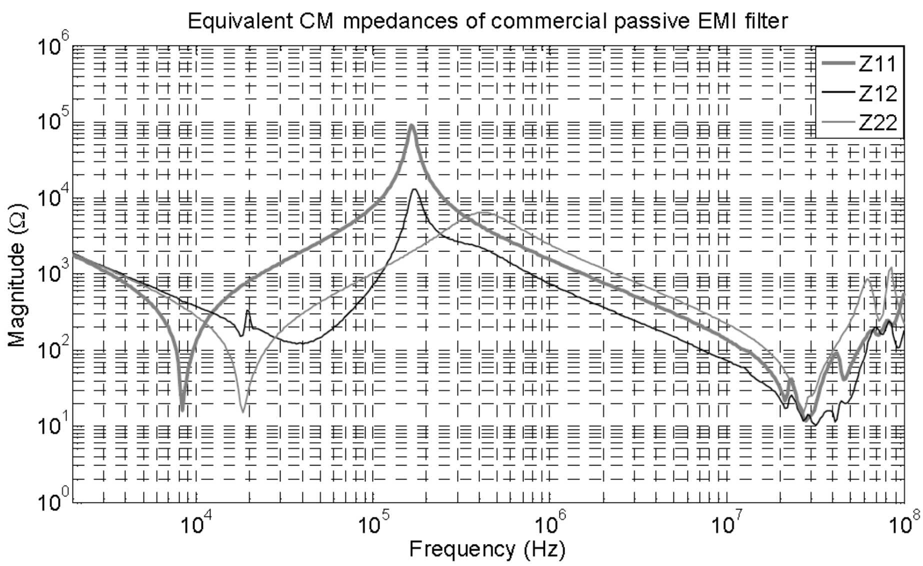

FIGURE 10. Magnitude of equivalent CM impedances of commercial EMI filter in frequency domain

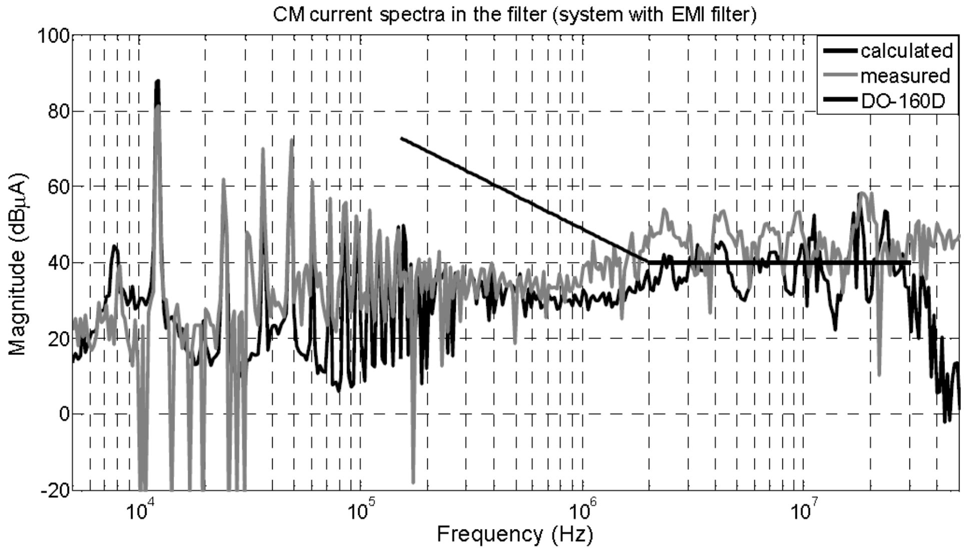

FIGURE 11. Comparison between measured and simulated common-mode current spectra at the input of the commercial EMI filter

