CHAPTER 5

ANALYSIS OF ACTIVE COMMON MODE EMI FILTER

5.1 INTRODUCTION

The proposed Active common mode EMI filter for switched mode PWM inverter fed Induction motor is effective for industrial applications. The proposed filter is based on current sensing and a compensation circuit which utilizes fast acting transistor amplifier for current compensation. The amplifier is biased with an isolated low voltage DC power supply. The ACEF used to mitigate the EMI noise independent of the source voltage. Switched mode PWM inverter output voltage is square waveform. It is easy to get the pure sinusoidal waveform using a filter. Active common mode EMI filter has quick frequency response. This filter is introduced in front of the source side. If there is any load variation this filter is not affected.

5.2 SWITCHED MODE PWM INVERTER SYSTEM FOR THREE PHASE MOTOR

Figure 5.1(a) and figure 5.1(b) shows the basic concept of the proposed active common-mode EMI filter (ACEF). This circuit is based on the topology using the current sensing and compensation (Son and Seung 2002). The noise source is the PWM inverter in Figure 5.1(a) and the input filter can be an additional passive filter, which gives additional insertion loss. In figure 5.1(b) the series-connected common-mode choke works as common-mode $L_{CM}$ current sensing element by the additional winding. The high frequency
current that passes through $L_{CM}$ generates the high frequency flux in the common-mode choke, which makes high frequency voltage to appear at the input terminal of trans-conductance amplifier. The output of the amplifier is connected to the output capacitor $C_O$ so that it is used for the current injection to the earth ground. In this filter circuit, injected current cannot be circulated within the system without using the coupling capacitor $C_C$ because a closed loop cannot be made. Thus it is used to provide low-impedance path of high frequency common-mode current for the internal circulation. The supply voltage of the filter circuit is used to give the bias voltage to the amplifier. At low frequency, impedance $C_C$ is large enough to isolate the bias voltage from the main voltage.

![PWM Inverter Systems for Three Phase Motor](image)

**Figure 5.1(a) PWM Inverter Systems for Three Phase Motor**

The required bias voltage of ACEF can be calculated as in equation (5.1) (Son and Sul 2003). For example, if 0.5 A of high frequency current at 1MHz should be supplied, then the bias voltage should be larger than 7.96 V in order to drive a 10 nF capacitor $C_O'$, which is the series impedance of the output capacitor $C_O$ and the Coupling Capacitor $C_C$

$$V_C \geq \max \left| \frac{i_0}{2\pi f C_O'} \right|$$ (5.1)
Figure 5.2 shows the application of the proposed ACEF. In this example a single-phase, three-phase and dc applications are shown. As introduced in, a push-pull amplifier is used and is connected to the dc-bus of the PWM inverter or any dc load system. In case of PWM inverter supplied by the commercial 50 Hz/220V utility lines, the dc-bus voltage is about 300 V<sub>dc</sub>. If the push-pull amplifier should be placed across the dc-bus capacitor as suggested in, then each transistor should be able to handle the full dc-bus voltage. The high-voltage/high-current PNP-transistor is hardly available; hence that limits its application. Moreover, the required voltage of the push-pull amplifier is very small compared to the dc-bus voltage as shown in equation (5.3) and it can make the inefficient voltage usage. However in the proposed circuit the additional low voltage supply can be used to drive the push-pull amplifier. This enables the use of low voltage devices and extends the application of the proposed ACEF. figure 5.2 (a) shows its application, when coupling capacitors are placed in between the dc-bus voltage and the filter supply voltage.
Figure 5.2  Configurations of Proposed ACEF: (a) ACEF using DC-Bus Coupling, (b) ACEF using AC Line Coupling for Single-Phase Application, (c) ACEF using DC-Bus Coupling, and (d) ACEF using AC Line Coupling for Three-phase Application

While coupling capacitors in figure 5.2 (a) isolate the dc-bus and the ACEF at low frequency, they make low impedance path at high frequency, which allows the internal circulation of high frequency leakage current between the system and the ACEF as introduced in. The filter supply voltage can be easily obtained by using a dc power supply fed to the control electronics such as a gate drive circuit. Unlike an ideal voltage source, there can be some voltage ripple in the filter supply, if a switched mode power supply (SMPS) is used for this dc power supply. In this case, the noise produced by the dc power supply may flow into the dc bus through the
coupling capacitors $C_C$ in figure 5.2 (a), which may affect the total conducted EMI including the PWM inverter and the proposed ACEF. Besides the high-frequency noise being produced by the PWM inverter, it can also be transmitted to the control via the coupling capacitors $C_C$ with the same manner.

