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Three-Phase Common-Mode Active EMI Filters for Induction Motor Drive Applications

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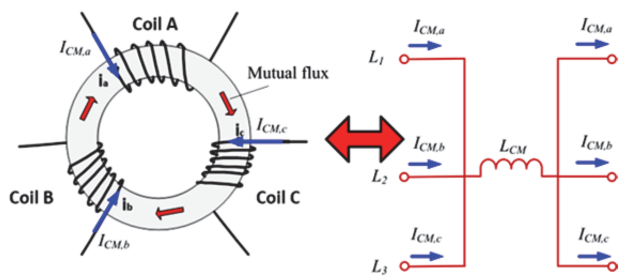
Abstract

In this paper, the conducted EMI reduction performances of active feed-forward current-sensing current-actuation (CSCA) and voltage-sensing current-actuation (VSCA) filters for a three-phase induction motor drive system are evaluated by experiments. For comparison purposes, the conducted EMI (CM emission, DM emission and total emission) of a three-phase induction motor drive with a conventional CM choke, a conventional CM choke in series with an active VSCA filter, and an active CSCA filter (where the CM choke was modified and used as a sensing current transformer) were compared to the case of a system without any filter inserted. Experimental results show that the active CSCA and VSCA filters can improve the CM reduction performance of the conventional CM choke by about 5 dB especially at low-frequencies. However, for DM comparisons, it shows that there is no different between cases with and without filters inserted.

Key words: Active CSCA filter, Active VSCA filter, Common-mode active EMI filter, Induction motor drives, Tree-phase common-mode choke

I. Introduction

Nowadays, modern power converters are being embedded into various applications because of their significant advantages such as high power conversion efficiency, cost and compact physical size [1]. The ultra-fast switching behavior of modern power converters can cause electromagnetic interference (EMI), while it is generally known that the failure/ malfunction of all electronic devices, equipment or systems is caused by EMI [2]. To eliminate EMI, passive or active EMI filters are generally installed between the power electronic converters and the grid [3]. However, in order to prevent bearing failures and severe vibrations in motor drive applications, common-mode (CM) noise must be eliminated [6]. Many methods have been proposed to suppress the CM emissions in the three-phase motor drive applications, i.e. modulation techniques [4], [5], multi-level multi-phase inverters [6]-[8] and active/hybrid filtering techniques [9]-[11]. However, these methods need to introduce a complicated design procedure or complex external circuits.



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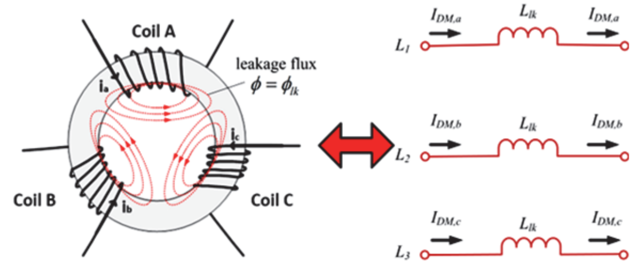

(b)

Fig. 1. Three-phase CM choke under: (a) CM current; (b) DM current.

As a result, for three-phase power converters, especially those for induction motor drive applications, passive EMI filters are widely used [12]-[14]. A CM choke is widely used because it is the simplest way to reduce CM emissions.

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However, a CM choke consumes up to 25% of the motor drive system volume [4]. Thus, to reduce the total size and weight, the CM inductance of a CM choke must be designed to be as small as possible by introducing C_Y where its value is limited by safety standards. To overcome these problems, an active-filter circuit is applied in series with the conventional CM choke to reduce low-frequency CM emissions [15]-[18]. Active-filter circuits can be categorized into 4 main types [15]. Recently, feed-forward current-sensing current-actuation (CSCA) [16], [17] and feed-forward voltage-sensing current-actuation (VSCA) [15] filters have been popularly used because it has been proved that current-canceling schemes are the most effective for high-impedance CM noise reductions [18].

However, it is necessary to determine how much CM noise can be reduced by adding two popular active-filters when compared to the case of adding a conventional CM choke, which is the aim of this paper.

