A feedback-type Common Mode Active Filter for Vehicular Induction Motor Drives

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***Abstract* –A common mode (CM) EMI active filter for automotive induction motor drives is proposed. The active filter is useful in compensating the CM voltage at the motor input, allowing an increase of the drive reliability and a reduction of the leakage high frequency CM currents which affect the vehicle Electromagnetic Compatibility (EMC). The active filter is based on a feedback-action and it is realized using linear amplifiers. These features lead to an increased efficiency and compactness. The system analysis and its experimental implementation are presented.**

Keywords: EMI filters, vehicles EMC, induction motor drives.

I. INTRODUCTION

The More Electric Vehicle (MEV) is a concept that has encountered a great success in the last years. It emphasizes the employment of electrical power systems in place of mechanical and hydraulic systems. The MEV concept simplifies the use of high power loads and enables the introduction of power electronics in order to optimize, in the automotive field, fuel economy, environmental emissions, performance and reliability [1]. In addition to the development of more electric vehicles, the use of voltage levels higher than 12 V in the vehicular environment is currently considered the solution to the increase of on board electrical power demand by defining new control strategies to suitably manage the power loads requirements [2], [3]. As a consequence, a growing use of switching power converters is expected in order to improve the flexibility of the load management and overall vehicle energy saving, leading to a strong increase of the on board electromagnetic (EM) emissions. When the vehicular electrical load is an induction motor drive, the high switching frequency of the power converter (usually a PWM inverter) is the cause for the arising of electromagnetic interference (EMI). A critical issue is the study and control of the EMI towards the power supply line since it can degrade the operation of other apparatus and systems that coexist in the vehicle, especially the sensitive electronic loads. In particular, high frequency current, lying on the vehicle frame, can jeopardize the vehicle EMC. On the other hand, as far as the electromagnetic disturbance at the output of a PWM inverter (i.e. towards the motor) is concerned, particular attention has to be paid to the common mode (CM) voltage. As a matter of fact, the CM voltage on the stator windings creates a shaft voltage by capacitive coupling through the motor air-gap and consequently electrostatic discharges are generated through the bearing lubricating film. Motor bearings suffer for such currents, that are the cause of a dramatic reduction of their lifetime [4]-[6].

Recently, many research contributions have been presented in technical literature in the field of devices for controlling and reducing the CM disturbance in induction motor drive. These remedies are applied both to industrial and vehicular drives. In [7]-[9] remedies based on the use of passive filters in the automotive environment are presented. In [10] active filtering techniques for vehicles DC/DC converters ripple attenuation are discussed. Such contributions are intended for the reduction of EMI disturbance towards the DC supply line. Several papers have been published in which the following advantages of common mode active filters applied to induction motor drives are highlighted: an increase of the motor reliability due to the increased lifetime of the bearings, an improvement of the electromagnetic compatibility due to the reduction of common mode ground current and of common mode EMI emission towards the supply [11]-[15]. In [16] the effects of a feed-forward active compensation device for the attenuation of the CM voltage towards the motor in an induction motor drive, typical for vehicle traction, is presented. In this paper a new configuration of CM active filter for a 1.1 kW 42 V induction motor drive is proposed. This device differs from the systems previously set-up [15], [16] because it is dedicated to motor drive supplied by low voltage DC bus, it utilizes linear circuits and it is based on a feedback-action. The proposed active filter is useful in compensating the CM voltage at the motor input, allowing an increase of the drive reliability and a reduction of the leakage ground current. The proposed system is a voltage-sensing voltage-compensating device and its operation is based on a feedback action. The design and the experimental implementation of the device are explained in detail and its performance is analyzed in terms of compensation capability and stability. Simulation and experimental results are given.

II. BASIC PROPERTIES OF THE FILTER UNDER STUDY

Classifications of the active filter topologies, used in controlling EMI, are given in [17]-[18]. This section presents a brief survey. In general the active filters operation is based on the detection of the disturbance at the source or at the receiver and on its compensation. On the basis of where the detection system is located, a first grouping of

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active filters can be done in: feedback and feed-forward schemes. In feedback active filters the disturbance is detected at the receiver while in feed-forward type the disturbance is detected at the source.

