CHAPTER 5

FUZZY BASED THREE-LEVEL SHUNT ACTIVE FILTER

5.1 INTRODUCTION

The conventional passive filters and the dynamic PWM technique discussed in previous chapters reduce the harmonics present in the input to the motor and the output ripple torque of the motor. In order to achieve better performance of the motor the harmonics and torque ripple are to be reduced further. Also the current ripple experienced at the instant of commutation during the fuzzy controlled dynamic PWM method has to be further reduced for reducing the current harmonics and torque ripple of the motor.

This chapter discusses the possible implementation of a fuzzy logic controlled three level Shunt Active Filter (SAF) which is connected in parallel to the stator terminals of the motor to experiment the reduction in harmonics and torque ripple of the motor. The block diagram of the motor drive system with Shunt active filter is shown in Figure 5.1
Ambrish et al (2000) has suggested the different control techniques like reactive power theory, notch filters, sliding mode controllers which are used to improve the power quality in the power system. Among many such filtering techniques, Singh et al (2005) expressed that the Shunt active filter is found to be effective filter to minimize the current harmonics for non-sinusoidal current sources. The modified shunt active filter with LCL filter presented by Tang et al (2012) gives motivation for the use of shunt active filters for non-linear, non-sinusoidal current applications. Further, it is possible to enhance the filtering performance by the use of multi-level converters with line inductor and DC link capacitor called as multi level Shunt active filters for the effective minimization of harmonics. Ali & Kayhan (2011) presented a hybrid filter topology to reduce torque pulsation, switching voltage harmonics and EMI noises in PMSM with direct torque hysteresis controllers. This gives motivation for the use of shunt active filter to a motor application. The multilevel converters can reduce the harmonic
content by the active filter because they can produce more levels of control than conventional converters and this feature helps to reduce the harmonics by the filter. Another advantage is that they can reduce the voltage ratings of the semiconductors and the switching frequency requirements. Saad & Zellouma (2009) and Cheng & Yuan (2000) suggested that in order to minimize the power consumption of the filter, instead of DC voltage sources, DC link capacitors can be used. The SAF exchanges the energy between the phases and average power of the SAF is zero.

Cirstea et al (2002) and Mikkili & Panda (2012) discussed that the Artificial Intelligence (AI) techniques are ideal methods for controlling the non-linear systems. Fuzzy logic may be the ideal soft computing technique for the system with inaccurate mathematical model, imprecise input output relation. Avik & Chandan (2011) proposed the predictive and adaptive Artificial Neural Network (ANN) techniques for predicting the compensation current for filtering operation of fixed power frequency applications. The control characteristics of the BLDC motor are highly nonlinear in nature. So Fuzzy logic based controllers are found to be an ideal method to control the filter operation.

The various filtering techniques suggested by different researchers are generally applied to systems with fundamental sinusoidal voltage profile, with fixed frequency and these are experimented in power system applications for minimizing the harmonics present in voltage/current. This chapter presents the three-level shunt active filter topology applied to the non sinusoidal voltage and current profile produced by the electronic commutator of the BLDC motor drive to minimize harmonics and to reduce ripple torque of the motor. Moreover the fundamental frequency of the voltage and current in this BLDC motor drive changes with the speed of the motor. This filter topology consists of a three-level inverter in which the control schemes are provided by
the fuzzy logic controller (FLC). This methodology is simulated and tested in real time to investigate the performance enhancement of the motor drive with the aid of MATLAB/ dSPACE (DS1103 PPC) real-time platform.

5.2 DESCRIPTION OF THE SYSTEM

The functional blocks of the BLDC motor drive system with the shunt active filter (SAF) is shown in the Figure 5.2. The three modules present in this system are:

1) Motor Drive System
2) Shunt Active Filter (SAF)
3) SAF Controller (dSPACE-DS1103)

Figure 5.2 Functional blocks of BLDC motor drive system with Shunt Active Filter
5.2.1 Motor Drive System

The BLDC motor drive system consists of a 3 phase inverter which acts as electronic commutator. The generation of switching gate signals for the commutator and the speed control are performed by the FPGA controller. The speed is controlled by PI control method. The current input to the speed controller is provided from the line currents sensed from the motor input, converted into 8 bit digital data. The instantaneous speed of the motor is estimated from the hall sensor input signal and the same is compared with the set speed. Based on the speed error, the speed is adjusted by varying the stator voltage.

