6.1 INTRODUCTION

Pulse-width modulated variable-speed drives have become common in many industrial and household applications. Besides many advantages such as energy savings and good controllability, frequency converters have also brought along some unwanted effects. The output voltage of the inverter consists of sharp-edged voltage pulses, which may cause excessive voltage stresses in the stator winding insulations of the motor. They may also give rise to leakage currents through the parasitic capacitances of the stator winding and produces bearing currents. Lower-order harmonics cause acoustic noise and power losses in the motor.

A means to overcome these problems is using a sinusoidal inverter output filter (sine-wave filter) (Finlayson 1998). As an additional advantage, the filter may bring along cost savings in other components of the drive system. The cost saving can be achieved by (i) the inverter can be rated smaller because a part of the magnetizing current is fed by the filter capacitors, (ii) unshielded cables can be used if the common-mode voltage is filtered (Hanigovszki et al 2006) and (iii) the load side EMI filter can be avoided. Conventionally, the drives equipped with a sinusoidal output filter are based on constant V/f control. However, the control performance can be
improved by using sensor less vector control (Salomaki et al 2006). If vector control is used, the sampling frequency should be sufficiently higher than the resonance frequency of the filter, which sets a constraint for the filter design.

The design of a sinusoidal filter is usually based on the resonance frequency of the filter (Akagi et al 2004). The resonance frequency has been set one decade below the switching frequency of the inverter. However, to minimize the filter cost, the resonance frequency should be closer to the switching frequency. In the filter design, the relative cost of the inductor and capacitor based on an estimate that the capacitor cost is half of the inductor cost for the same power rating.

Laminated iron-core inductors are usually used in sinusoidal output filters. Due to the eddy currents in the laminations, the resistance and the inductance of the filter inductor depend significantly on the frequency. Hence, a frequency-dependent inductor model is preferred to design the filter, if the switching frequency is high.

6.2 INVERTER OUTPUT FILTERS

Various inverter output filter topologies have been proposed. In passive filters, only passive components (inductor, capacitor and resistor) and their combinations are used. In the active filter design, a controlled semiconductor switch and passive components are utilized. These filters have the capability to suppress the differential mode or common mode noise, where some of them suppress both types of noises. A survey of various output filter topologies that are typically employed in industrial applications are presented below.
6.2.1 Output Reactor

The simplest differential mode filter is an output reactor. Figure 6.1 shows an output reactor consists of a three-phase inductor placed at the output of the inverter. It reduces $dv/dt$ of the motor terminal voltage and the PWM ripple current by increasing the load inductance. However, in some applications like long cables, the resonance may occur between cable capacitance and the reactor. In such cases, voltage overshoots may be further amplified at the motor terminals (Hanigovszki et al 2007). Generally, an output reactor, having 3%-5% impedance ratio is inserted at the inverter output. The impedance ratio of the reactor is calculated as given below

$$Z\% = \frac{2 \pi f_r L_D I_r}{V_r}$$  \hspace{1cm} (6.1)

where $Z\%$ is the impedance ratio, $L_D$ is the inductance value, $f_r$ is the rated motor frequency, $I_r$ is the RMS value of rated motor current, $V_r$ is the RMS value of rated motor voltage.

Figure 6.1 Utilization of an Output Reactor in a Motor Drive
6.2.2 Differential Mode LCR Filters

Figure 6.2 shows a standard commonly used differential mode LCR filter topology. It consists of a three-phase reactor, three capacitors and three damping resistors forming a second-order low-pass filter. The frequency components below the cut-off frequency are passed almost without reduction in magnitude, whereas the frequency components above the cut-off frequency are filtered. The cut-off frequency is expressed as

\[ f_0 = \frac{1}{2\pi \sqrt{LC}} \]  

(6.2)

This filter is classified into two types according to the filter cut-off frequency: differential mode dv/dt filter and differential mode sine filter (SF) (Hanigovszki et al 2007). The cut-off frequency of the differential mode dv/dt filter is above the PWM frequency, and its main aim is to reduce the dv/dt of the motor terminal voltage. The cut-off frequency of the differential mode SF is below the PWM frequency, thus it eliminates the differential mode PWM frequency components and switching ripple current, and makes motor terminal voltages sinusoidal. However, the control bandwidth of the inverter is limited by the filter cut-off frequency. Thus, there is a trade-off between the
differential mode suppression and the control bandwidth of the drive. In the differential mode dv/dt filter, voltage overshoots which may occur due to LC filter can be damped out using damping resistors $R_D$. Because of the damping, the differential mode dv/dt filter has better performance compared to the output reactor. In SF, $R_D$ damps oscillations due to disturbances in the inverter and control dynamics. The components of the SF are larger than those of the dv/dt filter, thus it increases system size and cost.