A further classification in CM or differential mode (DM) active EMI filters is done according to EMI active compensation is intended for CM or differential mode (DM) disturbance. Moreover EMI active filters can also be designed and set-up so to minimize high frequency disturbance either at the source side or load side, these possible realizations are called input and output active EMI filters, respectively.

In this paper the study is focused on a feedback-type CM output active EMI filter, for application within a vehicular PWM induction motor drive. In particular a voltage sensing-voltage voltage-compensating topology is considered. The reason of this choice lies on the good performance of the considered scheme in canceling the CM voltage at the motor input. Fig. 1(a) shows the schematic configuration without the active filter.

The CM disturbance source is represented by the voltage generator v_s with its internal impedance z_s, the disturbance receiver is the motor, modeled by its CM impedance z_r. In Fig. 1(b) the configuration with the insertion of active filter is reported.

The accurate determination of the values of z_s and z_r is crucial since the filter performance is sensitive to source and “victim” impedances. These values affect an important filter figure of merit, i.e. the insertion loss (*IL*), defined as the ratio of the voltage amplitude at the receiver, in a test configuration without the filter installed v^0_r, to the voltage amplitude with the filter installed v_r.

The voltage on the motor without CM active filter is given by:

$$v_r^o = v_s\left[z_r/\left(z_r + z_s\right)\right] \tag{1}$$

The voltage on the motor with the CM active filter is:

$$v_r = v_s\left[z_r/\left(z_i + z_s\right)\right] \tag{2}$$

where z_i represents the impedance seen by the CM generator with the active filter, as shown in fig 1(b), given by:

$$z_i = z_r\left(A+1\right) \tag{3}$$

in which A is the active filter amplifier gain. On such a basis the expression of the active filter *IL* can be obtained:

$$IL = \frac{v_r^0}{v_r} = \left(1 + \frac{A z_r}{z_s + z_r}\right) \tag{4}$$

The condition for maximizing the *IL* is: $z_s << z_r$. In our case the *IL* is maximized since the PWM inverter can be considered as an ideal voltage source, that means $z_s \approx 0$, while z_r, i.e., the CM impedance of the induction motor, ranges from $10^2\,\Omega$ to $10^3\,\Omega$.

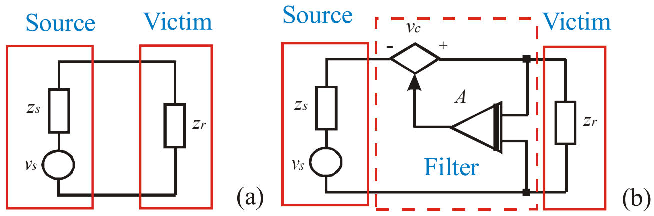

Fig.1. Schematic configuration of the CM noise generator and the victim (a); representation with the insertion of the feedback active filter (b).

III. FEEDBACK CM ACTIVE FILTER IMPLEMENTATION

In a motor drive without any filtering device, the CM voltage generated by the PWM inverter is directly applied to the motor terminals, as shown in Fig. 2 (a). Fig. 2 (b) illustrates a block diagram of the proposed feedback CM EMI active filter. In this configuration an error signal is obtained by a comparison of the CM voltage detected at the motor terminals with a voltage reference, v_{ref}, set to zero.

This error signal is processed by a PI regulator and then a linear power amplifier supplies the primary winding of a common mode transformer (CMT), that is used to inject the compensation voltage in the power cable. Fig. 3 shows a circuit scheme of the active CM EMI filter within a three phase power drive system. In order to investigate the performance and stability of the proposed device, the expression of the open loop transfer function is considered. It is given by the product of the following transfer functions: PI regulator, linear amplifier, CMT.

The PI regulator is expressed by:

$$T_{PI}(s) = K_P \frac{\left(s + K_I/K_P\right)}{s} \tag{5}$$

where K_p and K_I are the gains of the proportional and integral actions, respectively.

The linear amplifier is expressed by:

$$T_A(s) = \frac{K_A}{s + p_A} \tag{6}$$

where K_A is the gain of the amplifier in the operating bandwidth and p_A is the high frequency pole of the amplifier.

Finally the CMT can be represented as a band-pass filter, then its transfer function is given by:

$$T_{CMT}(s) = \frac{p_2 s}{\left(s + p_1\right)\left(s + p_2\right)} \tag{7}$$

where p_1 and p_2 are the low frequency and the high frequency poles, respectively.

