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EMI Reduction in DC-Fed Induction Motor by Active Common-Mode Compensator

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ABSTRACT

A novel common-mode (CM) EMI active filter for dc fed motor drives is proposed. The active filter performs both the compensation of the CM voltage at the motor input and the mitigation of the leakage high-frequency CM currents, thus increasing the drive reliability and the vehicle electromagnetic compatibility (EMC). The filter scheme is based on a voltage feedback action and also includes a feed-forward action by exploiting a suitably estimated CM current. An optimized design of the CM voltage detection/injection systems is implemented. Moreover, the active filter is supplied by a smaller voltage than the dc link value; this permits a more performing amplifier to be used. The active filter behavior is analyzed theoretically and its performance is assessed by simulation. The realized proposed system shows a good efficiency and compactness.

Index Terms- ***Active filter, electromagnetic conductive interference, induction motor drive, vehicles.***

INTRODUCTION

DC fed motor drives are currently used in a broad variety of applications. In particular, they are suited to vehicle applications (road and marine vehicles, aircrafts, etc.) and can be simply operated in a dc distribution system, such as in the case of some residential/commercial building dc grids [1], [2]. With reference to vehicles, the evolution of their electrical architectures has shown a growing use of electrical loads, such as drives and actuators. For example, the more electric vehicle (MEV) [3], [4] concept encourages the employment of electrical power systems aimed at a better use of the high power loads. This is possible due to the introduction of power electronics to optimize fuel economy, environmental emissions, performance, and reliability of the vehicles, including sea, undersea, and air vehicles [1]–[5]. Therefore, a massive use of switching power converters is expected to improve the flexibility of the load management and overall vehicle energy saving. On the other hand, as far as the pulse width-modulated (PWM) drives are concerned, two main problems are encountered, which are related to the inverter high switching frequency operation. The first is the electromagnetic interference (EMI) toward the on-board power supply lines that can degrade the operation of other sensitive devices and systems coexisting in the vehicle environment. The second problem is related to the drive reliability. Indeed, 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. The motor bearings suffer for such currents that are the cause of a dramatic reduction of the motor lifetime [6]–[8]. An additional problem is given by vibrations and noise generated by motor drives in both civil (passengers' comfort) and military (acoustic discretion) applications, producing bearing damage, which, in turn, amplifies the phenomenon. Technical literature exhibits several studies dedicated to the control and mitigation of the EMI in motor drives used both in industrial and in vehicular applications [9]–[28]. A comprehensive study, giving a generalization of harmonic and EMI active filters behavior, is presented in [9]. As for the reduction of EMI disturbance toward the supply line, a survey of EMI mitigation techniques is proposed in [10] and a comparative study of CMM and differential mode (DM) active EMI filters compensation performance is proposed in [11]. As for the automotive environment, [12]–[14] suggest remedies based on the use of passive filters. In [15], [16] design criteria are proposed to optimize the performance and size of EMI passive filters, while in [17], an active hybrid filter is devised in which a CM active filter is used to reduce the size of the CM inductor of a passive EMI filter. In [18], a feed-forward, current-controlled, current-source active filter forCMnoise cancellation is proposed, and in [19] and [20], a feedback current detecting and current compensating configuration of active filter is presented. As for the electromagnetic disturbance toward the motor, it should be noted that the reduction of CMEMI, in addition to the increase of the motor reliability, contributes also to the improvement of the electromagnetic compatibility (EMC), due to the reduction of common-mode ground current and of common-mode EMI emission toward the supply. In [21]–[24], feed-forward active CM filters are proposed to reduce CM voltage at the motor terminals. In [25], the effects of a feed-forward active compensation device for the attenuation of the CM voltage toward the motor in an induction vehicular motor drive are presented. Finally, a prototype of a feedback CM EMI filter for low voltage automotive drives has been developed in [26]. In [27], a further improvement of the filter described in [26] is proposed, being based on the introduction of an additional feed-forward action, based on a suitably estimated CM motor current. This paper extends and deepens The work developed in [27], presenting a theoretical analysis of the filter behavior, according to which the advantage of the additional feed-forward action, in terms of EMI suppression, is demonstrated. A more detailed description of the filter design, including the CM current estimator, is also given together with additional experimental results for the numerical evaluation of the improvement due to the feed-forward action. The considered application is a 1.1 kW, 42 V PWM vehicular induction motor drive, even if it can be applied to other voltage levels by a suitable choice of the power amplifier. The filter scheme is of the voltage-sensing voltage-compensating type with a new design of the CM voltage detection and injection systems. The feed forward action is introduced enhancing the performance of the proposed circuit both in terms of motor CM voltage reduction and in terms of EMI mitigation in the frequency range between 10 kHz and 1MHz. Furthermore, according to a design oriented to the optimization of the power to size ratio, a compact layout is obtained.

