CHAPTER 5

FUZZY CONTROLLER BASED PFC CUK CONVERTER DESIGN FOR THREE PHASE BLDC MOTOR WITH ELECTRONIC COMMUTATION

5.1 INTRODUCTION

In the previous chapter, the speed controlling scheme of the BLDC motor using PI controller has been discussed. The primary focus of this chapter is to enhance the performance of the speed control scheme by means of FLC. FLC has been researched extensively for theories in automation and control that pertain to problems associated with controlling systems cannot be modeled easily as stated by (Rambabu 2007). Uncertainty in several forms makes the world a complex place. Humans have been able to address this problem of ambiguity with their ability to think and adapt to an ever changing environment. Because of their inability to think and adapt, computers and other electronic devices, designed by man, are not capable of addressing complex and ambiguous situations. The uncertainty may arise due to partial information about the problem, or due to unreliable information, or due to receipt of information’s from more than one source about the problem which are conflicting (Ross et al 2004). In this situation the fuzzy set theory exhibits enormous potential for effectively solving the cases of uncertainty.

The dictionary meaning of the word “fuzzy” is “not clear, indistinct, non-coherent and vague”. By contrast, in the technical sense, fuzzy systems are precisely defined systems and fuzzy control is a precisely defined
method of nonlinear control. The main objective of fuzzy logic is to mimic (and improve on) “human-like” reasoning. Fuzzy systems are knowledge-based or rule-based systems (Yen & Wang 1997).

Particularly, the key components of fuzzy system’s knowledge base are a set of IF-THEN rules obtained from human knowledge and expertise with vague predicates that use a fuzzy reasoning such as Mamdani method and Sugeno method. The output membership functions of Sugeno type systems are either linear or constant whereas Mamdani type produces either linear or nonlinear output. The main difference between the two methods lies in the consequence of fuzzy rules. The Fuzzy Logic Controller (FLC) consists of four stages; fuzzification of inputs, derivation of rules based on knowledge, inference mechanism and defuzzification.

FLC may be regarded as a control technology that is smart and one which offers a method that systematically incorporates individual experiences and also facilitates implementation of nonlinear algorithms in the controller and features a series of linguistic statements. Generally, the fuzzy control algorithm is made up of heuristic decision rules and may be considered as being one which is adaptive. Additionally, it is a non-mathematical control algorithm which is starkly opposite to conventional feedback control algorithm is supported by a linguistic process. Control implementation like this comprises of input variable translation to a language as: positive big, zero, negative small and others that facilitates establishing control regulatory actions and thus allowing and ascertaining of control rules that enable decision process to generate suitable outputs. Fuzzy control (FC) that deploys linguistic information has many advantages including strength, robustness, being model-free, applicability of the universal approximation theorem as well as the rules-based algorithm that have been explicitly studied and presented by (Kim & Bien 2000; Timothy 1995).
Literature studies carried out previously searched potential aspects of the fuzzy control suitable for machine drive application that have been presented by (Tang and Xu 1994; Heber et al 1995). This evidence that a well designed direct fuzzy controller has the capability in terms of outperforming the conventional and usual proportional integral (PI) controllers as discussed in (Heber et al 1995; Xue et al 2006). Therefore, this work deploys the Fuzzy Logic Controller (FLC) for the purpose of BLDC motor speed control.

5.1.1 Reasons for Choosing Fuzzy Logic

In general, the most powerful way of conveying information is by natural language. The conventional mathematical methods have not fully tapped this potential of language. The scientist has said that the human thinking process is mainly based on conceptual patterns and mental images rather than on numerical quantities (Ross 2004). So when the problem of assembling computers with the capability to work out complex issues has to be solved, the human thought process has to be modeled. The efficient way to do this is to use models that attempt to emulate the natural language; the creation of fuzzy logic has put this power to proper use.