Thus, the filter supply should provide sufficient low impedance, to decouple such high-frequency noises. Coupling capacitors can also be connected to ac input lines of the system as shown in figure 5.2 (b) and it is possible to construct a separate input filter stage. The same idea can be extended to the 3-phase applications, which is shown in figure 5.2 (c) and (d). The proposed circuit works as follows. In this analysis, there is an assumption that coupling capacitors have sufficient low impedance at the frequency band of interest. If the inductance of the common-mode choke seen at the primary winding is $L_{CM}$ without the consideration of secondary winding, then the relation between input common-mode current and base current of the push-pull amplifier can be found as

$$\frac{i_a}{i_b} = \frac{-N s}{s + \omega} \text{ and } \omega l = \frac{N^2 r_{in}}{L_{cm}}$$  \hspace{1cm} (5.2)

where $N$ is the turn’s ratio between the primary winding and the secondary winding, $r_{in}$ is the input impedance of the push-pull transistor amplifier including the additional resistor. If the leakage inductance of common-mode choke can be negligible, the common-mode inductance $L_{CM}$ can be represented as

$$L_{cm} = \frac{N^2 \mu A_e}{l_e}$$  \hspace{1cm} (5.3)

where $\mu$ is the relative permeability, $A_C$ is the effective area, and is the effective length of the magnetic core. Thus, the cutoff frequency can be represented as equation (5.4) regardless of the number of turns.
If the bandwidth of the transistor amplifier is a first-order system, then the injection current of the amplifier can be derived as

\[ i_o = \frac{h_{fe}}{(1+s/\omega_T)} \cdot i_b = \frac{N h_{fe}}{(1+s/\omega_1)(s/s+\omega_1)} \cdot i_s \left( \frac{s}{s+\omega_1} \right) i_s \quad (5.5) \]

where \( h_{fe} \) is the AC current gain of the transistor.

Because the input common-mode current is the sum of injection current \( i_o \) and the load leakage current \( i_{g1} \), then the relation between \( i_g \) and \( i_o \) can be found as

\[ i_g = i_o + i_{g1} = \left( 1 + \frac{s}{\omega T} \right) \left( \frac{s}{s+\omega_1} \right) i_g \quad (5.6) \]

If the bandwidth of the transistor amplifier is high, then Equation (5.6) can be simplified as

\[ i_g \approx i_o + i_{g1} = \left( 1 + \frac{s}{\omega_2} \right) \left( \frac{s}{s+\omega_3} \right) i_g \quad (5.7) \]

where \( \omega_2 = \omega_1 (1+N h_{fe}) \) and \( \omega_3 = N h_{fe} \omega_T \).

If \( \omega_T \) is much higher then, equation (5.7) is approximated as
\[ i_g \approx i_o + i_{g1} = \left( \frac{1 + \frac{s}{\omega_1}}{1 + \frac{s}{\omega_2}} \right) i_g \]  

(5.8)

Figure 5.3 Frequency Response of Proposed ACEF

Figure 5.3 shows the frequency response of the proposed ACEF without including the effect of coupling capacitors. As it can be seen from the Figure 5.3, the approximation equation (5.8) holds only in the conducted EMI frequency band, 0.15–30 MHz. But the attenuation performance is degraded in the radiated EMI frequency band, 30–300 MHz, due to the limited bandwidth of the transistor amplifier. The maximum attenuation of \(1/(1 + \frac{N_{f}i}{\omega_1})\) is achieved between cutoff frequency \(\omega_1\) and resonance frequency \(\omega_r\). Simple passive filters can be inserted at the input or output of the transistor amplifier to reduce the effect of limited performance in the radiated EMI frequency band. Also as concerned with the inflow of low-frequency leakage current, it cannot be attenuated because of the nature of coupling capacitors and the sensing circuit.
\[ L_{\text{cm}} = L_{\text{cm}} \frac{1}{1 + \frac{s}{\omega_l}} \]  \hfill (5.9)

The equivalent inductance of the common-mode choke, due to the ACEF can be calculated using the relation shown in equation (5.2) and it is given as equation (5.9). Combined with equations (5.7) and (5.9), the input common-mode current, can be effectively suppressed without increasing the low frequency leakage current.