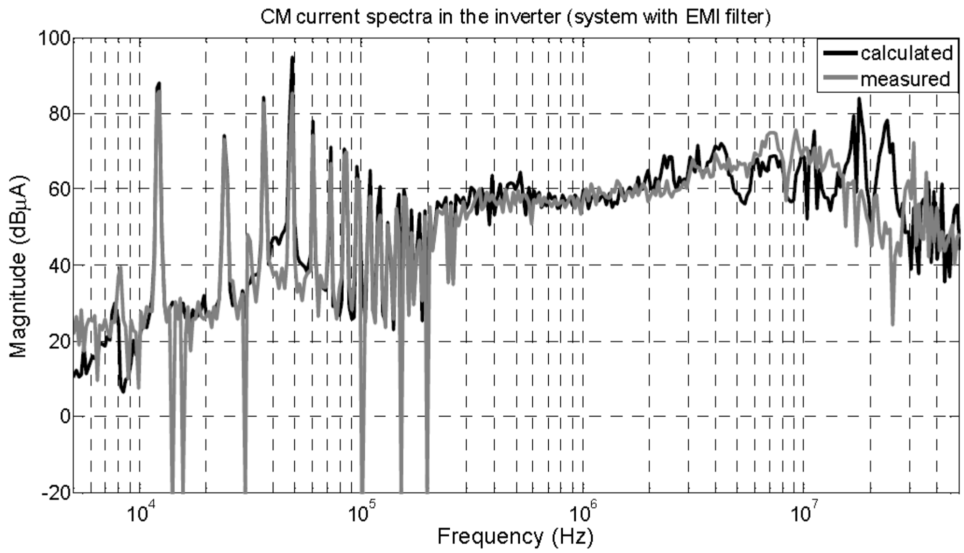

FIGURE 12. Comparison between measured and simulated common-mode current spectra at the input of the PWM inverter

Some examples of comparison between measured and calculated CM current spectra at the input of the commercial EMI filter and the input of the PWM inverter are illustrated in Figure 11 and Figure 12, respectively.

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 common-mode EMI filter adapted to the considered AC motor drive system in order to respect an applied EMC standard.

6. **Common-Mode EMI Filter Optimization Using Two-Port Network Model.** The main objective in this study 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 or at the load side. Thus, LC structure as shown in Figure 5 is chosen in this study, and added in the system. If we focus on minimizing CM current propagating to

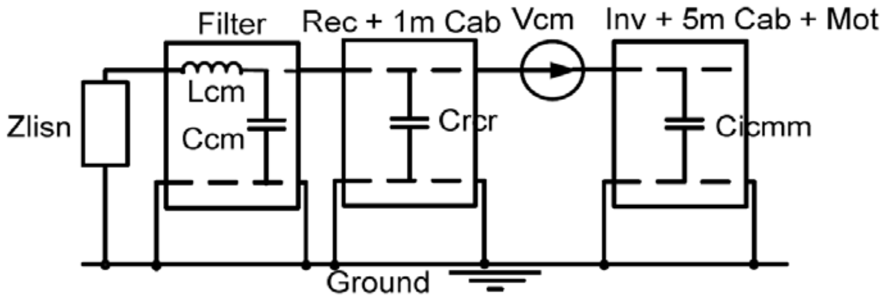

FIGURE 13. Considered system with insertion of a passive EMI filter at the input of AC motor drive

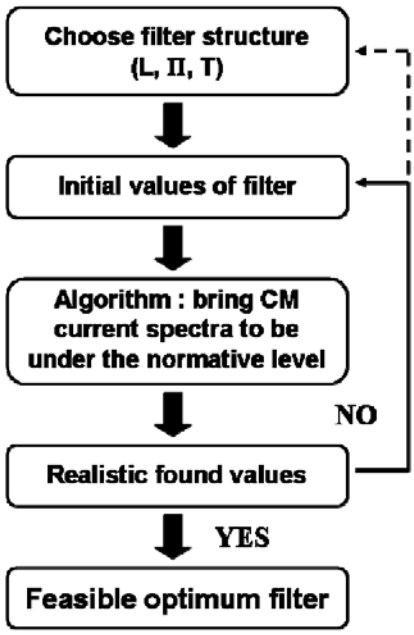

FIGURE 14. Flowchart for common-mode filter optimization algorithm

the electrical source side, the CM filter is located at the input of the rectifier as presented in Figure 13. By applying two-port network method, equivalent CM impedances of each part can be measured, and then the values of equivalent parasitic CM capacitances at low frequencies (LF) are obtained, which are $C_{rcr} \approx 595$ pF and $C_{icmm} \approx 8.5$ nF.