5.2.2 Shunt Active Filter

The main functionality of shunt active filter is to minimize the harmonic current and compensate reactive power. Among many active filter topologies developed, shunt active filters based on current controlled PWM converters are found to be effective when the load is highly nonlinear. Figure 5.3 shows the compensating methodology by the shunt active filter.

![Compensation methodology by the shunt active filter](image-url)
The shunt active filter is a current controlled PWM converter connected with line inductor with AC side and DC link capacitor on DC side. The switching gate pulses to the shunt active filter are generated in such a way to supply the required reactive current and harmonic compensation current to the stator input of the motor in order to minimize the harmonics. A fuzzy logic control algorithm is used to improve the performances of the three-level active power filters. The Fuzzy Logic Toolbox of MATLAB is used for implementing the fuzzy logic control algorithm. The shunt active power filter controller compensates the stator current of the BLDCM with low harmonic distortion which in turn reduces the ripple torque.

Figure 5.4 shows the structure of the Shunt active power filter. The SAF is basically a three phase three level current controlled inverter with line inductors (L_{af}) in AC side and DC link capacitors (C_1 and C_2) in DC side. Due to the simplicity of the construction, Diode clamped three level inverters are used for the three-level inverter. The diodes used in this three level inverter are to make the connection with the reference point to obtain Midpoint voltages. The switching devices are IGBTs which are connected with freewheeling diodes. A DC voltage source provides a steady DC voltage (V_{dc1}) to the DC side of the inverter which acts as active filter. In order to
produce an inverter of 3 levels, 2 DC link capacitors are required. The voltage across each capacitor is equal to \( V_{dc1}/2 \).

**Table 5.1 Three-Level inverter switching states**

<table>
<thead>
<tr>
<th>Levels</th>
<th>( G_{i1} )</th>
<th>( G_{i2} )</th>
<th>( G_{i3} )</th>
<th>( G_{i4} )</th>
<th>( V_{i0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( V_{dc1}/2 )</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>(-V_{dc1}/2)</td>
</tr>
</tbody>
</table>

The switching states of the three-level operation are presented in Table 5.1. Where, \( V_{io} \) is the phase-to-fictive middle point voltage and ‘\( i \)’ is the phase index (\( i = a \), \( b \) and \( c \)). The three voltage values (\( V_{dc1}/2 \), 0, \(-V_{dc1}/2\)) for the three levels are shown in Table 5.1

### 5.2.3 Shunt Active Filter Controller

The gating signals for the three-level shunt active filter is provided through a fuzzy logic control system derived with MATLAB/Simulink and implemented through dSPACE (DS1103) hardware.

The DS1103 is an excellent platform for developing rapid control prototype. This hardware board can be mounted on a dSPACE Expansion Box or dSPACE AutoBox to test the control functions in a laboratory. Its processing power and fast I/O are vital for applications that involve numerous actuators and sensors. This can be used with Real-Time Interface (RTI), the controller board is fully programmable from the Simulink block diagram environment. All I/O can be configured graphically by using RTI. This is a quick and easy way to implement the control functions on the board. The hardware specification as per the manufacturer are furnished below.
Some of the key functions of the dSPACE DS1103 PPC controller board are given below:

- Single-board system with real-time processor and comprehensive I/O
- CAN interface and serial interfaces ideally suited to automotive applications
- High I/O speed and accuracy
- PLL-driven UART for accurate baud rate selection

The control of electrical drives requires accurate recording and output of I/O values. It is possible to synchronize the A/D channels and D/A channels, and the position of the incremental encoder interface, with an internal PWM signal or an external trigger signal. Also, the serial interface (UART) is driven by a phase-locked loop to achieve absolutely accurate baud rate selection.