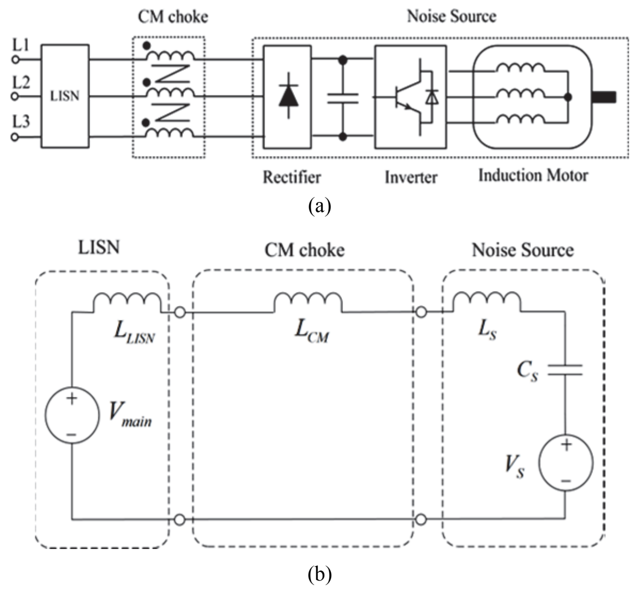


Fig. 2. Three-phase induction motor drive with a conventional CM choke: (a) Schematic; (b) CM equivalent circuit.

II. Operation of a Three-Phase Common-Mode Choke

Conventionally, to limit CM currents in three-phase motor drive applications, a three-phase common-mode choke is used. A three-phase common-mode (CM) choke is composed of three windings with an equal number of turns, where the three windings are wound in the same direction and placed in parallel. The three windings are connected specifically between three line wires i.e. L1, L2, and L3.

Fig. 1(a) and 1(b) show an equivalent circuit and the operational mechanisms of a three-phase CM choke while CM and DM currents pass through it, respectively. It can be concluded that when CM currents pass through it, mutual flux is accumulated. Thus, a huge amount of CM inductance is obtained, where the CM inductance can be defined by [19]:

$$L_{CM} = A_L N_L^2 \cdot \frac{\mu'(f)}{\left|\bar{\mu}(f = 0\text{Hz})\right|} \quad [\text{H}] \tag{1}$$

Eq. (1) shows that the CM inductance is dependent on the operational frequency, inductance per turn (A_L), number of turns (N_L), and permeability (both the real part (μ') and the complex permeability ($\bar{\mu}$)). Moreover, high permeability materials such as a ferrite core must be chosen and proper winding techniques should be applied in order to reduce the parasitic elements.

When DM currents pass through a CM choke, the mutual flux is canceled. However, the leakage fluxes across each of the windings still exist, which generates a small amount of leakage inductance. Although the leakage inductance increases the power loss, it can moderately eliminate DM currents. Theoretically, the DM inductance of a toroidal three-phase CM choke can be estimated by [19]:

$$L_{DM} \cong 2.5\mu_0 N_L^2 \frac{A_e}{l_{eff}} \left(\frac{l_e}{2} \sqrt{\frac{\pi}{A_e}} \right)^{1.45} \quad [\text{H}] \tag{2}$$

$$l_{eff} = l_e \sqrt{\frac{\theta}{2\pi} + \frac{1}{\pi} \sin\left(\frac{\theta}{2}\right)} \tag{3}$$

where θ is the winding angle (valid for $\theta > \pi/6$), A_e is the effective cross-sectional area, and l_e is the effective mean length of the core. To prevent core saturation due to DM currents, Eq. (4) must be satisfied.

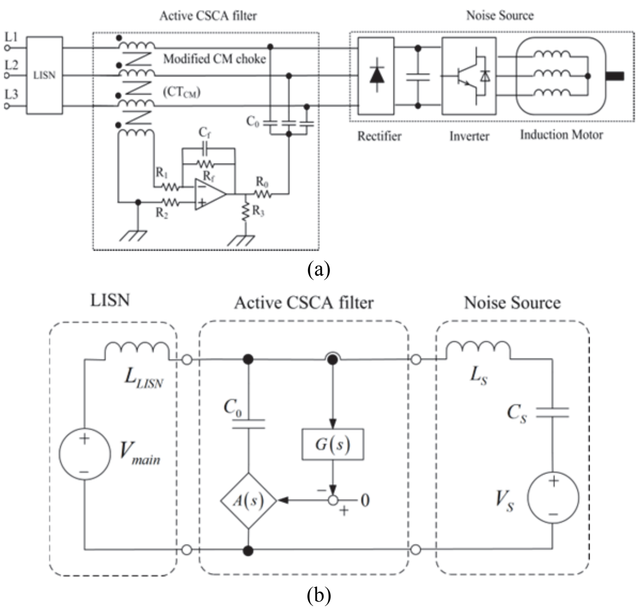
$$\frac{L_{DM} I_{DM}}{N_L A_e} < B_{sat} \tag{4}$$

where B_{sat} is the saturation flux of the chosen toroidal magnetic core. The CM inductance and leakage inductance of a three-phase CM choke can be measured. To measure the leakage inductance, two windings must be shorted while the left winding is measured for its leakage inductance. On the other hand, the CM inductance can be measured using an asymmetrical test circuit [20].