Many physical processes are not linear and especially to model them a reasonable amount of approximation is necessary. For a simple system, the mathematical expressions give precise description of the system behaviour. Similarly, for more complicated systems with considerable amount of available data, model-free methods provide robust methods to reduce ambiguity and uncertainty in the system. But for complex systems with less numerical data, fuzzy reasoning furnishes a way to understand the system behavior by relying on approximate input-output approaches. The primary strength of fuzzy logic is that it makes use of linguistic variables rather than numerical variables to represent imprecise data.
5.1.2 Fuzzy Logic Control Components

Fuzzy logic controller components characteristics and functionalities have been distinctly stated and presented in this section. Figure 5.1 shows that when input data is received by the fuzzy controller, it automatically translates the same into fuzzy form and the entire process is referred to as Fuzzification. Thereafter which fuzzy processing is carried out by the controller, entailing input information evaluation in line with the IF…THEN rules that are user generated through fuzzy control system programming and stages of the designing process.

After the fuzzy controller completes the stage of rule-processing stage and then reaches at the point of an outcome conclusion, Defuzzification process is started. During the final step, output inferences are converted by the fuzzy controller which converts it as “real” output data (e.g., analog counts). Thereafter, that data is used as an output module interface for the purpose of processing.

Fuzzy logic operational laws have been presented using linguistics terms as opposed to mathematical equations. Various systems are either too difficult to create an accuracy or even by using mathematical equations that are complicated in terms of application; thus it becomes almost practically
impossible to use traditional methods for such systems. Nevertheless fuzzy logics linguistic terms present definitive methods that are feasible and may be used to enhance system operational characteristics. The fuzzy logic controller may be regarded as the symbolic controller that belongs to a special class. Figure 5.2 shows fuzzy logic controller configuration.

![Fuzzy Logic Controller Diagram](image)

**Figure 5.2 Structure of fuzzy logic controller**

The fuzzy logic controller carries out three operative functions as below:

- Fuzzification
- Fuzzy inference
- Defuzzification

### 5.1.2.1 Fuzzification

The fuzzifier performs measurement of the input variables (input signals, real variables), scale mapping and fuzzification (Transformation 1). Thus all the monitoring input signals are scaled and the measured signals
(crisp input quantities which have numerical values) are transformed into
fuzzy quantities by the process of fuzzification. This transformation is
performed using membership functions. In a conventional fuzzy logic
controller, the number of membership functions and the shapes of these are
initially determined by the user. There are many different types of
membership functions, piecewise linear or continuous. The commonly used
membership functions are bell-shaped, sigmoid, gaussian, triangular and
trapezoidal. A membership function has a value between 0 and 1, and it
indicates the degree of belongingness of a quantity to a fuzzy set.

\[
\mu(x) = \begin{cases} 
\frac{x_i - M_{r1}}{M_{r2} - M_{r1}}, & M_{r1} \leq x_i \leq M_{r2} \\
\frac{M_{r3} - x_i}{M_{r3} - M_{r2}}, & M_{r2} \leq x_i \leq M_{r3} \\
0, & \text{otherwise}
\end{cases}
\]  

\text{(5.1)}

Figure 5.3 Triangle membership function

Figure 5.3 defines triangle membership function wherein the limits
have been defined by \( M_{r1}, M_{r2}, \text{and } M_{r3} \) and is given as in Equation (5.1)
Also Figure 5.4 shows the trapezoid membership function where the limits are defined as $M_{TP1}, M_{TP2}, M_{TP3}$ and $M_{TP4}$. And is given as in Equation (5.2)

$$
\mu(x_i) = \begin{cases} 
\frac{x_i - M_{TP1}}{M_{TP2} - M_{TP1}}, & M_{TP1} \leq x_i \leq M_{TP2} \\
1, & M_{TP2} \leq x_i \leq M_{TP3} \\
\frac{M_{TP3} - x_i}{M_{TP3} - M_{TP2}}, & M_{TP3} \leq x_i \leq M_{TP2} \\
0, & \text{otherwise}
\end{cases}
(5.2)
$$