Therefore the overall open loop transfer function is:

$$T(s) = G \frac{\left(s + K_I/K_P\right)}{\left(s + p_1\right)\left(s + p_2\right)\left(s + p_A\right)} \tag{8}$$

with $G = K_P K_A p_2$.

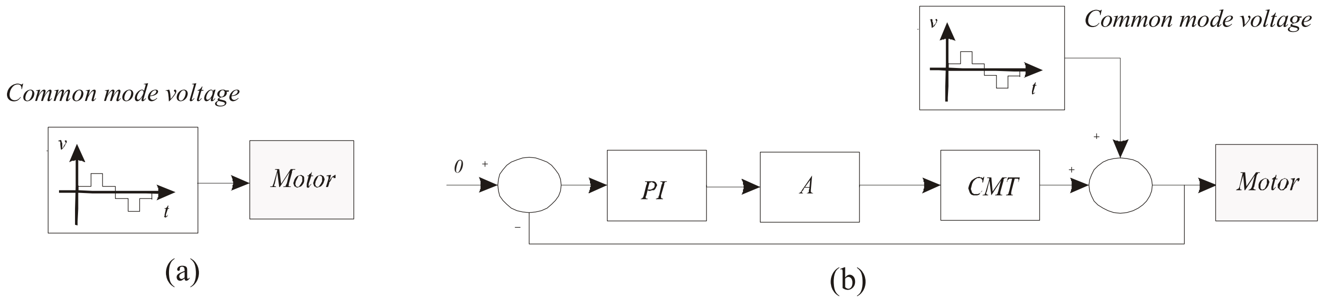

Fig.2. Schematic configuration of the CM voltage applied to the motor: without the CM active filter (a); with the CM active filter (b).

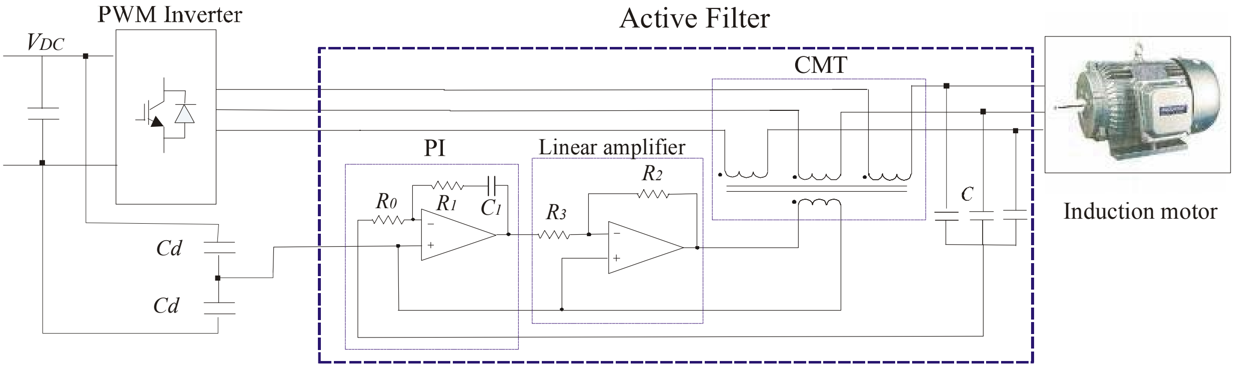

Fig.3. Circuit scheme of the active filter inserted in PWM induction motor drive.

The CM voltage is detected by using a three wye-connected capacitors C (see Fig.3), it is applied to a PI realized with an operational amplifier in inverting configuration which has a transfer function given by: $T_{PI} = -\frac{1 + s\,C_1 R_1}{s\,C_1 R_0}$ and the parameters of the PI are:

$$K_I = 1/C_1 R_0 \quad ; \quad K_P = R_1/R_0 \tag{9}$$

The linear amplifier is a power operational in inverting configuration, its gain is given by $-R_2/R_3$; taking into account the product gain-bandwidth (*GBW*), its transfer function can be expressed as:

$$T_A = -\frac{R_2}{R_3}\frac{1}{1 + sGBW(R_3/R_2)} \tag{10}$$

Being both the PI regulator and the power amplifier in inverting configuration their connection nullifies the phase inversion therefore the minus sign in the sum block in Fig. 2 (b) is obtained by the CMT. The power operational provides the current required by the CMT. The CMT is composed of a four windings wound toroidal magnetic core where three windings, intended as secondary, are series connected to each phase of the three phase line connecting the inverter and the motor. The fourth winding, intended as primary, is directly connected to the output of the power amplifier. The ratio of the primary to the secondary windings is set to one.