Fig. 2(a) and 2(b) show a schematic and a CM equivalent circuit of a three-phase induction motor drive with a conventional CM choke, respectively. According to Fig. 2 (b), the insertion loss of a three-phase induction motor drive with a conventional CM choke is derived as follows:

$$IL = 20\log\left[1 + \frac{sL}{R + Z_n}\right] \tag{5}$$

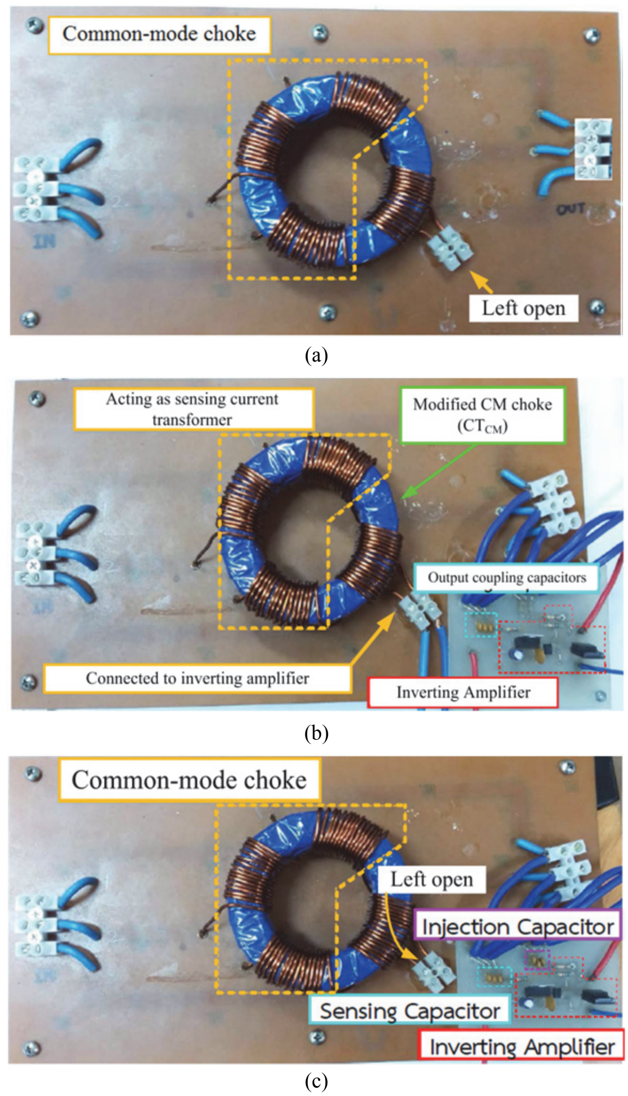
where Z_n is the noise source impedance, R is the CM impedance of the line impedance stabilization network (LISN), and sL is the CM inductance of a conventional CM choke.



(a)

(b)

Fig. 3. Proposed active CSCA filter for a three-phase induction motor drive: (a) Schematic; (b) Equivalent circuit of the proposed system.



(a)

(b)

(c)

Fig. 4. Implementation of proposed filter circuits for a three-phase induction motor drive; (a) With conventional CM choke; (b) With active CSCA filter (modified CM choke used as sensing current transformer); (c) With CM choke in series with active VSCA filter.

III. Operation of CM Active EMI Filters

According to the literature review in [15], the active-filter circuits used in power electronic systems can be categorized into the following 4 main types:

- Voltage-sensing current-actuation (VSCA) filter
- Voltage-sensing voltage-actuation (VSVA) filter
- Current-sensing current-actuation (CSCA) filter
- Current-sensing voltage-actuation (CSVA) filter

However, recently, feed-forward current-sensing current-actuation (CSCA) [16], [17] and feed-forward voltage-sensing current-actuation (VSCA) [15] have become the most widely recommended [18]. Thus, only CSCA and VSCA filters are discussed in this paper.