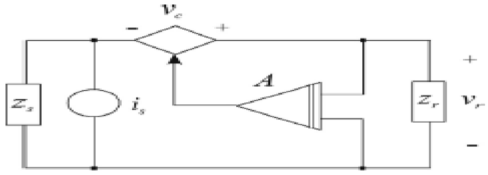


Fig. 1. Scheme of a feedback voltage-sensing voltage-compensating active filter.

II. DESIGN CRITERIA OF THE ACTIVE FILTER

A. Choice of the Active Filter Scheme

Classifications of the active filter topologies, used in controlling EMI, are given in [9], [11], and [30]. According to these classifications, the proposed circuit is a feedback voltage sensing, voltage-compensating type, shown in Fig. 1, and it behaves as a Butterworth low-pass filter. The main advantage of this choice lies on the good performance of the considered scheme in canceling the CM voltage at the motor input, due to the maximization of the filter insertion loss (IL) for the case under study [9], [26]. The main features of the chosen topology are summarized in Table I. The performance of the topology shown in Fig. 1 is improved by an additional feed-forward action, based on the injection of a signal proportional to the motor CM current, as proposed in this paper. A further improvement is achieved by the reduction of the filter supply voltage and a proper redesign of voltage detection and injection systems, as explained in the following.

IMPROVEMENT OF VOLTAGE DETECTION AND INJECTION SYSTEMS

The CM voltage (*V*CM) to be compensated is detected at the noise receiver (the motor) and compared with the desired *V*CM output, set to zero; the error signal is suitably processed by a feedback action, then it is amplified and injected to compensate the *V*CM. In order to perform an optimal compensation, the proposed circuit should be able to follow the rapid transitions due to the inverter switching. This implies the use of a power amplification stage which is characterized by high slew rate and high gain/bandwidth product (GBW). Actually, it represents the bottleneck of the system. A high GBW is bound to the availability on themarket. In general, the smaller is the amplifier supply voltage, the higher is its GBW. Therefore, a reduction of the operating voltage within the filter is advantageous. It can be obtained by a suitable modification of CM voltage detection and injection systems. In particular, to reduce the operating voltage of the filter by a factor *k*, the detected CM voltage has to be divided by *k* and the injected compensating voltage has to be multiplied by the same factor. Since a voltage-sensing scheme usually adopts a detection system constituted by three wye-connected capacitors *Cd* [26], a further capacitor *C*1 = 3*Cd* (*k* – 1) is used to detect a suitably divided CM voltage [24]. This calls for a voltage injection system with the capability to multiply the compensating voltage by *k*. Since aCMtransformer (CMT) is used for the voltage injection, a CMT with a turn ratio 1:*k* is realized. It should be observed that the turn ratio of the CMT is obtained by the minimum turns number at the primary winding, provided that the core saturation is avoided. In this way, small dimensions of the CMT are possible and the desired optimization of the power to size ratio is accomplished.

FEED-FORWARD ACTION BY CM CURRENT ESTIMATION

Within a feedback compensation system, a slight difference in the slope of the compensating voltage step is observed compared to the actual CM voltage step. This difference is mainly due to the limitation of the amplifier bandwidth but also to the delay of feedback signals propagation. As a consequence, a residual disturbance at the motor terminals, after the introduction of the active filter, is noticed. The residual disturbance exhibits a pulseshaped waveform similar to the motor CM current. Therefore, by taking a supplementary signal proportional to the motor CM current and adding it directly to the error signal, it is possible to compensate the delay of feedback signals propagation minimizing the residual disturbance. The additional signal can be obtained by a suitable estimation of the motor CMcurrent by sensing the CM voltage at the inverter terminals and applying it to

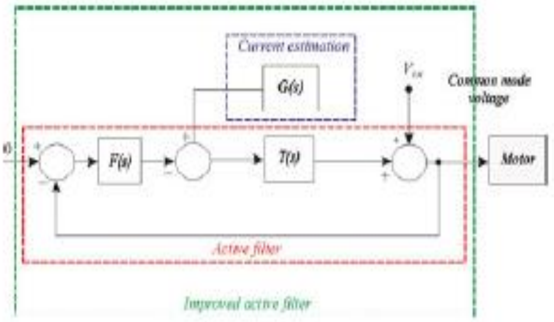


Fig. 2. Schematic configuration of the improved CM active filter.