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

The algorithm process used to optimize passive CM filter is described by the flowchart in Figure 14.

After optimization, to reduce CM currents propagating to electrical network, the obtained element values of optimized CM filter 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 Figure 15.

The algorithm used to bring CM current spectra to be under the normative level in the considered frequency range (150 kHz – 30 MHz) according to the EMC standard is shown below:

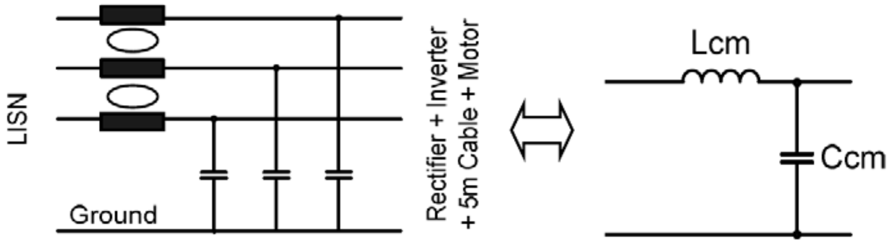

FIGURE 15. Single-phase representation of optimized CM filter structure

```
f = Tmes(:,1); %define frequency range (2 kHz – 100 MHz) (401 points)
diff = Tmes(:,1);
diff(:,1) = 0;
for i = 161 : size(f,1) %for frequency range of 150 kHz – 30 MHz
    if (20*log10(irec(i,1)/1e-6))−(gabrs(i,1)) >= 0 %irec is CM current in the
                                                      rectifier and gabrs is the DO-160D
                                                      normative level
        diff(i,1) = (20*log10(irec(i,1)/1e-6)−gabrs(i,1));
    end
end
```

6.2. **Common-mode current spectra issued from system with insertion of optimized passive CM filter.** By using the optimized values of CM filter obtained in the previous section, the minimized CM current spectrum is represented in Figure 16. We notice that CM current is greatly minimized.

However, to take into account the real behaviour of filter, parasitic elements of each component (L_{cm}, C_{cm}), which play generally important part, especially in HF, have to be added in the CM filter model in the optimization programming. This allows us to efficiently predict or estimate the optimized CM filter effectiveness.

In general, the simple model of the real behaviour of inductor is constituted of a resistance R_s in series with L_{cm} and a capacitance C_p in parallel as illustrated in Figure 17(a)

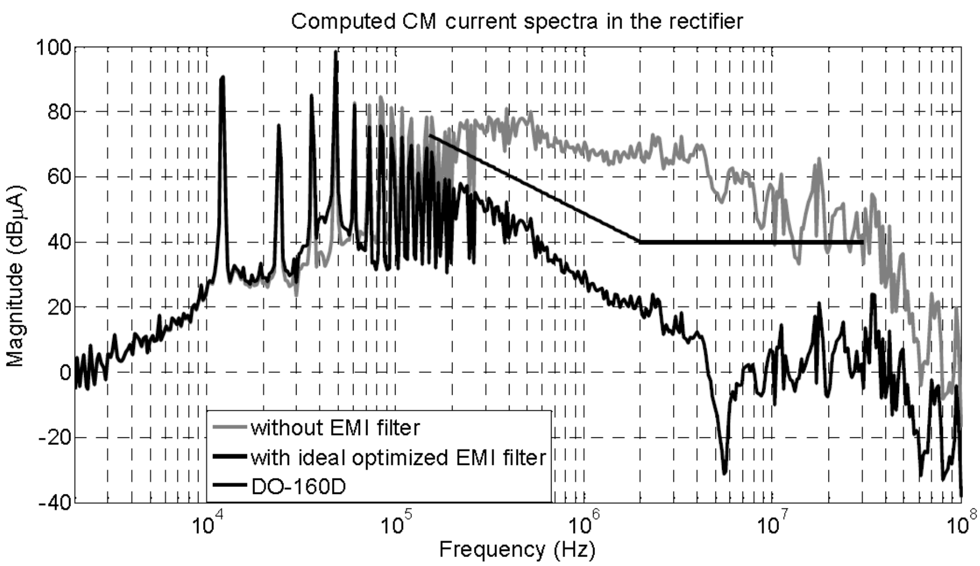

FIGURE 16. Common-mode current spectra in the rectifier without/with ideal optimized CM filter