Figure 5.4 Trapezoid membership function

The bell membership functions shown in Figure 5.5 are defined by parameters $M_b$, $w_d$ and $m$ as follows in Equation (5.3)

$$
\mu(x_i) = \frac{1}{1 + \left(\frac{|x_i - M_b|}{\omega}\right)^{2m}}
(5.3)
$$
where, \( M_b \), the midpoint and \( w_d \) is the width of bell function; \( m \geq 1 \), which shows the convexity of the bell function. Fuzzy controller inputs have been expressed using varying linguistic levels. Figure 5.6 shows the levels that include Positive High (PH), Positive medium (PM), Positive Low (PL) or Negative Low (NL), Negative medium (NM), Negative High (NH) or others. A fuzzy set expresses each level using either of the above said cases.

Figure 5.5 Bell membership functions

Figure 5.6 Several linguist levels of fuzzy controller with triangular membership function
5.1.2.2 Fuzzy inference

Fuzzy inference involves formulation of mapping output from a given input using fuzzy logic. The process of mapping as a result presents a basis which enables decision making or the purposes of pattern discernment. In the Fuzzy Logic Toolbox two kinds of fuzzy inference systems can be possibly implemented. The first is the Mamdani and the second is the Sugeno-type. Both types have different characteristics specifically in terms of determination of output.

Fuzzy inference systems application has been successful in many areas like computer vision, automatic control, decision analysis, data classification and expert systems. These systems possess a multidisciplinary nature and are referred to with various names for example; fuzzy-rule-based systems, fuzzy modeling, fuzzy expert systems, fuzzy logic controllers, fuzzy associative memory and simply (and ambiguously) fuzzy Mamdani’s fuzzy inference method which is among the most popular fuzzy methodology.

Mamdani’s method is considered as being amongst the first control systems that is made by deploying the fuzzy set theory. These are the efforts taken consciously and directed to control both the steam engine as well as boiler combination by fusing linguistic control rules and acquired human operators who were familiar and had prior experience in the same. Mamdani’s model in fuzzy algorithms is deployed for systems that are complex and that requires decision making.

In the fuzzy logic controller’s second phase, it is the fuzzy inference wherein both knowledge base and decision making logic exist. Both rule and data base are from the knowledge base. Data base includes input as well as output variables description. The decision making logic analyses the
control rules. Control-rule bases are further developed to facilitate relationship between output action and inputs obtained in the controller.

5.1.2.3 Defuzzification

Fuzzy output variables are generated from the inference mechanism output. Fuzzy logic controller is required to convert the internal fuzzy output variables into values that are crisp which enables the actual system to use such variables. The process of conversion is referred collectively as Defuzzification. There are many ways to carry out this operation. Among the various defuzzification strategies, the most common one is the max criterion method or max. Max criterion turns out the membership function wherein fuzzy control action attains the maximum value.

5.2 PROPOSED FUZZY BASED CONTROLLER IN BLDC MOTOR

In this chapter, the fuzzy controller has been proposed for the speed control of BLDC motor. This fuzzy controller replaces a conventional PI controller in order to improve the performance of the speed control scheme.

The FLC is a powerful tool in all types of real time applications and it provides better results than the conventional control method. The main purpose of fuzzy controller is to reduce the rise time deviations and settling time difference both in DC-link voltage and in motor speed. Figure 5.7 shows the second proposed speed control scheme with fuzzy logic controller based on the control of the reference DC-link voltage. Similar to previous chapter, the rotor position signals of the BLDC motor are obtained by Hall-effect sensors and it is used by an electronic commutator to generate the switching pulses for the VSI feeding the BLDC motor.
Figure 5.7 Fuzzy based proposed cuk converter design with BLDC motor

In Figure 5.7, the sensed speed ($\omega$) and the reference speed ($\omega^*$) are processed through the speed controller (PI controller) to obtain the equivalent reference DC-link voltage $V_{dc}^*$. The equation for the DC-link voltage is given by the Equation (5.4)

$$V_{dc}^* = K_p * e(t) + K_i \int_0^t e(t) \, dt$$  \hspace{1cm} (5.4)
The structure of FLC at DC-link voltage for generating the switching pulse to the proposed PFC cuk converter is shown in Figure 5.8. The error (Ve) is the difference between the reference DC bus voltage and the sensed DC bus voltage.

