A Simplified Active Input EMI Filter of Common-mode Voltage Cancellation for Induction Motor Drive

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Abstract— This paper presents the application of the active and passive electromagnetic interference (EMI) filters in order to solve practical problems and improve the passive EMI filter performance. First, the basic active filter topologies are discussed and the basis of discussion is based on an equivalent circuit model, which includes the possible combinations of the desirable attributes. Next, a simplified active input EMI filter (AIEF) is proposed, and a large common-mode (CM) inductor of passive EMI filter is replaced by small passive components and an active circuit. A prototype of AIEF verifies the effectiveness and validity with an induction motor drive and ac motor. The CM noise is analyzed using high-frequency (HF) current probe. Finally, the proposed circuit effectiveness is verified by experimental results.

I. INTRODUCTION

Nowadays, the broader use of power electronic based loads (rectifiers, inverter, motor control systems, etc) has led to a growth of power pollution and conducted electromagnetic emissions also have been produced because of the nonlinear voltage or current characteristics of these loads. So that, there are many researches on passive EMI filters have been done. But the size, cost and performance of EMI filter components are also important considerations in power application. With this reason, there have recently many articles of active common-mode or current ripple cancellation provides alternative approaches to the problem [1-6].

The high-speed switching devices such as IGBT’s have enabled to increase a carrier frequency of voltage-source of PWM inverters, thus leading to much better operating characteristics. However, high-speed switching can accompany the serious problems from a steep change in voltage or current such as: ground current escaping to earth through stray capacitors inside motors, conducted and radiated EMI and bearing current and shaft voltage [5, 6]. Consequently, many practical forms of active cancellation circuits have been reported in recently with the same operation. The general topologies of possible active EMI filters have been introduced in [3]. The nullification process was established to classify the basic noise cancellation methods and the insertion loss analysis of active EMI filters are introduced in [4]. They mainly focused on active filters that mitigate the common-mode EMI caused by a switched mode power supply.

In this paper, a simplified active input EMI filter is introduced in order to mitigate the conducted common-mode EMI. It can provide the sufficient attenuation under the limited LC products. The PWM inverter fed ac motor drive system included motors, ac drive system (front-end single-phase diode-bridge rectifier and PWM inverter system) leads, and other possible units that are using to develop a complete motor system. The analysis and experimental results is given, respectively.

II. BASIC ANALYSIS OF ACTIVE FILTER

Generalized topologies are identified by grouping combinations of passive elements with ideal active elements to construct filter varying complexity. A typical passive EMI filter and configuration is shown in Fig. 1 and consisted of CM choke, \( C_1 \) capacitors, DM choke and \( C_x \) capacitor. A good performance filter normally has a CM choke with few mH and CM capacitors are limited by safety considerations for ground leakage current that can calculate by equation (1).
The DM choke has lower value (typically < 1 mH) and sometime is used by the few percent leakage inductance of CM choke.

\[
C_y = \frac{I_{\text{leakage}}}{2\pi f \times 115 \times V}
\]  

(1)

where: \( I_{\text{leakage}} \) is the ground leakage current, \( V \) is ac line voltage, \( f \) is power line frequency that generally is equal to 50 or 60 Hz [7].

Reference [3] have been analyzed the feedback prototype of active filters as shown in Fig. 2 and their insertion losses (ILs) are summarizes as illustrated in Table I, where internal impedances of detecting and compensating unit are ignored as assumed in ideal case.

As shown in Fig. 2 the noise signal at receiver can be a noise voltage or current, and the compensating signal by active filter can be a voltage or current. \( Z_s \) represents the impedance of a noise receiver where one evaluates the noise power due to the noise source \( i_n \). \( Z_n \) is an internal impedance of the noise source \( i_n \). The insertion loss is defined as:

\[
IL = \frac{v_{s,w0}}{v_{s,w}}.
\]  

(2)

III. PROPOSED ACTIVE INPUT EMI FILTER DESIGN

The input filter can be an additional passive filter, which gives additional insertion loss as maintained in [2, 4]. So that, a small passive EMI filter is designed to reduce conducted EMI noise where is over the capability of active filter. Fig. 3 illustrates the application of the proposed active EMI filter designed with voltage detecting and voltage compensating (type IV). In the previous active common-mode filter [5, 6], the push–pull amplifier is used the dc voltage, which is supplied to the inverter, to power the active circuit. But in this work, the active input EMI filter is comprised of a common-mode choke with an auxiliary winding, a push–pull type emitter follower circuit using two complementary transistors \( T_1 \) (C3230) and \( T_2 \) (A1276) as shown in Fig. 3. The emitter follower is supplied from a separate source \( dV \). The high input impedance is used to minimize the value of \( C_1 \), for common-mode voltage detection. The coupling capacitors \( C_C \) connected to ac input lines of the system, it is possible to construct a separate input filter stage.