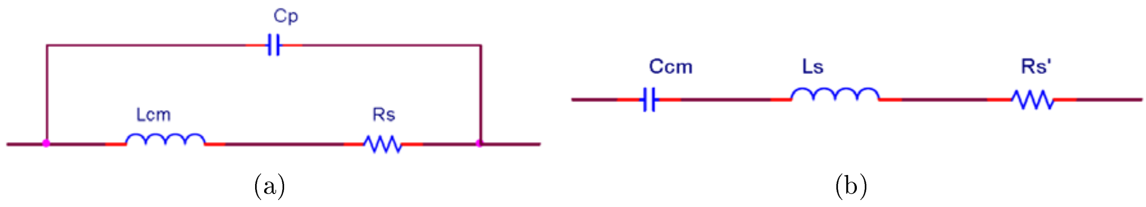

FIGURE 17. Real behavioural model of inductor (a) and that of capacitor (b)

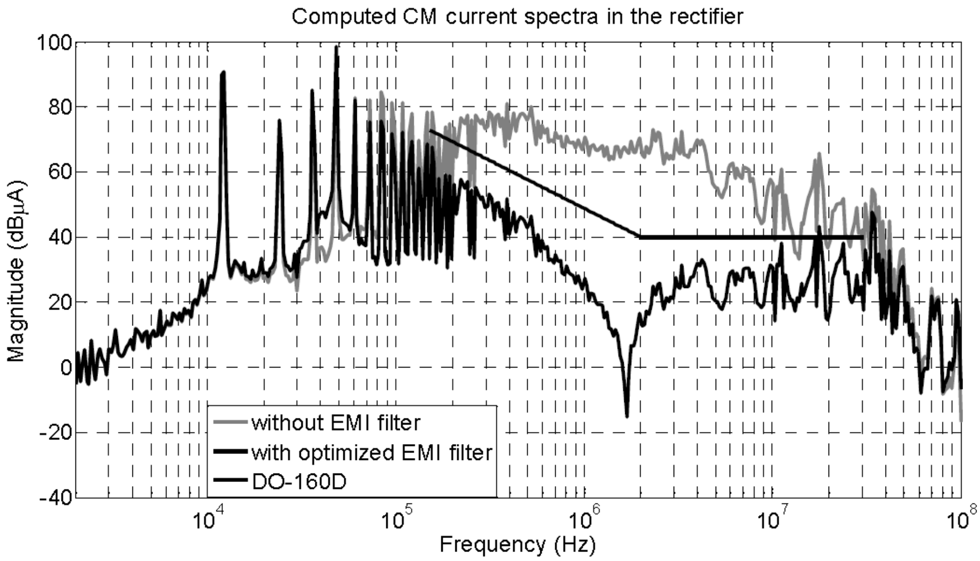

FIGURE 18. Common-mode current spectra in the rectifier without/with optimized CM filter taking into account its parasitic elements

and that of capacitor is constituted of a resistance $R_{s'}$, an inductance L_s in series with C_{cm} as illustrated in Figure 17(b). But in our case, the parasitic elements of C_{cm} could be neglected because C_{cm}(0.72 pF) is negligible before C_{rcr}(595 pF); 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 are 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 taking into account all parasitic elements in the model of the optimized CM filter is depicted in Figure 18.

According to the simulated results (Figure 16 and Figure 18), we agree that parasitic elements of passive CM filter play the part very importantly on its effectiveness, especially at HF. In practice, to realize this kind of EMI filter, we have to control its parasitic elements.