The fuzzy controller developed is based on standard Mamdani type fuzzy logic with two inputs and one output. The error voltage (Ve) and change in error voltage (Δe) are the two inputs and the output of the FLC is Vcc which is further processed to the PWM current controller to generate the switching pulse to the proposed PFC cuk converter.

5.2.1 Membership Functions and Rule Base

Fuzziness in a fuzzy set is characterized by its membership functions. The membership functions convert the degree of fuzziness into the normalized interval (0, 1) where the boundary values 0 and 1 resemble membership degrees of crisp set members. The FLC employed at DC bus voltage controller with five membership functions have been chosen for the inputs of error (e) and for the change in error (Δe).
The purpose of FLC in DC voltage controller is mainly to reduce the rise time and settling time difference both in DC-link voltage and in speed error. The chosen membership function is triangular membership function which is the most accepted and balanced choice in many applications.

The five input and output membership functions are linguistically described as NB – Negative Big; NS – Negative Small; ZE – Zero; PS – Positive Small; PB – Positive Big. The fuzzy membership functions for the input and output are shown in Figure 5.9. The purpose of fuzzy controller is to make humanlike decisions by using the knowledge about controlling a target system. This is achieved by suitable fuzzy rules that constitute a fuzzy rule base. The fuzzy rules are formulated by means of IF-THEN rules. The rule table which is shown in Table 5.1 contains 25 rules. The structure of the fuzzy control rules for the two inputs and one output can be expressed as

IF (e is NS and Δe is NS) THEN output is NB.

The two input variables (e and Δe) are fuzzified and represented in fuzzy set notations by membership functions. The defined ‘if…. and then….’ rules produce the linguistic variables.

(a) Error (e)
(b) Change in Error ($\Delta e$)

(c) Output fuzzy membership functions

Figure 5.9 Input and Output membership functions of FLC

Table 5.1 Fuzzy control rule table

<table>
<thead>
<tr>
<th>e \ $\Delta e$</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
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<td>NS</td>
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<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
</tr>
</tbody>
</table>

These variables are defuzzified into control signal for comparison with a carrier signal ($M_d$) to generate PWM gating pulse to the proposed PFC cuk converter.
5.3 RESULTS AND DISCUSSION

In this section, the simulation results for the proposed PFC cuk converter fed VSI operated BLDC motor with proposed FLC employed for speed control is presented.

The cuk converter design with the proposed controller is also modeled using MATLAB software in order to test the performance of the controller.

The parameters considered for simulation are same as that of Chapter 4. The simulation results demonstrate the effectiveness of the proposed FLC for speed control of BLDC motor.

Five case studies are considered to test the overall performance of the proposed PFC cuk converter with BLDC motor. Among these case studies, first four studies deal with different BLDC motor speed and the last case is mainly for BLDC motor under dynamic load conditions.

All the case studies are based on rise time deviations and settling time difference in both DC-link voltage and in motor speed.