### 5.3 RESULTS AND DISCUSSIONS

The proposed Active common-mode EMI filter for switched mode PWM inverter fed AC drive have been simulated by MATLAB/SIMULINK software (figure A1.2) and the performance investigation of the operation of induction motor has been carried out. To demonstrate the features of the proposed EMI filter scheme, a comparative study is performed with and without filter. The system parameters of the proposed ACEF are detailed in table 5.1.

#### Table 5.1 ACEF System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>RLE</td>
<td>-</td>
</tr>
<tr>
<td>Output frequency</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100</td>
<td>kHz</td>
</tr>
<tr>
<td>Capacitance ( C )</td>
<td>12500X10^{-6}</td>
<td>F</td>
</tr>
<tr>
<td>Coupling Capacitance ( C_c )</td>
<td>1250X10^{-3}</td>
<td>F</td>
</tr>
<tr>
<td>Parallel Capacitances ( C_{x1} ) and ( C_{x2} )</td>
<td>1250X10^{-3}</td>
<td>F</td>
</tr>
<tr>
<td>Common mode Capacitances ( C_{y1} ) and ( C_{y2} )</td>
<td>1250X10^{-3}</td>
<td>F</td>
</tr>
<tr>
<td>Inductance ( L )</td>
<td>120X10^{-3}</td>
<td>H</td>
</tr>
<tr>
<td>Common mode Inductances ( L_{\text{cm1}} ) and ( L_{\text{cm1}} )</td>
<td>1.0X10^{-3}</td>
<td>H</td>
</tr>
<tr>
<td>DC Control voltage ( V_c )</td>
<td>100</td>
<td>V</td>
</tr>
<tr>
<td>Push-pull amplifier</td>
<td>NEC 2SC3840 (PNP), 2SA1486 (NPN)</td>
<td>-</td>
</tr>
</tbody>
</table>
5.3.1 Proposed EMI Filter Circuit

The simulation circuit consists of an input active filter and PWM inverter. Input filter consists of a combination of ACEF and transistor amplifier. The base of input filter amplifier transistors Q1 and Q2 are biased by three winding mutual inductance $L_{CM1}$. Single phase 230 V AC supply is given to the input EMI filter. The EMI noise filter output is given in the rectifier input. A fixed DC voltage is given to the switched mode PWM Inverter. Rectifier and switched mode PWM inverter between LC tanks are used to maintain the constant current and voltage sources. Load side stray capacitance is grounded as shown in figure 5.4.

![Figure 5.4 ACEF with PWM Inverter Simulation Circuit](image)

5.3.2 Switched Mode PWM Inverter without EMI Filter

In MATLAB / SIMULINK model (figure A1.1), the input voltage of 230V single phase AC supply given to the power IGBTs switched-mode PWM Inverter circuit. Switched-mode PWM Inverter is operated at 180 degree mode of operation. This mode of operation is used to minimize the shoot through fault between two switches in the same arms. RLE Load is connected across the switched mode PWM Inverter. Conducted common
mode EMI noise interference waveform is measured in between line-ground voltage using three individual scopes. The output waveform of each phase voltage spikes shown in scope (Figure 5.6). The switching sequence of power MOSFET in Switched mode PWM inverter is 612, 123, 234, 345, and 456.

5.3.3 **Parameters of Pulse generator for Switched mode PWM Inverter**

Switched mode PWM Inverter is operated by six gate pulses generated from the PWM pulse generator parameters are shown in Table 5.2. The PWM generator has a pulse amplitude of 1V for all the six pulses, pulse width of 33.33% with a constant time period of 0.02 sec. The PWM pulse generator PG1 has a phase delay of zero degree, and the PWM pulse generator PG2 has a phase delay of 180 degree. The PWM pulse generators PG1 and PG2 are in the same arms. If there is no delay in between PG1 and PG2, shoot through fault will occur.