7. **Insertion of a Passive EMI Filter at the Output of the PWM Inverter.** In order to reduce or eliminate CM high frequency currents flowing through the motor windings, we put a passive EMI filter at the output of the inverter of the system as represented in Figure 19.

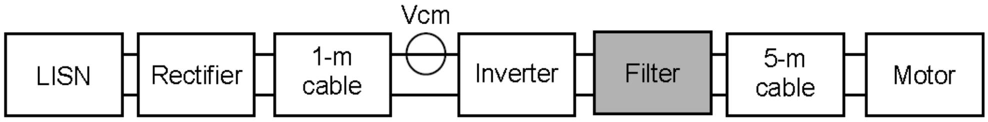

Figure 19. Representation of the system with an EMI filter at the output of the inverter, at CM standpoint by two-port networks in cascade

7.1. **Measured common-mode current for commercial EMI filter placed at the output of the PWM inverter.** When the commercial EMI filter (as depicted in Figure 6) is added at the output of the inverter as indicated in Figure 19, the reduced CM current spectrum is illustrated in Figure 20. The minimized CM current spectrum respects the applied standard level. Even though the chosen commercial EMI filter can reduce the CM currents on all the considered frequency range at the output of the inverter, we notice that the values of L and C are rather large. This increases the weight, volume, and cost of the PWM inverter. That is why, optimization of this kind of filter is necessary in order to acquire an optimum EMI filter.

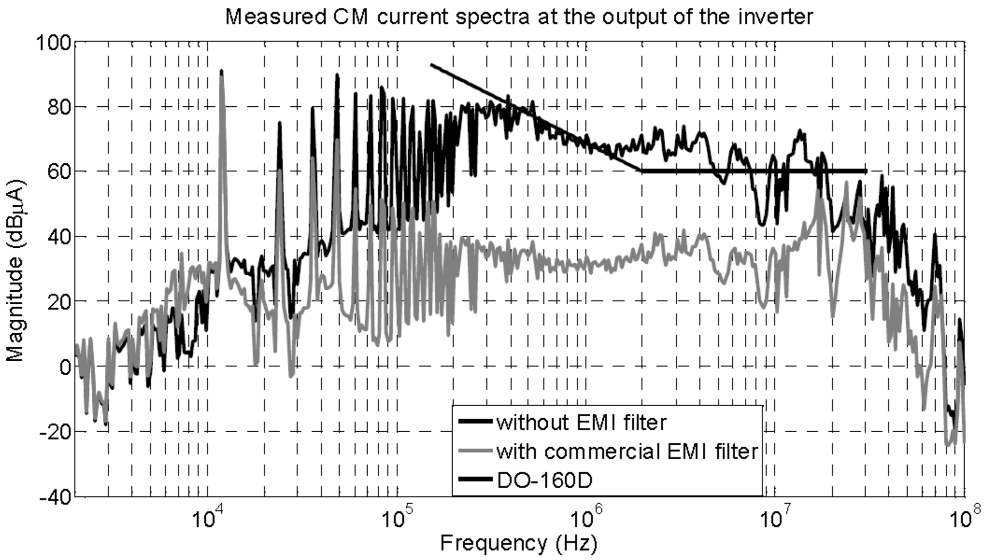

Figure 20. Common-mode current spectra in the system with/without the commercial EMI filter, at the output of the inverter

7.2. **Simulated common-mode current for optimized CM filter placed at the output of the PWM inverter.** As the DO-160D standard is applied for EMI level both 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 CM filter positioned at the output of the PWM inverter. The LC structure including parasitic elements is still used in this case.

For the optimized EMI filter, LC structure is still chosen and its equivalent model is shown in Figure 21.

After optimization, the obtained values are $L_{cm} = 0.123$ mH, $R_s = 1.03\ \Omega$, $C_p = 28.56$ pF, and $C_{cm} = 23.44$ pF (negligible before equivalent CM impedance of motor cable and motor ($C_{cmm} \approx 8$ nF)). These values are lower than those of the commercial filter. The simulated CM current spectra while inserting the optimized EMI filter at the inverter output is depicted in Figure 22.