A simple equivalent circuit reproducing the CM high-frequency motor impedance. In practice, the need for the knowledge of the CM high-frequency motor model is not a limitation, since the most relevant CM phenomenon, to be reproduced, is tied to the front-end capacitance toward ground. Therefore, the motor model can be approximated by only this capacitance, whose value is nearly constant for induction motors belonging to a given rated power class, as demonstrated in [31]. With the proposed approach, the additional signal is built starting from the CM voltage taken directly at the inverter's terminals by a capacitive detector. The performance improvement of the active filter with the addition of the feed-forward action based on the CM current estimation is proven by a frequency-domain analysis (see Section III) where the behavior of the circuit with/without the feed-forward action is compared. where *F*(*s*) is a low-pass filter, *T*(*s*) is a transfer function, including a linear amplifier, a power amplifier, and a commonmode transformer (CMT) and $G(s)$ is the transfer function of the CM current estimator. Each block is described in detail in the next section.

$$Vm = \frac{[Van+Vbn+Vcn]}{3} \qquad \text{-----(1)}$$

III. FREQUENCY-DOMAIN ANALYSIS OF THE ACTIVE FILTER

The main components of the active filter are the CMT and the power amplifier. The CMT is used to inject the compensation voltage into the power lines, the power amplifier is necessary to supply the primary winding of the CMT. An auxiliary linear amplifier is used to increase the error signal amplitude maintaining the power amplifier gain close to one. This last condition is necessary to optimally exploit the power amplifier bandwidth. Finally, a low-pass filter introduces a further real pole that, together with the power amplifier real pole, by a suitable open-loop transfer function gain, can give a couple of complex conjugate poles in the closed loop transfer function. The transfer functions of the different sections of the active filter are described in Table II. Usually, the high-frequency pole of the CMT is quite higher than the highest frequency pole of the power amplifier. This occurs since the power amplifier bandwidth is limited to avoid oscillations, whereas the CMT is realized with a suitable magnetic material guaranteeing a high bandwidth. This hypothesis will be experimentally verified, as explained in Section V.

IV.SIMULATION RESULTS

The MATLAB simulink is used to simulate the design with and without filter. Here the simulink models for with filter and without filter have been shown, while the simulation results of all i.e. with and with out filter are shown .

The Matlab/Simulink model for with out filter is shown below in Fig. 3:

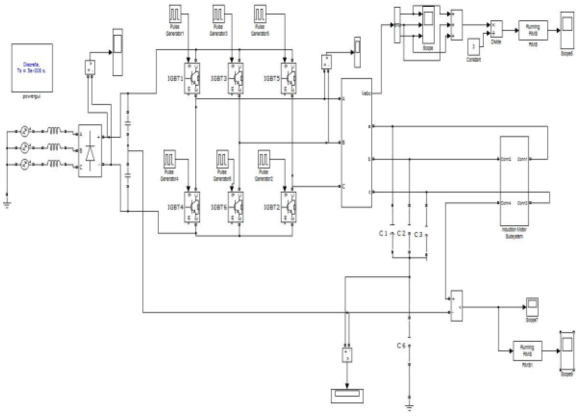


Fig 3: Simulation diagram for without filter

The Matlab/Simulink model for with out filter is shown below in Fig. 4:

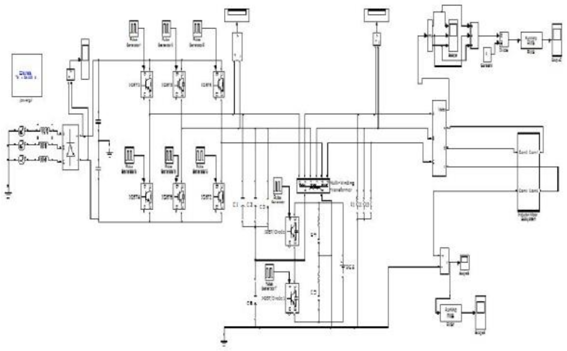
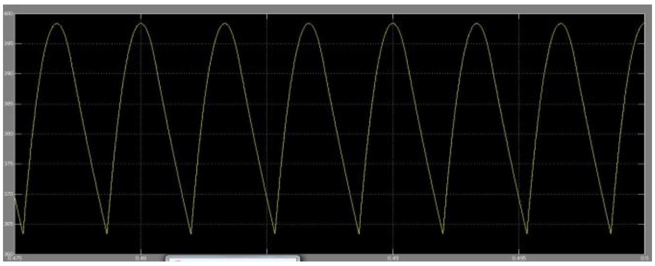
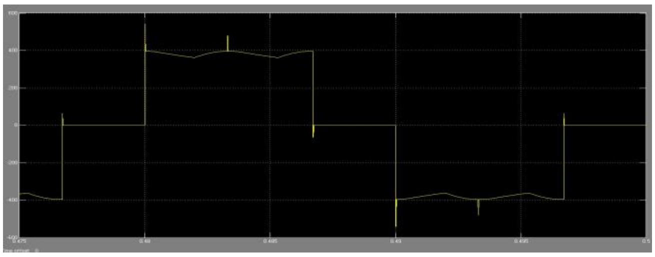