The CMT is used to re-inject the common mode voltage, on the three phase line connecting the inverter and the motor, so performing the sum of the CM voltage generated by the motor and the compensating voltage due to the feedback action. The CMT is designed according to the following criteria: it has to work in linear region in order to obtain a good transfer of the compensating voltage to the motor terminals; a unique layer of turns have to wound around the magnetic core in order to avoid high frequency capacitive coupling between the turns layers; a realization as compact as possible should be set-up [15]. Furthermore the CMT bandwidth should be great enough to manage the CM voltage frequency content. It should be noted that the minimum primary turns number must be compatible with the rated current of power output stage.

The bandwidth of the CMT is about 1 MHz; it has been experimentally measured using the test rig described in [16].

IV. EXPERIMENTAL ARRANGEMENT

The CM EMI active filter is devoted to a vehicular motor drive having the features described hereinafter.

The motor drive under study is formed of a PWM IGBT voltage source inverter, with a switching frequency of 5 kHz and a 42V induction motor with a rated power of 1.1 kW. As far as the active filter is concerned, it has been realized by using a detection system formed of three star connected capacitors, whose values are: C=1nF.

The PI is designed with K_I= 0.1 and K_P= 10.

The power amplifier is realized by a BurrBrown OPA541. It has a rated power supply of ±40 V and it is able to reproduce the CM voltage to be applied to the primary of CMT (±21 V) with the required current and its *GBW* is equal to 1.6 MHz. Since, in our case, the rise time of the CM voltage is about 1 μs, the corresponding frequency of $1/\pi\tau_r$ = 0.32 MHz is contained into the bandwidth by setting p_A= 2 10^6 rad/s and consequently K_A= 5. Finally, as for the CMT, a single core of N30 ferrite has been utilized with 18 turns for each windings.

The measured lower cut-off frequency of the CMT is about 1 kHz and the upper cut-off frequency is equal to about 10 MHz. This corresponds to set p_1= 6.28 10^3 rad/s and p_2= 62.8 10^6 rad/s into eq (7). In Fig. 4 a photo of the active filter prototype is shown. By using eqs. (5-10) the values of the components for the PI and power amplifier can be identified. They are reported in Table I.

On the basis of the overall active filter features, a stability analysis is performed.

In Figs. 5 and 6 the Bode and Nyquist diagrams of the system open loop transfer function are plotted, respectively. It is possible to observe that, with the chosen design, the system is stable having an infinite gain margin and a phase margin, P_m, equal to 44.5 degrees.

Table I. Parameters values of the PI and the power amplifier.

	Parameter	Value
PI	R_0	47 kΩ
	R_1	470 kΩ
	C_1	100 µF
Power amplifier	R_2	50 kΩ
	R_3	10 kΩ

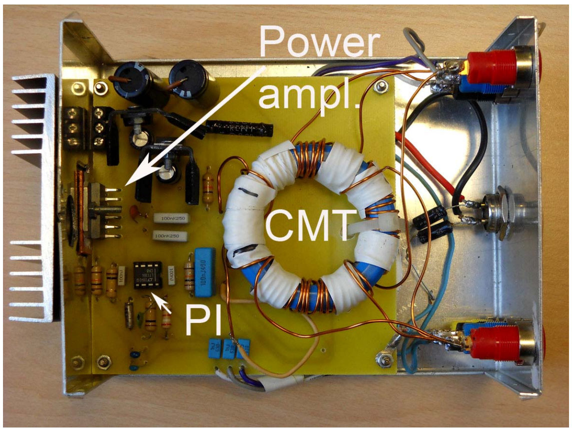

Fig.4. Picture of the active filter prototype.