5.3.1 Case 1: BLDC Motor under 1500 rpm

The analysis FLC based speed control scheme is made by considering the motor speed as 1500 rpm. The proposed BL PFC cuk converter is driven by a single phase 230 V supply.
Figure 5.10 BLDC motor stator voltage for all the three phases for Case 1
(a) Stator current for R phase

(b) Stator current for Y phase

(c) Stator current for B phase

Figure 5.11 BLDC motor stator current for all the three phases in Case 1
The output of the proposed converter is the DC bus (DC-link) voltage of the three-leg VSI. The speed of the BLDC motor is directly proportional to the DC-link voltage of the three-leg VSI. Hence, the proposed cuk converter is mainly used to maintain the DC-link capacitor voltage. The proposed FLC based speed control scheme reduces the rise time deviations and settling time difference in DC-link voltage and in speed error. The three-leg VSI is connected to stator of the BLDC motor to run the motor at desired speed. The three phase stator voltage and stator current waveforms are illustrated in Figure 5.10 and Figure 5.11, respectively.

![Electromagnetic torque of the BLDC motor for Case 1](image)

**Figure 5.12 Electromagnetic torque of the BLDC motor for Case 1**

![Speed of the BLDC motor for Case 1](image)

**Figure 5.13 Speed of the BLDC motor for Case 1**
The stator voltage waveforms for the three phases R, Y and B are obtained for the simulation time between 0 sec and 0.3 sec. Similarly, the stator current waveforms for the three phases R, Y and B are noted for the simulation time from 0.2 sec to 0.3 sec. The electromagnetic torque waveforms of PI employed DC voltage controller and FLC employed DC voltage controller are shown in Figure 5.12. From the Figure 5.12, it is found that the peak over shot of the torque has been reduced in FLC when compared with conventional PI controller.

![Figure 5.14 DC-link voltage of the VSI for Case 1](image)

Figure 5.14 DC-link voltage of the VSI for Case 1

![Figure 5.15 DC-link current of the VSI for Case 1](image)

Figure 5.15 DC-link current of the VSI for Case 1
The speed of the BLDC motor for conventional PI and proposed fuzzy based control scheme are shown in Figure 5.13. From this figure it is noticed that the speed of the motor for conventional controller gets settled at 0.06 sec and for fuzzy controller it gets settled at 0.03 sec. After getting settled it remains at the same speed of 1500 rpm throughout the simulation time of 0.3 sec. The DC-link voltage of the three-leg VSI for conventional PI and proposed fuzzy based control scheme obtained for the simulation time from 0 sec to 0.3 sec is shown in Figure 5.14. It is noticed from the figure that the DC-link voltage gets settled at 0.07 sec for PI controller whereas for fuzzy controller it gets settled at 0.03 sec.

**Figure 5.16 Source voltage, current, power factor and current THD of the AC source in case 1**
The DC-link voltage of 200 V is maintained at the three-leg VSI to run the motor at the desired speed. Similarly, the DC-link current for conventional PI and proposed fuzzy based control scheme is shown in Figure 5.15. It is found from the figure that the rise time in current has been reduced in FLC when compared with conventional PI controller.

Thus from the above discussion, the rise time deviations and settling time difference in both DC-link voltage and in motor speed has significantly reduced for fuzzy control scheme when compared with the conventional PI controller. The Figure 5.16 (a) - (d) shows the source voltage, source current, power factor of input AC source and current THD of the AC source, respectively.

5.3.2 Case 2: BLDC Motor under 2000 rpm

Further, the investigation is made for the FLC based speed control scheme by considering the motor speed as 2000 rpm. As discussed, the front-end proposed cuk converter is controlled by fuzzy based speed control scheme to maintain the DC-link voltage. Thus the speed control scheme generates the suitable PWM pulse for the proposed cuk converter to run the motor at the desired speed.

The stator voltage and stator current waveforms for the three phases R, Y and B are presented in Figure 5.17 and Figure 5.18, respectively. The stator voltage waveforms for the three phases are obtained for the simulation time between 0 sec and 0.3 sec.