A. Current-Sensing Current-Actuation (CSCA) Filters

This type of active-filter circuit was proposed and implemented in [16], [17]. The main principle of this method is to boost the input impedance of a power electronic system with an active multiplication method using a proposed active-filter circuit. By introducing this proposed active-filter circuit in parallel with a power electronic system, the input impedance of the system can be boosted by a factor of the current gain of the CSCA filter. As a result, a larger current gain provides a better CM noise reduction performance.

The insertion loss of the system with an active multiplication method can be derived as [16]:

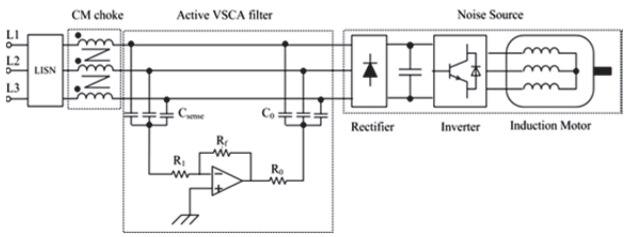
$$IL = 20\log\left[1+\frac{sL}{R+Z_n}+A\left(\frac{sL+Z_n}{R+Z_n}\right)\right] \tag{6}$$

where A is the open-loop gain of an op-amp. As shown in Eq. (6), by adding an active-filter circuit, the input impedance of the system can be boosted by a factor of $A\left(sL+Z_n/R+Z_n\right)$.

However, the active-filter circuit proposed in [16] is only implemented for a single-phase power electronic system. With an active multiplication method, the CSCA filter for a three-phase motor drive system is modified and proposed as shown in Fig. 3.

B. Voltage-Sensing Current-Actuation (VSCA) Filter

The VSCA filter circuit was proposed and implemented in [15]. This topology uses a Y-capacitor to sense the line voltage, and it uses the actuator stage in order to cancel the CM noise current. Ideally, the Y-capacitor value should be chosen as large as possible to minimize the size of the CM



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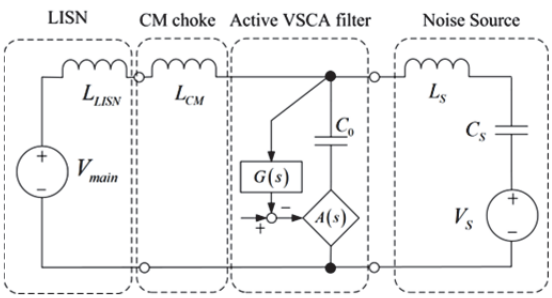

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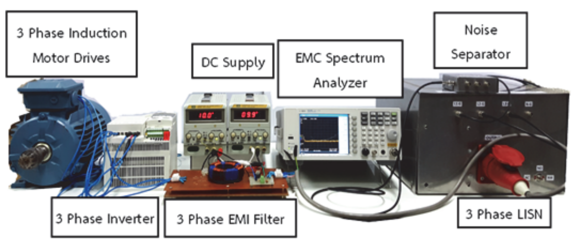
Fig. 5. Proposed active VSCA filter for three-phase induction motor drives: (a) Schematic; (b) Equivalent circuit of the proposed system.



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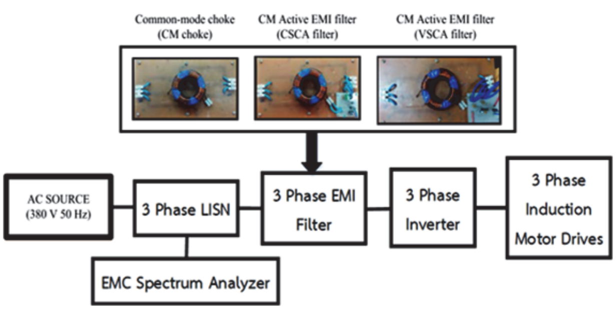


(b)

Fig. 6. Depictions of: (a) EMI measurement setup; (b) Testing block diagram.

choke. However, the Y-capacitor value is limited by safety standards. The main concept of this method is to virtually boost the capacitance of the existing C_Y value by controlling the feedback-frequency response. Thus, the size of the CM choke can be reduced.