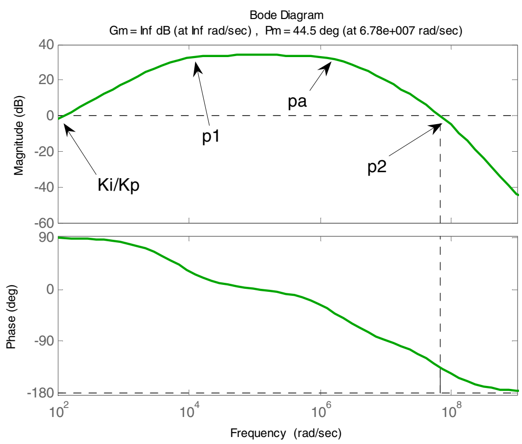

Fig.5. Bode diagram of the filter open loop transfer function.

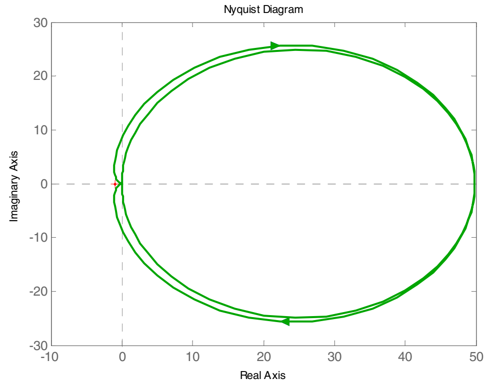

Fig.6. Nyquist diagram of the filter open loop transfer function.

V. SIMULATION AND EXPERIMENTAL RESULTS

A simulation and experimental analysis is performed in order to evaluate the active filter performance. In particular, the system model, described in Section III, has been implemented in Matlab/Simulink. A description of the motor high frequency model is deeply given in [16].

As shown in Figs. 7, 8 and 9, the active filter performs a strong attenuation both in the CM voltage at the motor terminals and in CM current on the ground connection of the motor itself. In Fig. 8 the compensating voltage generated by the active filter is shown together with the CM voltage produced by the PWM inverter. A detail of a CM voltage step with the corresponding compensating action is highlighted. The slight difference in the slope of the compensating voltage step, respect to the case of the CM voltage is the cause for the residual disturbance at the motor terminals after the introduction of the active filter.

The active filter has been experimentally tested, for the case of the previously described induction motor drive supplied by a 42 V DC bus. A digital oscilloscope (Tektronix TDS7254B) has been used to capture the time domain waveforms. Fig. 10 shows the curves obtained by the induction motor drive when no filter is used. In particular the blue upper trace represents the CM voltage without compensation, while the red lower trace is the CM current measured on the ground connection of the motor. It should be noted that the CM current profile is due to the derivative effect depending on the capacitive behavior exhibited by the motor towards ground. Fig. 11 shows a zoom of a single step transition of the CM voltage and the corresponding pulse of the CM current. The rise time of the CM voltage is about 130 ns, while the rise time of the current pulse is about 14 ns. The current pulse amplitude is of about 3 mA. On the basis of the CM current rise time, a maximum frequency, f_c, of the spectrum envelope can be estimated by:

$$f_c = {}^{1}\!/_{\pi\tau_r} \qquad (11)$$

where τ_r is the rise time. In our case f_c is about 22 MHz.

The effect of the active filter insertion is illustrated in Fig. 12. The CM voltage measured on the motor (middle green trace) shows the compensating action performed by the active filter. In particular the reduction of the peak to peak amplitude is around the 50%. The considered case is the worst condition since the rise time of the CM voltage to be compensated is much lower than the response time of the compensating circuit (limited by the power amplifier bandwidth). On the other hand, despite a slight increase of the CM current maximum amplitude, an improvement on its spectrum is observed because of the increase of the current pulse rise time up to about 100ns. This corresponds to a maximum frequency, f_c, equal to 3 MHz. However the CM current shows an under-dumped behavior due to the presence of the CMT secondary inductance inserted in the line between the inverter and the motor. This inductance causes a line impedance mismatch. All these phenomena are observable in Fig. 13 that zooms the waveforms of Fig.12. Fig. 14 shows the zoom of the CM voltage generated by the inverter, the filtered CM voltage and the corresponding CM current, obtained with a CM voltage rise time equal to 1μs. In this case the amplitude of the compensated CM voltage is further lowered as well as the current amplitude. Only the effect of the line impedance mismatch is noticeable in the CM current that still exhibits an oscillatory behavior. In order to suppress this residual oscillation on the CM current, a first- order capacitor-resistor termination [19] on the motor is used. In particular the resistor is designed according to the following relationship:

$$R_f > \sqrt{4L_c/C_f} \qquad (12)$$

where L_c=2.2 mH is the inductance of each secondary winding of the CMT. Imposing C_f=100nF, (12) is satisfied by R_f=300 ohm. The adoption of such a solution, together with the active filter, leads to a practically perfect compensation of both CM voltage and current, as in Fig. 15.