![Figure 2. Feedback-type active filters [3].](image)

Figure 2. Feedback-type active filters [3]. (I) Current detecting and voltage compensating, type I. (II) current detecting and current compensating, type II. (III) voltage detecting and current compensating, type III. (IV) voltage detecting and voltage compensating, type IV.

<table>
<thead>
<tr>
<th>Type</th>
<th>Insertion Loss (IL)</th>
<th>Amplifier gain</th>
<th>Condition for maximum IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>( 1 + \frac{A_1}{z_x + z_n} )</td>
<td>Trans-impedance ( v_c = -A_1 \cdot i_x )</td>
<td>( A_1 \gg z_x + z_n )</td>
</tr>
<tr>
<td>Type II</td>
<td>( 1 + \frac{z_n}{z_x + z_n} \cdot A_2 )</td>
<td>Current gain ( i_c = -A_2 \cdot i_x )</td>
<td>( z_n \gg z_x )</td>
</tr>
<tr>
<td>Type III</td>
<td>( 1 + \frac{A_3}{z_x</td>
<td></td>
<td>z_n} )</td>
</tr>
<tr>
<td>Type IV</td>
<td>( 1 + \frac{z_x}{z_x + z_n} \cdot A_4 )</td>
<td>Voltage gain ( v_c = -A_4 \cdot v_x )</td>
<td>( z_x \gg z_n )</td>
</tr>
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where \( v_{s,w0} \) is the receiver’s voltage without and any filter installed and \( v_{s,w} \) is the receiver’s voltage with filter installed.

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A. Selection of \( C_1 \)

The ceramic capacitors \( C_1 \) placed at the inverter input terminals of the inverter. Indeed, the resistors can be used to replace the capacitors \( C_1 \). However, there are not attractive because the resistors add more power losses to the system due to the flowing of the normal-mode currents.

The \( C_1 \) selection must be based on the maximum current that can be drawn from the main source to the inverter. If a large value of \( C_1 \) is chosen, the inverter power devices can be subjected to excessively high current pulse (capacitor charging current). Therefore, these capacitors should be selected as small as possible. The inverter for adjust speed drive is operated with the nominal current 6.4 A, and fed by a single-phase ac input system. Assuming that the inverter’s switches are turned on within 500 ns, the maximum value of \( C_1 \) for 240 V is expressed:

\[
6.4 = \frac{240}{500 \times 10^{-9}} \cdot C_{1,\text{max}}
\]

Hence, \( C_{1,\text{max}} \approx 15 \text{ nF} \).

In the test setup, \( C_1 = 390 \text{ pF} \) is selected as shown in Fig. 3 to get high input impedance for CM voltage detection.

B. Complementary Transistors

The complementary transistors use in [5, 6] are the high frequency and high voltage devices. It is quite difficult to find and expensive. In this paper, the low voltage complementary transistors are proposed because they are the commercially available for cost optimization. The transistors used in the practical implementation are A1276 and C3230. The characteristic of the both transistors are described in the table II.

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<tr>
<td>( V_{CEO} ) [V]</td>
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</tr>
<tr>
<td>C3230-NPN</td>
<td>30</td>
</tr>
<tr>
<td>A1276-PNP</td>
<td>-30</td>
</tr>
</tbody>
</table>

C. Separated DC Power Supply

In the test setup, the separate 15 Vdc power supply is realized by a single-phase rectifier supplying the two capacitors \( C_0 \) connect in series. This power supply is applied to power the active circuitry. In order to remove the dc components, the capacitors \( C_0 \) are connected as illustrated in Fig.3. The small capacitance of \( C_0 \) makes the large variation of the neutral point potential \( V_0 \) [5]. Thus, \( C_0 \) is chosen as a value large enough to reduce the voltage variation. In the practical work, the capacitor of 2.2 \( \mu \text{F} \) is selected for \( C_0 \).