The basic principle of this topology is to boost the equivalent capacitance at a high frequency using proper shaping of the feedback loop as shown in Eq. (7)

$$Z_{act}(s) = \frac{1}{sC_0} \cdot \frac{1}{1 + G_{sense}(s)} \tag{7}$$

Eq. (7) shows that the capacitance can be virtually boosted by the factor of the gain G_{sense} at high frequencies. This characteristic is remarkable since the capacitance value of the Y-capacitor at a low frequency can be kept below safety standards. The VSCA filter circuit is modified and proposed, as shown in Fig. 5, where it is composed of a CM choke (L_{CM}), a coupling capacitor (C_0), a coupling resistor (R_0), a sensing capacitor (C_{sense}), and an inverting amplifier circuit. According to Fig. 5 (b), the insertion loss of the proposed system can be derived as [23]:

$$IL_{CM,estimate} = 20\log\left| s^2\left(\frac{L_{CM} Z_{act} Z_n}{Z_n + R}\right) + s\left(\frac{L_{CM} + Z_{act} Z_n R}{Z_n + R}\right) + 1 \right| \tag{8}$$

IV. Experimental Validations and Discussions

The aim of this paper is to determine how much CM noise can be reduced by adding two popular active-filters when compared to the case of adding only a conventional CM choke. Thus, the EMI reduction performance of a three-phase induction motor drive: with the conventional CM choke, the conventional CM choke in series with an active VSCA filter, and an active CSCA filter were verified by experiments. All of the cases used a CM choke. Therefore, for the sake of a fair comparison, identical CM chokes, where the CM inductance was equal to 3.5 mH, were used in all cases. However, it should be noted that only the case of the active CSCA filter the CM choke was used as the sensing current transformer.

A. *Selected Components of the Three-Phase CM Choke Prototype*

Fig. 4(a) shows the CM choke used in the experiments. The CM inductance (L_{CM}) is 3.5 mH. The designed parameters are: toroidal ferrite core (Vacuumschmelze# T60006-L2080-V091) with an outside diameter of 86 mm, number of turns = 15, copper size = AWG#18, and space between windings = 20 degree. It should be noted that, as shown in Fig. 4(a), there are four windings in the same core. However, in this case one winding is left open.

B. *Selected Components of the Active CSCA Filter Prototype*

For the active CSCA filter, the selected components were designed as shown in Table I [16], [17], [24], [25]. It should be noted that, as shown in Fig. 4(b), there are four windings in the same core acting as a current transformer (CT_{CM}). There is no significant difference between the current transformer and the CM choke except for the number of windings. As a result, in this experiment, the CM choke shown

TABLE I
SELECTED COMPONENTS FOR THE ACTIVE CSCA FILTER PROTOTYPE

Component	Specification
Op-amp	Texas Instruments: OPA847
CT_{CM}	Vacuumschmelze# T60006-L2080-V091 N = 4x15 turns, AWG#18, 3.5 mH
R_1, R_2, R_3, R_f	5.6 kΩ
R_0	1 kΩ and 10 kΩ
C_f	Ceramic capacitor, 10 pF
C_o	Y-capacitor, 3x10 nF

TABLE II
SELECTED COMPONENTS FOR THE ACTIVE VSCA FILTER PROTOTYPE

Component	Specification
Op-amp	Texas Instruments: OPA847
L_{cm}	Vacuumschmelze# T60006-L2080-V091 N = 3x15 turns, AWG#18, 3.5 mH
C_{sense}	Ceramic capacitor, 3x 1 nF
R_1, R_2	5.6 kΩ
R_0	1 kΩ and 10 kΩ
C_o	Y-capacitor, 3x10 nF

in Fig. 4(a) was used. However, in this case one winding was connected to the inverting amplifier as shown in Fig. 4(b). Moreover, to maximize the op-amp's gain, it is recommended to use a C_f of about 10 pF [16].

C. Selected Components of the Active VSCA Filter Prototype

For the active VSCA filter, selected components were designed as shown in Table II [15], [16], [24], [25]. It should be noted that in order to prevent the op-amp saturation caused by low-frequency components (50/60 Hz), the mentioned components must be attenuated in a feedback loop.

D. Experimental Setup

The measurement setup and a testing block diagram of the experiment are shown in Fig. 6(a) and 6(b), respectively. The noise source is an induction motor drive (a three-phase inverter: ABB#ACS350 and a three-phase induction motor: ABB#M2QA100L4B, 3 kW). The noise source was powered through a three-phase line impedance stabilization network (LISN) including a CM and DM noise separator network [21], [22]. Referring to the CISPR 16 standard, the conducted EMI is measured through an EMC spectrum analyser (Agilent Spectrum Analyser: N9320B) with the frequency range of interest going from 150 kHz up to 30 MHz and BW at 9 kHz. Moreover, all of the equipment was installed on the metal ground reference plane.