**Table 5.2 Parameters of Pulse Generator**

<table>
<thead>
<tr>
<th>Pulse generator</th>
<th>PG1</th>
<th>PG2</th>
<th>PG3</th>
<th>PG4</th>
<th>PG5</th>
<th>PG6</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase delay</td>
<td>0(^0)</td>
<td>0.000056 X 180(^0)</td>
<td>0.000056 X 120(^0)</td>
<td>0.000056 X 60(^0)</td>
<td>0.000056 X 240(^0)</td>
<td>0.000056 X 60(^0)</td>
<td>Degrees</td>
</tr>
</tbody>
</table>

5.3.4 **Pulse Generator Waveform for Switched Mode PWM Inverter**

The PWM pulses are generated by the pulse generator and six pulses are given sequentially to the each power IGBTs. The figure 5.5 shows the PWM pulse waveform for power IGBTs. The upper group switch S1 is fired at \( t = 0^0 \), then S3 is fired with a delay at \( t =120^0 \) and S5 is fired with
at a delay $\omega t = 240^\circ$. In the same way the lower group switch S2 is fired with a delay at $\omega t = 180^\circ$, then switch S6 is fired with a delay at $\omega t = -60^\circ$ and switch S4 is fired with a delay at $\omega t = 60^\circ$.

Figure 5.5 Six Pulses Waveform for PWM Inverter
5.3.5 Output Voltage Waveform Switched Mode PWM Inverter without EMI Filter

Figure 5.6 shows the simulated output voltage waveform of each phase with respect to ground of the switched mode PWM Inverter. Since there is no EMI filter connected in front of the source side, spikes are produced during the high dv/dt spike. These spikes will affect circulation of the common mode EMI current. Due to this reason, the nearby power IGBTs will be damaged.

Figure 5.6 Output Voltage Waveform of Switched Mode PWM Inverter without Filter
5.3.6 Switched Mode PWM Inverter with Filter

In MATLAB / SIMULINK model (figure A1.2), of the switched mode PWM Inverter, 230V AC supply is given to the input EMI filter. In input EMI filter, Inductance alone is varied, keeping the capacitance constant. The input EMI filter mitigates the EMI noise. The output of the EMI filter is given to the input of the rectifier. The fixed DC voltage from the rectifier is given to the switched mode PWM Inverter. In between the rectifier and inverter, an inductance is used to maintain the constant current. A capacitor is connected across the supply voltage to maintain the voltage constant.

Figure 5.7 Output Voltage Waveform of Switched Mode PWM Inverter with Filter
5.3.7 Output Voltage Waveform of Switched Mode PWM Inverter with EMI Filter

In switched mode PWM inverter an active common-mode EMI filter is used to reduce the EMI noise. By varying the inductance value, the high transient voltage and EMI noise current are reduced as shown in the Figure 5.7.

![Figure 5.7](image)

Figure 5.8 Harmonic Profiles in Full Load of the Line Voltage using (a) Without ACEF (b) With ACEF

Figure 5.8 (a) shows the total harmonic distortion spectrum without active common mode EMI filter at full load. In this condition, THD value is 33.37%. When an active common mode EMI filter has been introduced, there will be a great reduction in the THD of about 2.90%. Figure 5.8 (b) shows the total harmonic distortion spectrum with active common mode EMI filter.

Figure 5.9 (a) shows the total harmonic distortion spectrum without active common mode EMI filter at half load. In this condition, THD value is 32.10%. When an active common mode EMI filter has been introduced, there will be a great reduction in the THD of about 1.80%. Figure 5.9 (b) shows the total harmonic distortion spectrum with active common mode EMI filter.
Figure 5.9 Harmonic Profiles in Half Load of the Line Voltage using (a) Without ACEF (b) With ACEF

Figure 5.10 Harmonic Profiles in Quarter Load Voltage using (a) Without ACEF (b) With ACEF

Figure 5.10 (a) shows the total harmonic distortion spectrum without active common mode EMI filter at quarter load. In this condition, THD value is 32.07%. When an active common mode EMI filter has been introduced, there will be a great reduction in the THD of about 1.69%. Figure 5.10 (b) shows the total harmonic distortion spectrum with active common mode EMI filter.
The overall comparison of the total harmonic distortion value with and without active common mode EMI filter at three different load conditions Viz. full load, half load and quarter load has been clearly presented in the figure 5.11. It has been understood that the THD values for different load conditions with active common mode EMI filter are very low.