5.3 **REFERENCE CURRENT ESTIMATION**

The control methodology includes the estimation of harmonic compensation current for the shunt active filter to compensate the reactive power to the input of the motor. Different methods are proposed by the researchers for the identification of harmonic currents. Saad & Zellouma (2009) described the $p-q$ theory method which is used to estimate the compensating harmonic reference currents with minimum computational complexity. This method provides better performance when unbalanced stator currents, better steady state accuracy and very good transient response.
Figure 5.5 Reference current estimation using instantaneous power theory

The reference currents \((i_a^*, i_b^*, i_c^*)\) are computed based on \(\alpha-\beta\) transformation. Figure 5.5 shows the principle of instantaneous power theory (p-q theory) for generating the reference harmonic currents for the three phases. The three phase stator voltages \((V_a, V_b, V_c)\) and the stator current \((i_a, i_b, i_c)\) are transformed to the bi-phase system based on \(\alpha-\beta\) transformation for computing the real and imaginary powers. The transformed voltage and current are shown in the equations (5.1) and (5.2)

\[
\begin{bmatrix}
V_{\alpha} \\
V_{\beta}
\end{bmatrix} = \sqrt{2 \over 3} \begin{bmatrix}
1 & -1/2 & 1/2 \\
0 & \sqrt{2/3} & -\sqrt{2/3}
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

(5.1)

\[
\begin{bmatrix}
i_{\alpha} \\
i_{\beta}
\end{bmatrix} = \sqrt{2 \over 3} \begin{bmatrix}
1 & -1/2 & 1/2 \\
0 & \sqrt{2/3} & -\sqrt{2/3}
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

(5.2)

From equation (5.1) and (5.2), the active and reactive powers are calculated as per equation (5.3)

\[
\begin{bmatrix}
p \\
q
\end{bmatrix} = \begin{bmatrix}
V_{\alpha} & V_{\beta} \\
-V_{\beta} & V_{\alpha}
\end{bmatrix} \begin{bmatrix}
i_{\alpha} \\
i_{\beta}
\end{bmatrix}
\]

(5.3)
The values of instantaneous power \( p \) and \( q \), which are composed of real and imaginary powers, contain DC and AC components. The harmonic components of \( p \) and \( q \) are filtered using high pass filter with low cutoff frequency (\( \approx 5 \) Hz) and processed for estimation of harmonic currents. The harmonic component of the stator current will be the reference current required for the current supplied by the shunt active filter in order to compensate the reactive power requirement. The reference harmonic current in \( \alpha-\beta \) frame can be estimated by the equation (5.4).

\[
\begin{bmatrix}
i_{h\alpha} \\
i_{h\beta}
\end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}
\]

(5.4)

By using the inverse \( \alpha-\beta \) transformation the reference currents \( (i_{ref}) \) in a-b-c reference frame are obtained from equation (5.5)

\[
\begin{bmatrix}
i_a^* \\
i_b^* \\
i_c^*
\end{bmatrix} = \sqrt{2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{h\alpha} \\ i_{h\beta} \end{bmatrix}
\]

(5.5)

The estimated reference harmonic current based on the above methodology is used in Fuzzy logic controller to generate the reference voltage profile and to obtain the gating signals to the three-level inverter acting as a shunt active filter.

5.4 FUZZY LOGIC CONTROLLER FOR SHUNT ACTIVE FILTER

The control methodology implemented with fuzzy controller is shown in Figure 5.6 to generate the reference voltage profile for the effective shunt compensation. The per phase reference harmonic current \( (i_{ref}) \) and the
filter injected current \( (i_i) \) are used to compute the current error \( (ce) \). The current error \( (ce) \) and the derivative of the current error \( (dce) \) is considered as the inputs to the Fuzzy system. The equivalent output \( (code) \) is generated during fuzzy operation and processed for obtaining sinusoidal reference output voltage \( (V_r) \).

![Figure 5.6 Fuzzy control scheme](image)

Due to the simplicity in computation, triangular membership functions are preferred. The input current error \( (ce) \) and the derivative of the current error \( (dce) \) are fuzzified with five fuzzy sets (NM: Negative Maximum, N: Negative, Z: Zero, P: Positive, PM: Positive Maximum) using triangular membership functions. The output \( (code) \) is fuzzified into five fuzzy sets (NM: Negative Maximum, N:Negative, Z:Zero, P:Positive, PM: Positive Maximum) using triangular membership functions. The defuzzification is done using ‘centroid’ method and the code is processed for generating \( (V_r) \) which is further used to generate switching pulses to the three level inverter based SAF.