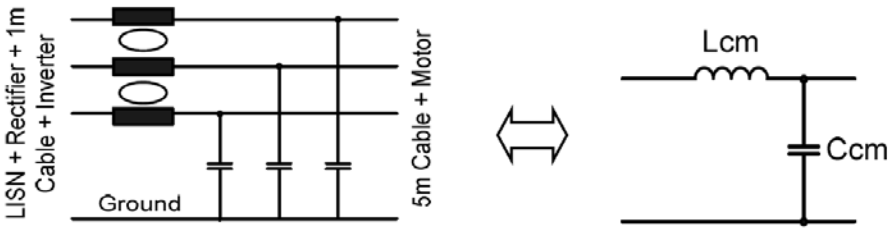

FIGURE 21. Equivalent model of optimized CM filter

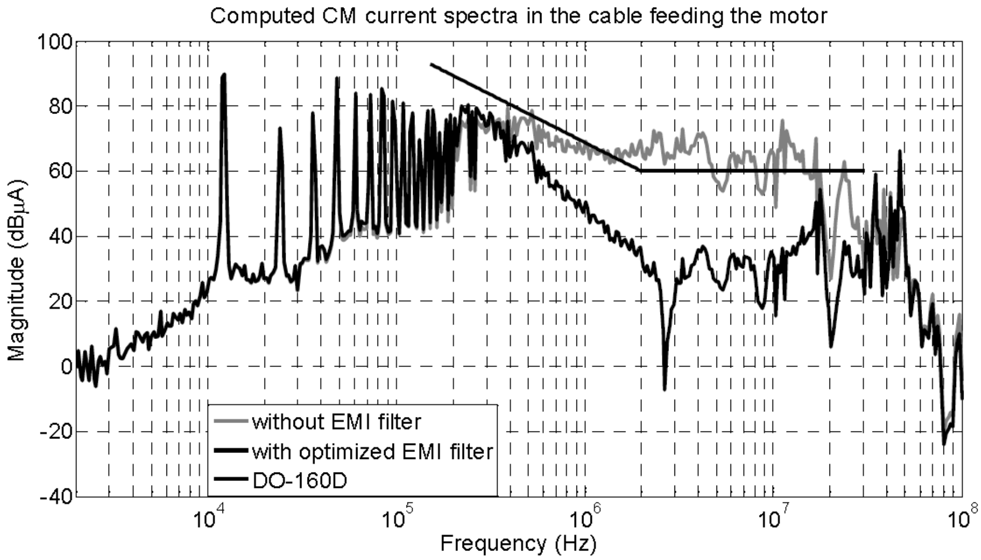

FIGURE 22. Common-mode current spectra in the power cable feeding the motor in the system without/with optimized CM filter placed at the output of the inverter

The result shows that the optimized EMI filter taking into account its parasitic elements can effectively reduce the CM currents flowing through the motor windings on the considered frequency range. In addition, at HF, it can reduce the CM currents better than the commercial filter used in this study.

8. **Conclusions.** The passive common-mode EMI filter adapted to a considered three-phase adjustable-speed AC motor drive was optimized based on two-port network model. This filter optimization can be trustworthy owing to validation of the applied model capable of predicting or estimating CM currents at each node of the system fairly correctly up to 10 MHz. The results show that the optimized CM filter reduces CM conducted noise emissions better than the commercial EMI filter used in this study. The reason is that the first one is determined from the true values of CM impedances of the system contrary to the second one designed for generic propagation impedances of source and load, which are equal to 50 Ω/50 Ω, 0.1 Ω/100 Ω or 100 Ω/0.1 Ω. Moreover, 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 power converter as presented in this paper, and effectively used in other dc or ac motor drive systems. The effectiveness of the EMI filter depends on the objective. In this paper, the normative level DO-160D was chosen to design the low-pass CM filter and to demonstrate its effectiveness. In practice, the parasitic elements of the EMI filter should be controlled so as not to degrade its effectiveness, especially at HF.

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