5.4  EXPERIMENTAL RESULTS

5.4.1  Implementation of ACEF for Switched Mode PWM Inverter

Figure 5.12 shows the block diagram of an ACEF for switched mode PWM Inverter. Switched mode PWM pulses are generated by 8051 microcontroller. The amplitude of this pulse is +5V and it is boosted to +12V using the driver circuit. Driver circuits consist of an optocoupler, PNP and
NPN Darling ton pairs. An output pulse of 12V amplitudes from the driver circuit is given to the gates of the switched PWM Inverter. EMI filter consists of LC filter and transistor amplifier. The output of the EMI filter is given the single phase silicon bridge rectifier. The rectified 100V DC voltage is given to the voltage source switched mode PWM inverter. The output of the switched mode PWM inverter is connected to the FHP induction motor drive.

Figure 5.12 Block Diagram of ACEF for Switched Mode PWM Inverter

To implement the proposed system in hardware, a prototype model has been developed with the half HP induction motor drive with the voltage rating of 110V/50Hz single phase AC supply.
5.4.2 **Power Supply Unit**

The various levels of voltage ranges required for the data acquisition electronic circuitry are +5 V, +12V and -5 V. The circuit diagram to get those ranges of power supply from the standard 230 V single phase ac supply from source. The ac voltage is stepped down using a step down transformer and is rectified and passed through the filter and a voltage regulator to get the desired type of positive or negative supply. The circuit diagram of power supply unit is shown in figure 5.13.

![Figure 5.13 Power supply unit](image)

5.4.3 **EMI Filter Input Voltage Waveform**

Figure 5.14 shows the input voltage waveform of 110V, 50Hz single phase AC which is given to the Pi type EMI filter through isolation transformer.
5.5 EMI FILTER

Electromagnetic interference filter can be broadly classified into two types.

a. T-type EMI filter

b. Pi-type EMI filter

5.5.1 T-type EMI Filter Circuit Diagram

Figure 5.15 shows the T-type EMI filter. In this filter the inductance value can be varied while the capacitance value remains constant. T-type filter will not reduce the common mode noise.
5.5.2 Pi Type EMI Filter

This filter varies the inductance value only by mutual inductance principle and while the capacitance is remaining constant. So if there are any loads fluctuations the system quickly comes to stable state (figure A1.6). The figure 5.16 shows the connection diagram of Pi-type EMI filter (Cadirci et al 2005). The Pi-Type filter (Model: 62–LMB–030-5-11) Specifications are shown in table 6.3.
### TABLE 5.3 Specification of Pi-Type Filter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>$C_X = 0.1$, $C_Y = 3300$</td>
<td>µF</td>
</tr>
<tr>
<td>Inductance:</td>
<td>$L_1 = 14$</td>
<td>mH</td>
</tr>
<tr>
<td>Number of turns</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Output and coupling capacitor</td>
<td>$C_o = C_c = 10$</td>
<td>nF</td>
</tr>
<tr>
<td>Control voltage</td>
<td>$V_c = 15$</td>
<td>V</td>
</tr>
<tr>
<td>Maximum Control current</td>
<td>$I_{c_{max}} = 3$</td>
<td>A</td>
</tr>
<tr>
<td>Frequency</td>
<td>$f_T = 100$</td>
<td>MHz</td>
</tr>
<tr>
<td>Current ratings (max)</td>
<td>3 – 200</td>
<td>Amps</td>
</tr>
<tr>
<td>Voltage ratings (max)</td>
<td>50 - 250V / 50Hz</td>
<td>V/Hz</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-25° to +85° C</td>
<td>°C</td>
</tr>
<tr>
<td>Leakage current range</td>
<td>0.35mA to 3mA max</td>
<td>mA</td>
</tr>
<tr>
<td>Insertion loss range</td>
<td>Effective filtering from 100 KHz to 30MHz</td>
<td>Hz</td>
</tr>
</tbody>
</table>

#### 5.6 RECTIFIER IC

The Single phase silicon bridge type rectifier has low forward voltage drop and peak surge overload current will be around 200 – 400 Amperes (figure A1.5). It consists of four terminals, two input and two output terminals. The two input terminals are connected to the EMI filter and the two output terminals are connected to the switched mode PWM Inverter.