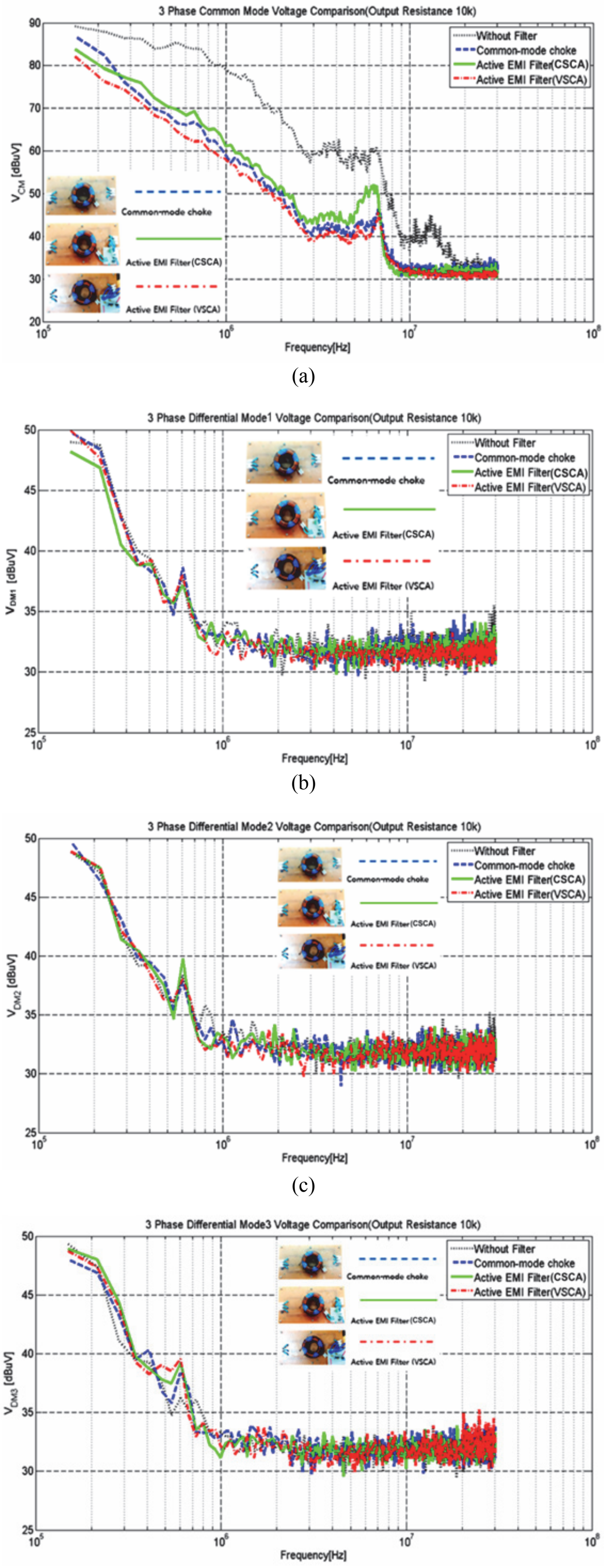
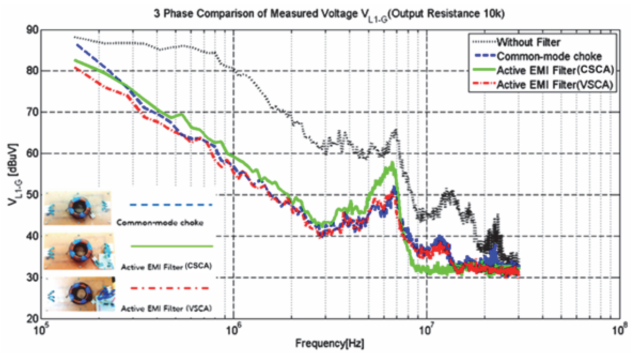


Fig. 7. Comparisons of the conducted EMI of an induction motor drive (operating at 500 rpm): without a filter, with the conventional CM choke, with a CSCA filter (R_0 = 10 kΩ), and with a VSCA filter (R_0 = 10 kΩ). (a) CM; (b) DM1; (c) DM2; (d) DM3.