**Table 5.2 Fuzzy associate memory for the control action**

<table>
<thead>
<tr>
<th>( dce )</th>
<th>( ce )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM</td>
<td>NM</td>
</tr>
<tr>
<td>N</td>
<td>NM</td>
</tr>
<tr>
<td>Z</td>
<td>N</td>
</tr>
<tr>
<td>P</td>
<td>N</td>
</tr>
<tr>
<td>PM</td>
<td>Z</td>
</tr>
</tbody>
</table>
The fuzzy rules are created based on relating the per unit value (pu) of current error \( (ce) \), derivative of current error \( (dce) \) and the output \( (code) \). The \( (dce) \) will be positive, negative or zero depending on the nature of variation of current error. \( (dce) \) will be positive if \( (ce) \) is increasing, Zero if constant, negative if \( (ce) \) is decreasing. Fuzzy rules are generated for optimal operation and are tabulated in Table 5.2. Figure 5.7a, 5.7b and 5.7c show the normalized triangular membership functions for the inputs and output variables. Figure 5.7d shows the Fuzzy surface view of the variables.

![Figure 5.7 (a)](image1)

![Figure 5.7 (b)](image2)

**Figure 5.7 (Continued)**
Figure 5.7  (a) Membership functions for input variable $ce$, (b) Membership functions for input variable $dce$, (c) Membership functions for output variable $code$, (d) Fuzzy surface view for inputs and output

5.5 FILTER GATE CONTROL

The output of the fuzzy logic controller provides the reference voltage ($V_r$) which will be compared with two triangular carrier signals both spaced half cycle apart. Figure 5.8 shows the general block diagram for
generating of gating signal for the SAF. \( G_i \) refers the gating signals, \( i \) denotes the three phases \((i=1,2,3)\) and \( j \) denotes the four switches in each phase \((j=1,2,3,4)\) of a three level inverter acting as SAF.

The DC link voltage in the SAF is \( v_{dc} \) then the voltage across the capacitors will be in any of the three levels \( V_{dc}/2, 0, -V_{dc}/2 \), which are normalized to \( 1,0,-1 \). For predicting the gating signals, two intermediate voltage signals are assigned as \( v_{i1} \) and \( v_{i2} \). These signals are estimated based on the comparison of \( v_r \) with the triangular carrier signals.

\[
\text{If } v_r \geq \text{carrier 1 } \rightarrow v_{i1}=1 \\
\text{If } v_r < \text{carrier 1 } \rightarrow v_{i1}=0 \\
\text{If } v_r \geq \text{carrier 2 } \rightarrow v_{i2}=0 \\
\text{If } v_r < \text{carrier 2 } \rightarrow v_{i2}=-1
\]

The control signals for the switches are obtained as per the following conditions

\[
\text{If } (v_{i1} + v_{i2}) = 1 \rightarrow G_{i1}=1, G_{i2}=1, G_{i3}=0, G_{i4}=0
\]
If \((v_{i1}+v_{i2}) = 0\) → \(g_{i1} = 0, g_{i2} = 1, g_{i3} = 1, g_{i4} = 0\)

If \((v_{i1}+v_{i2}) = -1\) → \(g_{i1} = 0, g_{i2} = 0, g_{i3} = 1, g_{i4} = 1\)

The above control signals \((g_s)\) are directly applied to the switching devices of the three level SAF.

### 5.6 DESIGN OF SHUNT ACTIVE FILTER ELEMENTS

The filter inductance and capacitance are designed based on the voltage across each capacitor, the triangular carrier sampling signal frequency \((1/T_c)\) and the maximum change of current per sampling duration \((i_{s_{\text{max}}})\). If the maximum capacitor voltage change is \(V_{dc1}/2\), then the minimum value of capacitance is calculated as

\[
C = C_1 = C_2 \geq \left| \frac{2T_c i_{s_{\text{max}}}}{V_{dc1}} \right| \tag{5.6}
\]

In order to avoid the resonance condition, the minimum value of inductance is determined as

\[
L_{\text{af}} > \frac{1}{(2\pi f_{sw})^2 C} \tag{5.7}
\]

Where \(f_{sw}\) is the switching frequency

An experimental prototype of SAF is developed in the laboratory to test the performance of the SAF with Brushless DC motor with a lower voltage rating. The design parameters of the brushless DC motor and the ratings of each device are presented in Table 5.3.
Table 5.3 Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Inductance (Laf)</td>
<td>300mH</td>
</tr>
<tr>
<td>Filter capacitance(C₁, C₂)</td>
<td>500µF</td>
</tr>
<tr>
<td>Stator voltage (rated)</td>
<td>300V</td>
</tr>
<tr>
<td>Speed (rated)</td>
<td>2000 rpm</td>
</tr>
<tr>
<td>Stator Current (rated)</td>
<td>7.2 A</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>4</td>
</tr>
</tbody>
</table>