6.2.3 Common Mode Inductor

The simplest passive common mode filtering method is adding a Common Mode Inductor (CMI) between the inverter output and the motor as shown in figure 6.3. In the CMI, three-phase windings are wound in the same direction around a common core, thus it causes a net flux which provides high common mode impedance and suppresses the Common Mode Current (CMC). Since the sum of symmetrical three-phase currents is zero, they do not cause a net flux in the core, and the differential mode inductance of the CMI is ideally zero. The passive common mode filtering is a cost-effective method of reducing such CMCs, and reductions of the original CMC is as low as 10% have been reported (Muetze and Heng 2010). Since the circulating type bearing currents are induced by the CMC, the amplitude of the circulating bearing current is also reduced by approximately the same percentages as reported in Muetze and Binder (2006).

![Figure 6.3 Utilization of a Common Mode Inductor in a Motor Drive](image-url)
The CMC with peak magnitude $I_{cm}$ causes magnetic field intensity with amplitude $H$ which results in the flux density $B$. Therefore, a CMI represents a common mode inductance $L_{cm}$ in the common mode circuit (Muetze 2009). The inductance $L_{cm}$ is given by equation (6.3), where $\lambda$ is the total flux linkage in the core, $\mu$ is the permeability of the magnetic core, $A_c$ and $L_c$ are the cross sectional area and the circumferential length of the toroidal core respectively, and $N$ is the number of turns per-phase.

$$L_{cm} = \frac{\lambda}{I_{cm}} = \frac{N.B.A_c}{I_{cm}} = \frac{N_\mu.H.A_c}{I_{cm}} = \frac{N^2_\mu.L_c}{\pi L_c}$$ (6.3)

If the magnetic field caused by the peak current $I_{cm}$ exceeds the saturation flux density $B_{sat}$, the performance of the CMI decreases, because the value of the inductance $L_{cm}$ decreases with increasing degree of saturation. Therefore, a CMI should be designed according to the $B_{sat}$ value of the core such that the peak current does not saturate the core. The maximum number of turns for a given core is determined (keeping $I_c$ and $\mu$ constant) as

$$N \leq \frac{I_c \pi B_{sat}}{I_{cm \max} \mu}$$ (6.4)

Inductance values of the CMIs are typically a few mH and the equivalent common mode capacitances of motors at several kW power ratings are in the order of few nF. The peak CMC is related to the common mode voltage (CMV) change with high $dv/dt$, which corresponds to MHz range. At such frequencies, the impedance of the CMI is predominant than the motor common mode impedance. Thus it effectively suppresses the CMC. However, at the CMV frequencies (PWM frequencies) the common mode impedance of the motor is much higher than that of the CMIs, thus it does not suppress the
CMV on the motor. Therefore, the voltage buildup in the bearings which is same as that of CMV is not eliminated. As a result the shaft voltage and EDM type bearing currents are not suppressed by the CMI (Akagi and Tamura 2006).

The CMC has an oscillatory waveform when the CMI is inserted. The CMI suppresses the spikes on the CMC, if the core is of low-loss type. It causes oscillation and it does not reduce the rms value of the CMC significantly. In lossy cores, the series equivalent of the CMI is an inductance series to a resistance which represents the core loss. The quality factor (Q) of the CMI given in equation (6.5) is the ratio of its inductance to its resistance at a given frequency and it is a measure of loss characteristics.

\[ Q = \frac{\omega L}{R} \]  

(6.5)

The lower the quality factor of the inductor, the more lossy characteristics it has. A CMI with lossy core increases the common mode resistance as well as the inductance in the common mode equivalent circuit and helps to damp the oscillation faster, resulting in less rms CMC. Generally, toroidal cores used in CMIs have high core losses at high frequencies related with the CMC, and they can successfully damp the oscillation of the CMC and reduces the rms value of the CMC.

6.2.4 Active Common Mode Voltage Filter

In order to suppress the CMV, active filters have been also utilized. They consist of semiconductor switches as well as passive component (Son and Sul 2003). The filter shown in figure 6.4 is an active common-noise canceller (ACC) for eliminating the CMV generated by a PWM inverter. The filter is composed of a CMV detector with three \( C_1 \) capacitors, a common
mode transformer with 1:1 turn ratio, a push-pull emitter follower, and two $C_0$ capacitors which form DC bus midpoint. The neutral point of $C_1$ capacitor indicates the CMV value. The mapped voltage is applied to the common mode transformer (CMT) secondary winding after buffering by the emitter-follower. The CMT utilized in this method is same as explained previously, except an emitter follower is connected to the secondary winding of the CMT instead of a damping resistor. The filter superimposes a compensating voltage at the inverter output. The compensating voltage applied has the same amplitude as, but opposite polarity to the CMV produced by the inverter. As a result, the CMV applied to the load is cancelled completely, and the CMC is eliminated. However, the method is problematic due to complexity and reliability, and power semiconductor switches utilized to increase the cost of the filters significantly.