D. CM Transformer

In this case, the CM transformer is the same as a conventional CM choke of passive EMI filter, except for connecting a tightly coupled additional winding (auxiliary winding) to the output of the emitter follower and it applies the detecting CM voltage to the CM transformer. The two primary windings of CM transformer with the same polarity are connected between LISN and inverter input plug. Then the polarity of the compensating voltage \( V_C \) is opposite to the CM voltage generated by the inverter. Because of the CM transformer played in role of CM choke of passive EMI filter, so the value of \( L_{cm} \) should be a few mH. In the test setup, \( L_{cm} = 3 \text{ mH} \) is selected within 1:1:1 winding ratio.

IV. SYSTEM CONFIGURATION AND EXPERIMENTAL RESULTS

In this section, the conducted EMI measurements have been setup: LISN 10A, high frequency current probe 10 kHz to 250 MHz bandwidth, an inverter motor drive, ac motor and EMC spectrum analyzer.

![Figure 3. Configuration of experimental system](image323x464 to 544x592)

![Figure 4. Common-mode EMI measurement.](image492x357 to 503x382)

The operation without load and with load is presented with the completed configuration shown in Fig. 3. An induction motor (1/2 hp, 220/380 V, 2.0/1.15 A, 50/60 Hz) is used as a load of the PWM inverter. The input filter circuit is implemented separate from PWM inverter circuit. A single-phase LISN 10 A is used to provide the stable source impedance at the high frequency while the high frequency current probe is also connected to EMC spectrum analyzer to observe CM noise as shown in Fig. 4. Because of using current probe to measure CM noise, the received results from current probe are equal to \( 2I_{CM} \) [7]. The CM current or voltage attenuation can be calculated from equations (4) and (5).

\[
A_{dB} = 20 \log \left( \frac{|I_{CM}|_{dB}}{|I_{CM}|_{dB}} \right) - 6 \text{ dB} \quad (4)
\]

\[
V_{dB} = 20 \log \left( \frac{|V_{CM}|_{dB}}{|V_{CM}|_{dB}} \right) - 6 \text{ dB.} \quad (5)
\]

where \( |I_{CM}|_{dB} \) and \( |V_{CM}|_{dB} \) are CM current and voltage measured using high frequency current probe, respectively.
The conducted EMI noise is composed of CM and DM noise. Both of them are separated, but DM is not discussed in this article with assumption that some appropriate DM components are installed for each design stage. The CM spectrum of the system without any EMI filter of both operations is shown in Fig. 5, and the conducted EMI spectrum of the both operations when the proposed AIEF is installed in the system demonstrated in Fig. 6. The experimental results of both operations are shown in Figs. 6 and 7.

V. DISCUSSION

According to the measuring results above, it can be discussed as follows:
1) In case of the operation without load, the result is given about 35 dB of the IL at 1.5 MHz to 15 MHz when the proposed AIEF is installed, but it cannot comply with the limit-line at low frequency from 150 kHz to 1.5 MHz as shown in Fig. 6(a). When the \( C_{y1} \) and \( C_{y2} \) is installed, it adds more attenuation at low frequency up to 35 dB of the IL from 150 kHz to 3 MHz and 20 dB from 3 MHz to 20 MHz as shown in Fig. 6(b), respectively.
2) When the motor is run within full load, the result is given about 20 dB of the IL at the high frequency from 600 kHz until 15 MHz as shown in Fig. 7(a). While the \( C_{y1} \) and \( C_{y2} \) is installed, it gains about 40 dB of the IL at 150 kHz to 4 MHz and 20 dB of the IL from 4 MHz to 8 MHz. It can comply with the limit-line whole the specified frequency range as shown in Fig. 7(b).

As the results, the proposed AIEF can work as active CM voltage canceller and passive EMI filter that can comply with EN 55022 class A conducted.

VI. CONCLUSION

This paper presents a simplified active input EMI filter based on the CM voltage detecting and voltage compensation technique. This proposed AIEF is reliable to suppress CM voltages generated by PWM inverter using low voltage complementary transistors as the push-pull amplifier. The experimental results of two operated conditions, no load and full load of induction motor, are demonstrated the effectiveness of this AIEF using HF current probe over the frequency range 150 kHz to 30 MHz.

REFERENCES