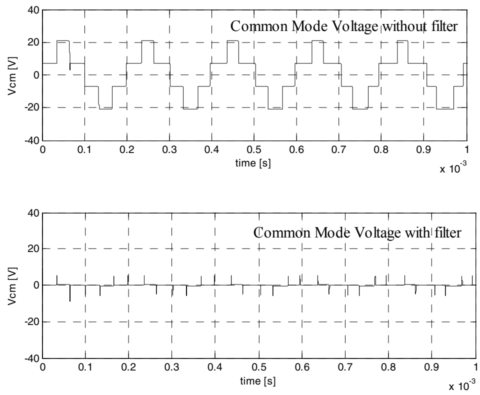

Fig. 7. CM voltage without and with the active filter (simulation).

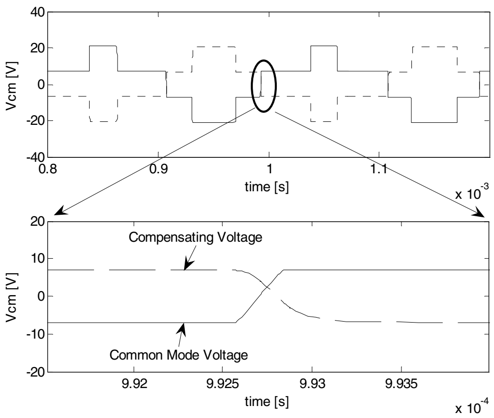

Fig.8. Detail of CM voltage and compensating voltage (simulation).

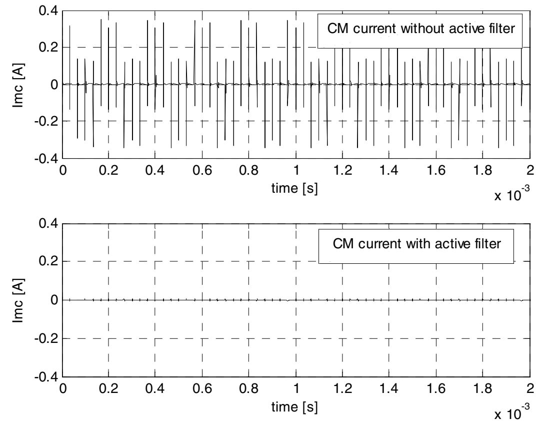

Fig. 9. CM current without and with the active filter (simulation)

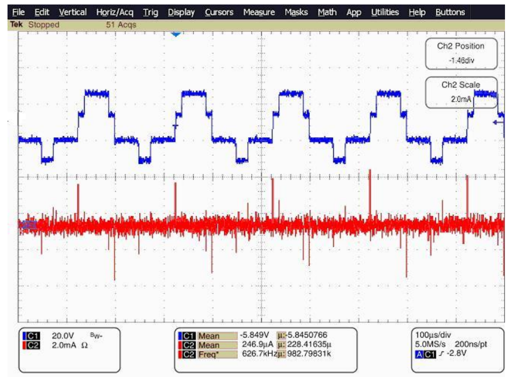

Fig. 10. CM voltage and current without the active filter (experimental).

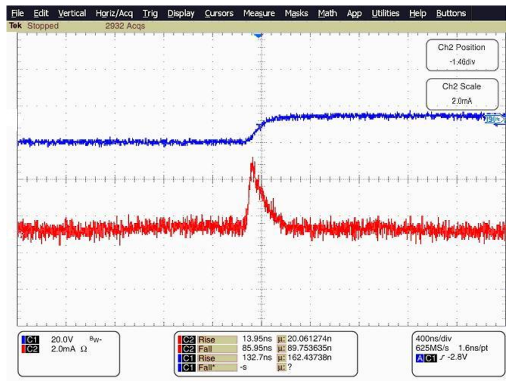

Fig. 11. Zoom of the CM voltage (upper trace) and current (lower trace) without the active filter (experimental).