Figure 6.4 Motor Drive with Active Filter
6.3 RESULT AND DISCUSSIONS

The proposed ACEF with various output filter configurations have been simulated by MATLAB/SIMULINK software (figures A1.7 to A1.11) 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 different configuration of output filters. The system parameters of the proposed ACEF with different output filter configurations are detailed in table 6.1.

Table 6.1 Parameters of Different Output Filter Configurations

<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_{cm1} and L_{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), NEC 2SA1486 (NPN)</td>
<td>-</td>
</tr>
</tbody>
</table>
6.3.1 Output Waveform of Switched Mode PWM Inverter with EMI Filter Incorporating Delta Connected Output Capacitor Filter

Figure A7 shows the MATLAB/SIMULINK model of switched mode PWM Inverter with EMI filter incorporating delta connected output capacitor filter. The output waveform of the proposed filter with delta connected capacitor filter is shown in figure 6.5. It is clearly understood that the output waveform of each phase voltages (Vr0, Vy0 and Vb0) are in distorted form during switching operation. Further, there is a decrease in each phase voltage of about 56.52% approximately which in turn disturbs the stable operation of the system. In addition, change in load patterns will affect the delta connected output capacitor filter.

![Figure 6.5 Output Waveform of Proposed Filter with Delta Connected Output Capacitor Filter](image)

6.3.1.1 Spectrum of Delta Connected Output Capacitor Filter

The FFT Analysis has been carried out for the phase voltage (Vr0) to determine the total harmonic distortion which is depicted in the
figure 6.6. In this condition, the THD value is found to be 34.64%. When an output delta connected capacitor filter has been introduced, there will be an increase in the THD value.

![Harmonic Profiles of the Line Voltage using Output Delta Connected Capacitor Filter Spectrum](image)

**Figure 6.6** Harmonic Profiles of the Line Voltage using Output Delta Connected Capacitor Filter Spectrum

### 6.3.2 Output Waveform of Switched Mode PWM Inverter with EMI Filter Incorporating Star Connected Output L and C Filter

Figure A1.8 shows the MATLAB/SIMULINK model of a switched mode PWM inverter with EMI filter incorporating star connected output inductor and capacitor filter. The output waveform of the proposed filter with start connected output inductor and capacitor filter is shown in figure 6.7. It is clearly learnt that the output waveform of each phase voltages (Vr0, Vy0 and Vb0) are in distorted form during switching operation. Further, there is a decrease in each phase voltage of about 34.78% approximately which in turn
which disturbs the stable operation of the system. In addition, change in load patterns also affects the star connected output inductor and capacitor filter.

![Figure 6.7 Output Waveform of Proposed Filter with Star Connected Output Inductor and Capacitor Filter]

6.3.2.1 Spectrum of Star Connected Output Inductor and Capacitor Filter

The FFT Analysis has been carried out for the phase voltage (Vr0) to determine the total harmonic distortion which is depicted in the figure 6.8. In this condition, The THD value is found to be 34.67%. When a star connected inductor and capacitor filter has been introduced, there will be an increase in the THD value than the nominal value.
6.3.3 Output Waveform of Parallel Connected Output Capacitor Filter

Figure A1.9 shows the MATLAB/SIMULINK model of a switched mode PWM inverter with EMI filter incorporating output capacitor filter connected in parallel. The output waveform of the proposed filter with output capacitor filter connected in parallel is shown in figure 6.9. It is clearly understood that the output waveform of each phase voltages (Vr0, Vy0 and Vb0) are in distorted form during switching operation. Further, there is a decrease in each phase voltage of about 39.13% approximately which in turn which disturbs the stable operation of the system. In addition, change in load patterns also affects the output capacitor filter connected in parallel.
6.3.3.1 Spectrum of Parallel Connected Output Capacitor Filter

The FFT Analysis has been carried out for the phase voltage (Vr0) to determine the total harmonic distortion which is depicted in the figure 6.10. In this condition, The THD value is found to be 35.10%. When a parallel connected capacitor filter has been introduced, there will be an increase in the THD value when compared with than the nominal value.
6.3.4 Output Waveform of Switched Mode PWM Inverter with EMI Filter Incorporating Series Connected Output Inductor Filter

Figure A1.10 shows the MATLAB/SIMULINK model of a switched mode PWM inverter with EMI filter incorporating series connected output inductor filter. The output waveform of the proposed filter with output inductor filter connected in series is shown in figure 6.11. It is clearly understood that the output waveform of each phase voltages (Vr0, Vy0 and Vb0) are in distorted form during switching operation. Further, there is a decrease in each phase voltage of about 43.47% approximately which in turn
which disturbs the stable operation. In addition, change in load patterns also affects the output inductor filter connected in series.