5.7 RESULTS AND DISCUSSIONS

The simulated and experimental results of the BLDC motor drive system with and without the application of SAF are presented and compared to investigate the effectiveness of the filter in enhancing the performance. The magnitude of the harmonics is considered as percentage of the fundamental quantity for analyzing the voltage and current harmonics. The fundamental frequency of quantity is considered as 100% and further order of harmonics is mentioned with reference to the fundamental component.

5.7.1 Stator Current

The simulated stator current waveform and corresponding harmonics spectrum for the two-level inverter without filter are presented in Figure 3.7a and Figure 3.8a. The harmonics present in the stator current is 32.06%THD. The simulated stator current and the harmonic spectrum with SAF are presented in Figure 5.9 and observed that the harmonics are reduced to 4.15%THD. The fifth and the seventh order harmonics are reduced to very low level. It is observed that the profile of the stator current waveform has changed from pulsating trapezoidal profile to the smooth profile where the current ripples are very much reduced. This is due to the SAF which
supplies/observes the reactive current in such a way that the smooth profile of the stator current is obtained.

![Simulated stator current profile With SAF and corresponding FFT window (THD =4.15%)](image)

**Figure 5.9** Simulated stator current profile With SAF and corresponding FFT window (THD =4.15%)

The experimental observation of the stator current and the harmonics spectrum for the same without the application of SAF is presented in Figure 5.10a and Figure 5.10b respectively. It is observed that the harmonic components are 36.96% THD. Moreover the profile of the stator current is merely a trapezoidal profile. Due to the 120° electronic commutation, there are three transitions in the half cycle of the current wave. They are two transitions on the rising, falling sides and another on the peak middle portion of the current waveform. For a three phase BLDCM, there are six commutation torque ripples for every 360° electrical, as the six current transitions occur. The fundamental torque ($T_e$) for 120° electrical trapezoidal current in BLDCM is stated by Krishnan (2001) given in Equation (5.8).

$$T_e = 2.011 I_s \lambda_p$$  \hspace{1cm} (5.8)

Where $I_s, \lambda_p$ are stator current and peak value of flux linkage respectively.
Figure 5.10 Experimented stator current (a) waveform without SAF (b) Harmonics spectrum without SAF (c) waveform with SAF (current ratio 10:1) (d) Harmonics spectrum with SAF (current ratio 10:1)
The experimented waveform for the stator current and harmonics spectrum with the SAF is presented in Figure 5.10c and Figure 5.10d. It is observed that the harmonics are greatly reduced to 12.1%THD. The third order harmonics is reduced to very low value and the fifth order harmonics is reduced from approximately 25% to 7%. Also the seventh and ninth order harmonics are greatly reduced to almost zero level.

5.7.2 Stator Voltage

The simulated stator voltage profile and the corresponding harmonic spectrum without the filter are presented in Figure 3.5a and Figure 3.6a respectively. As per simulated response, it is observed that the harmonics present in the stator voltage without SAF is 42.36%THD. The simulated stator voltage profile and the corresponding harmonic spectrum with the presence of SAF is presented in Figure 5.11. The simulated harmonic spectrum of stator voltage with SAF is reduced to 11%THD.

![Simulated stator voltage profile with SAF and Harmonics spectrum](image)

**Figure 5.11 Simulated stator voltage profile with SAF and Harmonics spectrum**

The experimented three phase stator voltage without SAF is presented in Figure 5.12a and the harmonics spectrum is presented in Figure 5.12b. It is observed that the stator voltage profile is a non sinusoidal stepped voltage due to the two level inverter based commutation system. The
harmonics present in the stator voltage without SAF is 51.96%THD. The experimented stator voltage profile with SAF is presented in Figure 5.12c. It is observed that the trapezoidal nature of voltage profile is changed towards the continuous sinusoidal profile. The harmonic spectrum for the same presented in Figure 5.12d and observed that the harmonics reduced to 13.33%THD.