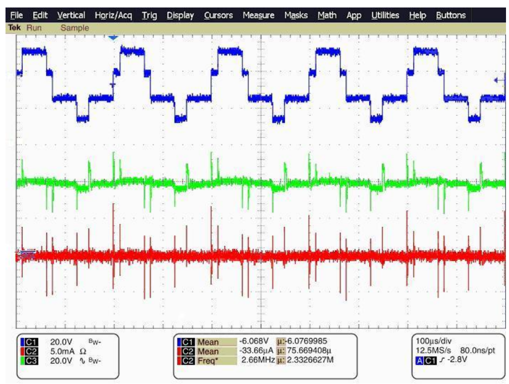

Fig.12. Measured: CM voltage generated by the inverter (upper trace); filtered CM voltage (middle trace); CM current (lower trace), (experimental).

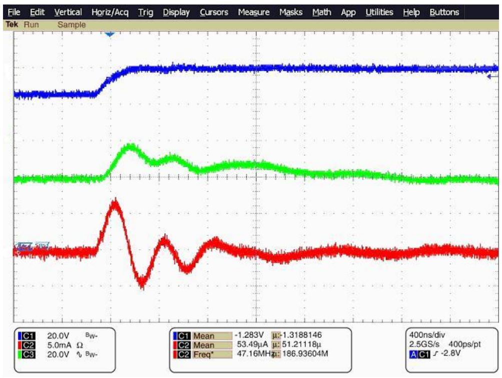

Fig.13. Zoom of the measured: CM voltage generated by the inverter (upper trace); filtered CM voltage (middle trace); CM current (lower trace), (experimental).

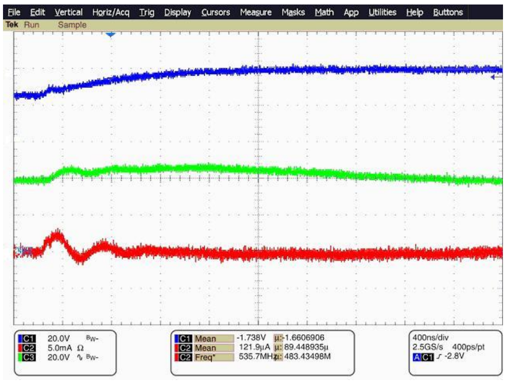

Fig.14. Zoom of the measured: CM voltage generated by the inverter (upper trace); filtered CM voltage (middle trace); CM current (lower trace) with a CM voltage rise time of 1μs, (experimental).

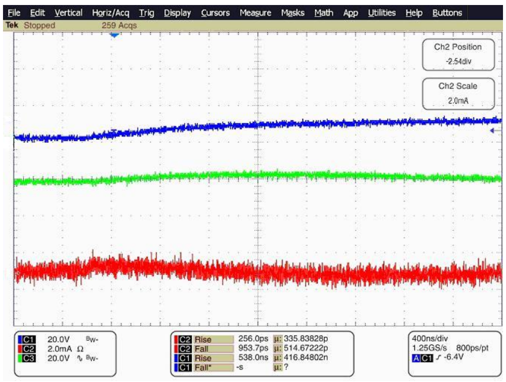

Fig.15. Zoom of the measured: CM voltage generated by the inverter (upper trace); filtered CM voltage (middle trace); CM current (lower trace) with a CM voltage rise time of 1μs and a first-order capacitor-resistor termination on the motor (experimental).

VI CONCLUSIONS

In this paper the design and set up of a CM EMI active filter for automotive induction motor drives is proposed. The system is a voltage-sensing voltage-compensating device. Its operation is based on a feedback action and on the use of linear amplifiers, it lessens the CM voltage on the motor terminals and the related leakage CM current flowing through the vehicle frame. A detailed description of the filter design and operation is given and the analysis of the system stability and performance is presented. The active filter has been built in laboratory and it has been tested in a 1.1 kW 42 V induction motor drive. Simulation and experimental results demonstrate the effectiveness of the proposed device in the attenuation of the CM disturbance.

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