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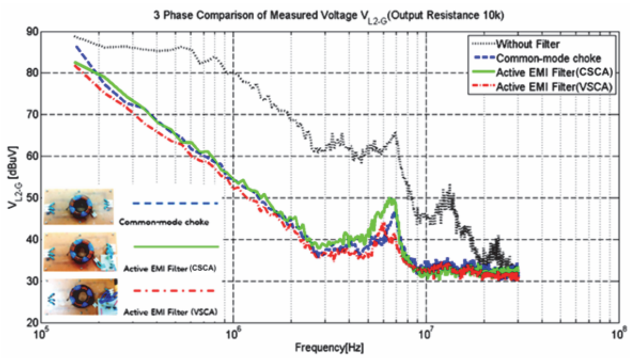

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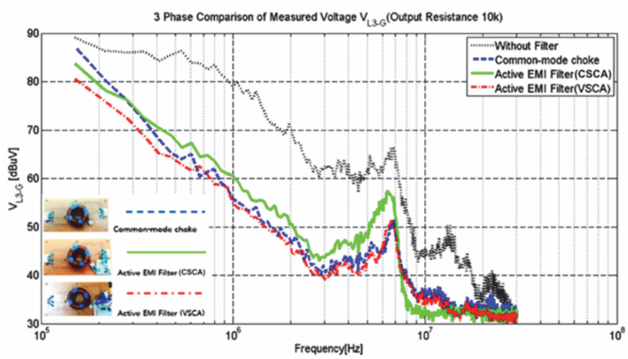


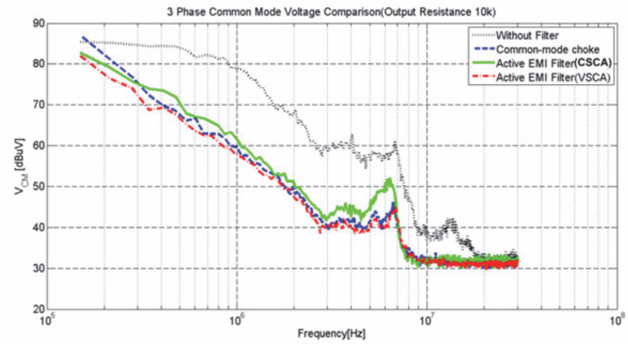
(c)

Fig. 8. Comparisons of the conducted EMI of an induction motor drive (operating at 500 rpm): without a filter, with the conventional CM choke, with a CSCA filter (R_0 = 10 kΩ), and with a VSCA filter (R_0 = 10 kΩ). (a) L1-to-ground; (b) L2-to-ground; (c) L3-to-ground.

For comparison purposes, the conducted EMI (CM emission, DM emission, and total emission) of a three-phase induction motor drive: with the designed CM choke, the designed CM choke including an active VSCA filter, and an active CSCA filter (where the CM choke was modified and used as a sensing current transformer) were measured and compared.

E. *Experimental Results and Discussions*

To verify the conducted EMI reduction performance of the designed active VSCA and CSCA filters, three tests were conducted as follows:



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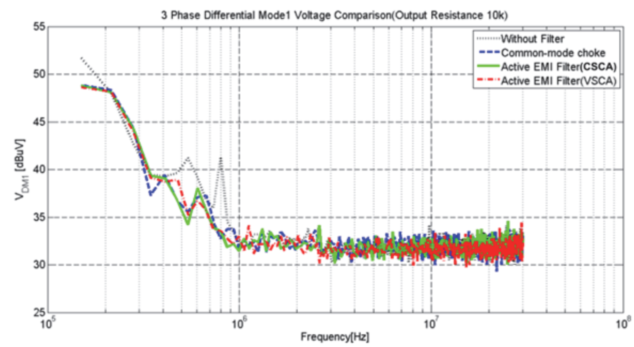


(b)

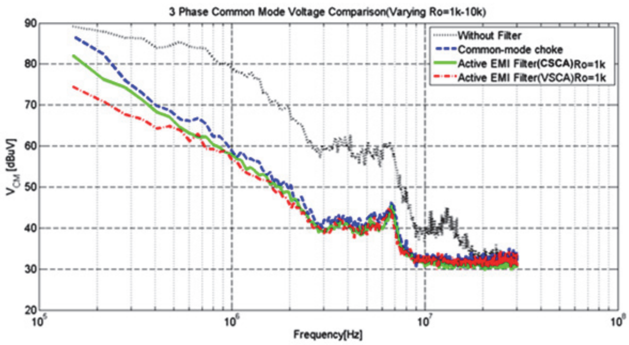
Fig. 9. Comparisons of the conducted EMI of an induction motor drive (operating at 1200 rpm): without a filter, with the conventional CM choke, with a CSCA filter (R_0 = 10 kΩ), and with a VSCA filter (R_0 = 10 kΩ). (a) CM; (b) DM1.