#### 5.6.1 Rectifier Output Waveform

Figure 5.17 shows the output waveform of rectifier. The rectifier input voltage is 110V and the output is 100V. The rectifier output is given to the filter to get a constant DC voltage.
Figure 5.17 Rectifier Output Waveform

5.7 SWITCHED MODE PWM INVERTER MODULE

The figure 5.18 shows the switched mode PWM inverter module. It consists of six IGBTs and an LC filter. The inductance is used to maintain constant current and the capacitance is used to maintain constant voltage. The inverter circuit CT60 IGBTs are used in Inverter module (figure A1.9). Their voltage and current ratings are 900V/60A. Output of the switched mode PWM inverter module is connected to the three phase FHP induction motor.
5.8 MICRO CONTROLLER

Microcontroller consists of four ports. Port 1.0 to 1.5 is used to generate +5V PWM pulses as shown in figure 5.19. Port 2.0 acts as toggle switch, 2.1 as increment switch and 2.2 as decrement switch. One important advantage of microcontroller is that it has inbuilt input and output ports.

5.8.1 Microcontroller Output PWM Pulse

Figure 5.19 shows the PWM output pulse for the microcontroller. It will generate the +5V PWM pulse for the three phase PWM inverter each switch. This +5V PWM pulse is amplified to +12V using driver circuit.
5.9 DRIVER CIRCUIT

The driver circuit (figure A1.3), is used to boost the microcontroller output voltage. The output voltage of 5V, from microcontroller is not enough to drive the IGBTs. Driver circuit amplifies the 5V into 12V.

When the LED is in off position, the transistor $T_2$ gets forward biased. So transistors $T_3$ and $T_4$ get forward biased. So transistors $T_3$ and $T_4$ act as a Darlington pair, which is used to improve the current gain. The amplified output is given to the IGBT gate. This causes the induction motor to run.

When $T_1$ is forward biased, transistors $T_2$, $T_3$ and $T_4$ are reverse biased. When 12V supply is given to the capacitor, it gets charged from positive to negative polarity. The negative voltage of this capacitor is used to...
hold the IGBT in OFF position. The +5V PWM pulse from Microcontroller is not sufficient to drive the IGBTs. The +5V pulse is amplified to +12V pulse, using a driver circuit. The +5V pulse is given to the opto coupler. It is used to isolate the controller part. The Driver circuit consists of NPN Darlington pair and UJT.

5.9.1 Output Waveform of Driver Circuit

Figure 5.20 shows the driver output pulses for an inverter without EMI filter. The waveform contains the small value of voltage spikes caused by EMI in the switched mode PWM inverter.
5.10 OUTPUT VOLTAGE WAVEFORM OF PWM GATE PULSE

Figure 5.21 shows the gate pulse for IGBT\textsubscript{1} and IGBT\textsubscript{3} with 60\degree delay. The IGBT\textsubscript{3} is switched ON with a delay of 60\degree after the IGBT\textsubscript{1} is switched off.

![Figure 5.21 Output Voltage Waveform of PWM Gate Pulse](image)

5.11 OUTPUT WAVEFORM FOR FHP MOTOR LOAD

Figure 5.22 shows the output voltage waveform for without EMI filter for switched mode PWM inverter FHP motor drive. The EMI filter is not connected in front of the source side. So the waveform contains spikes while the inverter switch turning ON and OFF (dv/dt) transient period. These spikes affect the EMI noise.
Figure 5.22 Output Voltage Waveform for FHP motor Load without Filter

Figure 5.23 shows the output voltage waveform for with EMI filter for switched mode PWM Inverter fed FHP motor drive. The EMI filter is connected in front of the source side. The spikes which are not produced while turning ON and OFF (dv/dt) transient period are eliminated using EMI filter.
5.12 Harmonic Analysis

Order of harmonics is found out by using spectrum analyzer. In spectrum analyzer, when the fundamental frequency matches with the switching frequency, 5\textsuperscript{th} order harmonic occurs. This harmonic is analyzed by using Fast Fourier Transform without filter (Rashid Muhammad 2003). The Fractional Horse Power (FHP) Motor Ratings are furnished in table 5.4. The FHP motor resistance and inductance are measured by using LCR meter.
Table 5.4 Fractional Horse Power Motor Ratings

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage ($V_s$)</td>
<td>110</td>
<td>V</td>
</tr>
<tr>
<td>Frequency ($f$)</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Angular Speed ($\omega$)</td>
<td>314</td>
<td>rad/sec</td>
</tr>
<tr>
<td>Resistance ($R$)</td>
<td>4.7</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Inductance ($L$)</td>
<td>158.5</td>
<td>mH</td>
</tr>
</tbody>
</table>