![Output Waveform of Proposed Filter with Series Connected Output Inductor Filter](image)

**Figure 6.11** Output Waveform of Proposed Filter with Series Connected Output Inductor Filter

### 6.3.4.1 Spectrum of Series Connected Output Inductor Filter

The FFT Analysis has been carried out for the phase voltage ($V_{r0}$) to determine the total harmonic distortion which is depicted in the figure 6.12. In this condition, the THD value is found to be 47.80%. When a series connected output inductor filter has been introduced, there will be an increase in the THD value when compared with than the nominal value.
6.3.5 Output Waveform of ACEF Connected in Source and Load Side

Figure A1.11 shows the MATLAB/SIMULINK model of ACEF connected in source and load side with respect to the load. The output waveform of the proposed filter with ACEF connected in source and load side is shown in figure 6.13. It is clearly understood that the output waveform of each phase voltages (Vr0, Vy0 and Vb0) are symmetrical with a decrease in phase voltage. In addition, change in load patterns also affects the ACEF connected in the load side.
Figure 6.13  Output Waveform of ACEF Connected in Source and Load Side

6.3.5.1  Spectrum of ACEF Filter Connected in Source and Load Side

The FFT Analysis has been carried out for the phase voltage (Vr0) to determine the total harmonic distortion which is depicted in the figure 6.14. In this condition, The THD value is found to be 2.54%. Though the THD value is nominal but there will be a reduction in the voltage profile.
6.4 EXPERIMENTAL RESULTS

6.4.1 Hardware Implementation of ACEF with Different Configurations of Output Filters

Figure 6.15 shows the block diagram of switched mode PWM inverter with ACEF incorporating different configuration of output filters. Switched mode PWM pulses are generated by 8051 microcontroller. The amplitude of this pulse is +5V and it is boosted to +12V using driver circuit. Driver circuits consist of an optocoupler, PNP and NPN Darlington pairs. An output pulse of 12V amplitude 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 taken to the single phase silicon bridge rectifier.

Figure 6.15 Block Diagram of ACEF with Different Configurations of Output Filters

The rectified 100V DC 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 through the output filter.

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 shown in the figure 6.16.
6.4.2 Output Voltage Waveform of ACEF with Different Configuration of Output Filters

The output voltage waveform of the proposed ACEF with different configuration of output filters are presented in the figures 6.17 to 6.21. It has been understood that the spikes are not produced while turning ON and OFF (dv/dt) transient. Due to the presence of EMI filter, spikes are eliminated in the switched mode PWM inverter but the output phase voltages (Vro, Vyo and Vbo) are not identical. The occurrence of distorted voltage waveform in the each phase results in unstable condition. Due to a distorted output voltage waveform, harmonics and heat will be generated.
Figure 6.17  Output Voltage Waveform of ACEF with Delta Connected Capacitor Filter
Figure 6.18  Output Voltage Waveform of ACEF with Star Connected L and C Filter
Figure 6.19  Output Voltage Waveform of ACEF with Capacitor Filter Connected in Parallel
Figure 6.20  Output Voltage Waveform of ACEF with L Filter Connected in Series
Figure 6.21 Output Waveform of ACEF Connected in Source and Load Side
6.5 SUMMARY

An output filter of various configurations in addition to the ACEF with their effects to change in load voltage has been studied. In order to analyze the performance of the proposed configurations of the output filters, the simulation work has been carried out. The proposed configuration of the output filters has been implemented in hardware for validation of the simulation results. A prototype model has been developed with the half HP induction motor drive. The simulation and the experimental results have been presented which clearly indicated the close agreement between them.

Due to the presence of various output filters, the high transient voltage has been reduced reasonably. But there is a reasonable decrease in the each phase voltages. In addition, the change in load patterns also affects the output filters.

In the performance point of view, a detailed comparative analysis has been made for the proposed ACEF and ACEF with various output filter arrangements. Due to the presence of EMI filter, the high transient voltage, EMI noise and THD has been reduced reasonably in the proposed ACEF. When the various output filters has been introduced, the voltage waveform will be distorted in nature. Further, the value of the THD has been greatly increased. In the case of ACEF connected in source and load side, the THD value is nominal but it will be affected by the change in load variations. Hence, it is clearly realized that the proposed ACEF with input filter configuration is predominant in its performance.