1) Induction Motor Operating at 500 rpm

The measured conducted EMI of a three-phase induction motor drive without a filter was compared to the cases of one with the designed CM choke, with the designed CM choke including an active VSCA filter, and with an active CSCA filter (where the designed CM choke is used as a current transformer). Figs. 7(a)-(d) show conducted EMI comparisons in terms of CM and DM emissions, while Fig. 8(a)-(c) show conducted EMI comparisons at the line-to-ground and neutral-to-ground.

It is obvious that the CM noise was dramatically reduced when a filter was applied when compared to the case of the noise source without any filter inserted as shown in Fig. 7 (a). Moreover, a CM attenuation of about -5 dB was gained when introducing active CSCA and VSCA filters. This was especially true at low-frequencies. However, for DM comparisons, it shows similar results in all of the cases as shown in Fig. 7(b)-(d).

For the measured total noises at the line-to-ground and neutral-to-ground, comparison results are shown in Fig. 8(a)-(c). It can be seen that when the proposed filters were inserted, the total noises were dramatically reduced when compared to the case of a noise source without any filter inserted. The total noises can be suppressed up to 25 dB.



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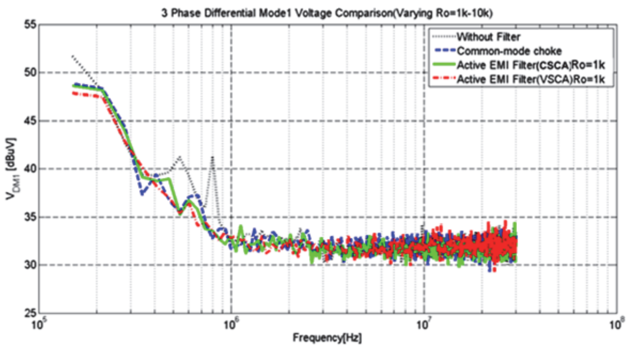

(b)

Fig. 10. The comparisons of conducted EMI of the induction motor drive (operating at 500 rpm) among: without filter, with conventional CM choke, with CSCA filter (R_0 = 1 kΩ), and with VSCA filter (R_0 = 1 kΩ). (a) CM; (b) DM1.

Similarly, a noise source with CSCA and VSCA filters especially at a low-frequency can be improved by about 5 dB when comparing to the case of that with only a CM choke.

2) Induction Motor Operating at 1200 rpm

This case is similar to the previous subsection. However, the motor speed was changed from 500 rpm to 1200 rpm. Fig. 9(a) and 9(b) show only the measured CM and DM1 emissions. The DM2 and DM3 emissions were not shown here because the results were similar to those of DM1. Although, the speed of motor was changed to 1200 rpm, the compared CM and DM emissions were slightly different from the case of the induction motor operating at 500 rpm.

- Varying the R_0

In this subsection, R_0 was changed from 10 kΩ to 1 kΩ. A CM attenuation of about -10 dB was gained when introducing active VSCA filters. This was especially true at a low-frequency. It should be noted that changing R_0 did not affect the CM reduction performance of the active CSCA filters. Moreover, in terms of DM comparisons, it shows similar results in all of the cases as shown in Fig. 10 (a)-(b).

V. CONCLUSIONS

For three-phase induction motor drive systems, the conducted EMI reduction performance (in terms of CM, DM and total noises) of the classical passive filter (three-phase CM choke) were evaluated and compared to the cases of that with the two most popular active filters (active CSCA and VSCA filters). From the obtained experimental results, it can be concluded that the active CSCA and VSCA filters can improve the CM reduction performance of the conventional CM choke by about 5 dB. This is especially true at low-frequencies. However, for the DM comparisons, there are no significant differences between the cases with and without an inserted filter. However, the total noises can be suppressed by up to 25 dB. Improving the CM reduction performance of an active VSCA filter can be achieved by properly adjusting the value of R_0. However, this cannot be done with an active CSCA filter. Moreover, from the experiments conducted in the study, it can be concluded that varying the operational speed of the motor has a slight affect on the conducted EMI level.

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