Figure 5.12 (Continued)
Figure 5.12 (a) Experimented three phase Stator voltage without SAF. (b) Harmonics spectrum of stator voltage without SAF. (c) Experimented per phase stator voltage profile with SAF. (d) Harmonic spectrum for stator voltage with SAF.

5.7.3 Speed and Torque

The simulated speed with SAF and torque profile for the BLDC motor with and without SAF is presented in Figure 5.13. The Simulation is carried out at a speed of 2000 rpm with load at simulation time 0.2ms. Figure 5.13a and Figure 5.13b show the simulated speed response of the BLDC motor with SAF. The simulated torque profile without SAF is shown in Figure 5.13c, and the torque increases with the increase of load at 0.2s. The torque ripple quantity during the steady operation is observed as 3.5Nm. This ripple in the torque is mainly because of the commutation current ripple and the harmonics associated with the stator current.
Figure 5.13  Simulated speed and torque profiles (a) speed with SAF at 2000rpm  (b) torque profile without SAF  (c) torque profile with SAF
5.8 PERFORMANCE COMPARISON

The performance of the Fuzzy logic based SAF for minimizing the harmonics and torque ripple in BLDC motor drive is investigated in simulation and in real time operating condition. Figure 5.14 shows the %THD comparison bar graphs for stator voltage and stator current of two-level inverter and two level inverter with SAF.

![Figure 5.14 THD comparisons](image)

(a) for stator voltage (b) for stator current

Figure 5.14 THD comparisons (a) for stator voltage (b) for stator current
The torque ripple comparison for with and without SAF is shown in Figure 5.15. While operating without SAF, the ripple torque increases as the load increases. The torque ripple is very much reduced while operating with SAF. It is observed that at low and high loading, the torque ripple is comparatively higher and in the nominal loading conditions, the ripple torque is less and almost constant. This is due to the fuzzy based system which maintains the filter operation in its best performance within the operating region. The Experimental setup for this work is shown in Figure 5.16.

![Figure 5.15 Torque ripple comparison for different techniques with variable load](image)

The SAF improves the THD and reduces the torque ripple. The presence of SAF improves the power factor and makes the load to draws less current from the source. This leads to less $I^2R$ losses in the stator windings. All these performance enhancement leads to better efficiency of the overall operation. The efficiency of the entire system with and without SAF is observed during the experimentation and presented in Table 5.4 for 25% of full load and observed that the SAF improves the overall efficiency nearly 6%.
Table 5.4 Efficiency Comparison With and Without SAF

<table>
<thead>
<tr>
<th></th>
<th>Parameter</th>
<th>Input power (W)</th>
<th>Output power (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With SAF</td>
<td>Motor</td>
<td>175.2</td>
<td>153</td>
<td>87.32</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>181.4</td>
<td>153</td>
<td>84.34</td>
</tr>
<tr>
<td>Without SAF</td>
<td>Motor</td>
<td>186.1</td>
<td>153</td>
<td>82.21</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>193.85</td>
<td>153</td>
<td>78.92</td>
</tr>
</tbody>
</table>

Figure 5.16 Experimental setup

5.9 CONCLUSION

This chapter discusses the implementation of the fuzzy logic controlled three level Shunt Active Filter for effective minimization of harmonics and the torque ripple of the BLDC motor. The entire system is simulated using MATLAB Simulink environment and observed a considerable reduction of current harmonics and this leads to reduction of torque ripple. The functionality of the SAF is tested in real time with an experimental setup using three-level voltage controlled current source inverter.
and the controller implemented with dSPACE. The experimental observations are compared with the simulated results and observed that there is a considerable reduction in harmonics and the torque ripple which confirms the effectiveness of the filter. Moreover, the overall efficiency is improved by 6% while using the SAF.

It is observed that the shunt active filter is effective for compensating the harmonic currents. It has less influence in minimizing the voltage harmonics. The higher order voltage harmonics causes more electromagnetic interference. Moreover the hardware requirements have to be minimized for developing a cost effective system. Considering these facts, it is proposed to analyze the possibilities of developing a multilevel inverter based drive system for BLDC motor so that the voltage and the current harmonics are reduced. The next chapter discusses the implementation of the three level inverter which acts as the commutation system cascaded with the LC low pass filter for effective minimization of harmonics and torque ripple of the BLDC motor.