1. Line to Line Voltage with $n=5$

where $n$ is order of odd harmonics

\[ V_{ab} = \sum_{n=1,3,5}^{\alpha} \frac{4V_s}{n\pi} \cos \frac{n\pi}{6} \sin n \left( \cot \frac{\pi}{6} \right) \] (5.1)

\[ V_{ab} = \sum_{n=5}^{\alpha} \frac{4 \times 110}{5 \pi} \cos \frac{5 \pi}{6} \sin 5 \left( 314Xt + \frac{\pi}{6} \right) \] (5.2)

\[ V_{ab} = 276.32 \times 0.9989 \times \sin 5\left[ 314 \times t + \frac{\pi}{6} \right] \] (5.3)

2. Line Current with $n=5$

\[ \theta_n = \tan^{-1} \left( \frac{n\omega L}{R} \right) \] (5.4)

\[ \theta_n = \tan^{-1} \left( \frac{5 \times 314 \times 158.5}{4.7 \times 10^3} \right) = 88.92^0 \] (5.5)
\[ I_a = \frac{\alpha}{\sum_{n=1,3,5}} \left[ \frac{4V_s}{\sqrt{3} \times n \times \pi \sqrt{R^2 + (n \pi \omega L)^2}} \cos n \frac{n \pi}{6} \right] \sin(n \omega t + \theta_n) \quad (5.6) \]

\[ I_a = \frac{\alpha}{\sum_{n=5}} \left[ \frac{4 \times 110}{\sqrt{3} \times 5 \times \pi \sqrt{4.7^2 + (5 \times \pi \times 314 \times 158.5 \times 10^{-3})}} \cos \frac{5 \pi}{6} \right] \sin(5 \times 314t - 88.92^0) \quad (5.7) \]

\[ I_a = -0.0033 \sin(1570t - 88.92^0) \quad (5.8) \]

3. Line-line RMS Voltage

\[ V_L = 0.8165V_s \quad (5.9) \]

\[ V_L = 0.8165 \times 110 = 89.815V \quad (5.10) \]

4. The fundamental Line voltage \( V_{L1} = 0.7797V_s \)

\[ V_{L1} = 0.7797 \times 110 = 85.76V \quad (5.11) \]

5. The RMS Value of the Voltage between the phases is

\[ V_{rms} = 0.4717V_s = 0.4717 \times 110 = 51.88V \quad (5.13) \]

6. The RMS value of fundamental Line – Line Voltage is,

\[ V_{p1} = \frac{V_{L1}}{\sqrt{3}} = \frac{85.76}{\sqrt{3}} = 49.5V \quad (5.14) \]

7. Total harmonic distortion = \( \frac{0.24236V_s}{0.7797V_s} = 31.08\% \quad (5.15) \)

8. \( V_{Ln} = 0.00666V_s = 0.00666 \times 110 = 0.7326V \quad (5.16) \)

9. Distortion factor = \( \frac{V_{Ln}}{V_{L1}} = \frac{0.00666V_s}{0.7797V_s} = 0.854\% \quad (5.17) \)

10. Order of harmonics 5\textsuperscript{th} therefore \( V_{L5} = \frac{V_{L5}}{5} = \frac{85.76}{5} = 17.15V \quad (5.18) \)
a) Harmonic Factor = \( \frac{V_{L5}}{V_{L1}} = \frac{17.15}{85.76} = 19.99\% \) \hspace{1cm} (5.19)

b) \( DF_5 = \frac{V_{L5}}{5} = 0.816\% \) \hspace{1cm} (5.20)

5.13 SUMMARY

In order to mitigate the EMI noise, the concept of active common mode EMI filter for switched mode PWM inverter fed three phase induction motor has been proposed. The configuration of the active common mode EMI filter with dc bus coupling and ac bus coupling applicable for single phase and three phase applications were developed. The frequency response of the proposed ACEF without the effect of coupling capacitance clearly indicates the conducted EMI frequency band.

The simulation of the proposed ACEF for switched mode PWM inverter fed AC drive has been carried out. In the performance point of view, a detailed comparative analysis has been made for the proposed ACEF with and without filter arrangement. The simulated voltage and current waveforms of the proposed ACEF for switched mode PWM inverter has been presented without EMI filter. It has clearly predicted that the spikes are produced during high dv/dt transient in the output voltage which in turn damages the nearby components. Due to the presence of EMI filter, the high transient voltage, EMI noise and THD have been reduced reasonably. In order to validate the simulated results, the proposed system has been implemented in hardware for with and without filter combination. There is a close agreement between the simulated and the experimental results.