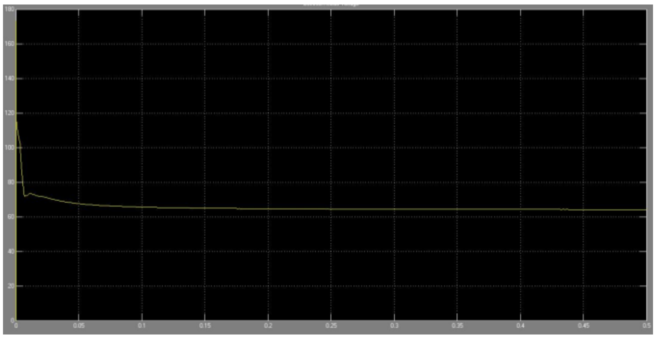
Fig 4: Simulation diagram for without filter



(a)

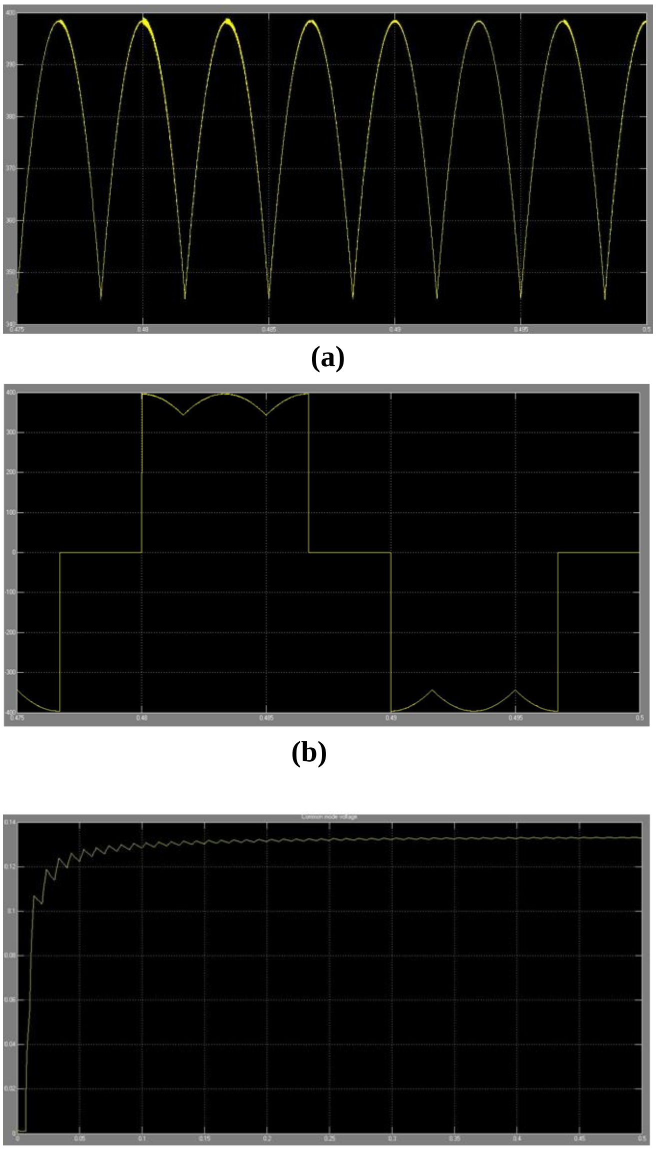


(b)



(c)

Fig 4: simulation results with out filter (a)rectified output, (b)Inverted output (c)Common mode voltage



(a)

(b)

(c)

Fig 5: simulation results with filter (a)rectified output, (b)Inverted output (c)Common mode voltage

V. CONCLUSION

The paper presents a novel CMactive filter for inductive motor drives. The filter scheme is based on a voltage feedback action with an optimized design of the CM voltage detection/ injection systems. Moreover, it uses an additional feedforward signal obtained by a suitable estimation of the motor CM current which improves the performance in terms of EMI reduction. The effectiveness of the improved active filter is theoretically demonstrated. The filter is designed and simulated using linear amplifiers that allow an efficient and compact realization. The proposed simulation results shows a reduction of the CM EMI in the frequency range of interest.

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