Similarly, the stator current waveforms of all the three phases R, Y and B for this case are noted for the simulation time between 0.2 sec and 0.3 sec.
Figure 5.17 BLDC motor stator voltage for all the three phases in Case 2
Figure 5.18 BLDC motor stator current for all the three phases in Case 2

(a) Stator current for R phase

(b) Stator current for Y phase

(c) Stator current for B phase
The electromagnetic torque of the BLDC motor for PI and fuzzy controller are shown in Figure 5.19. From the Figure 5.19, it is observed that the rise time in the torque has been considerably reduced in FLC when compared with PI controller. The BLDC motor speed for conventional PI and proposed fuzzy based speed control scheme are shown in Figure 5.20. From this Figure 5.20, it is found that the speed of the motor for conventional controller gets settled at 0.05 sec and for fuzzy controller it gets settled at 0.04 sec. After 0.04 sec speed remains constant at 2000 rpm throughout the simulation time of 0.3 sec.

![Figure 5.19 Electromagnetic torque of the BLDC motor for Case 2](image1)

![Figure 5.20 Speed of the BLDC motor for Case 2](image2)
The DC-link voltage of the three-leg VSI for conventional PI and proposed fuzzy based speed control scheme is shown in Figure 5.21 are obtained for the simulation time from 0 sec to 0.3 sec. It is found from the figure that the DC-link voltage gets settled at 0.05 sec for PI controller whereas for fuzzy controller it gets settled at 0.028 sec. The DC-link voltage of 271.33 V is maintained at the three-leg VSI to run the motor at the desired speed. Similarly, the DC-link current for conventional PI and proposed fuzzy
controller are shown in Figure 5.22. From the figure it is noticed that, the rise time in current has been reduced in FLC when compared with conventional PI controller. Thus the rise time deviations and settling time difference in both DC-link voltage and in motor speed has been considerably reduced by FLC when compared with the conventional PI controller. The Figure 5.23 (a) - (d) shows the Source voltage, Source current, power factor of input AC source and current THD of the AC source, respectively.

![Graphs of Source voltage, current, power factor and current THD of the AC source in case 2](image)

**Figure 5.23** Source voltage, current, power factor and current THD of the AC source in case 2

### 5.3.3 Case 3: BLDC Motor under 2500 rpm

The analysis is also carried out by setting the motor speed as 2500 rpm. The fuzzy based speed control scheme is employed to change the PWM pulse for the proposed cuk converter. Thus, it helps to maintain necessary
Figure 5.24 BLDC motor stator voltage for all the three phases in Case 3

(a) Stator voltage for R phase

(b) Stator voltage for Y phase

(c) Stator voltage for B phase
(a) Stator current for R phase

(b) Stator current for Y phase

(c) Stator current for B phase

Figure 5.25 BLDC motor stator current for all the three phases in Case 3
voltage at the DC-link capacitor of the three-leg VSI to run the motor at the desired speed. Figure 5.24 and Figure 5.25 are the stator voltage and stator current waveforms for the three phases (R, Y and B) respectively. The three phase stator voltage waveforms are noted for the simulation time from 0 sec to 0.3 sec. Similarly, the three phase stator current waveforms (R, Y and B) for this case are obtained for the simulation time between 0.2 sec and 0.3 sec.

Figure 5.26 Electromagnetic torque of the BLDC motor for Case 3

Figure 5.26 shows the electromagnetic torque of the BLDC motor for PI and fuzzy controller. From the Figure 5.26, it is evident that the torque rise time has been considerably reduced in FLC when compared with PI controller. Figure 5.27 shows the BLDC motor speed for conventional PI and proposed fuzzy based speed control scheme.

It is observed from the Figure 5.27 that, the speed of the motor for conventional controller gets settled at 0.040 sec whereas for fuzzy controller it gets settled at 0.025 sec. After 0.025 sec the speed remains constant at 2500 rpm throughout the simulation time of 0.3 sec.
Figure 5.27 Speed of the BLDC motor for Case 3

Figure 5.28 DC-link voltage of the VSI for Case 3

Figure 5.29 DC-link current of the VSI for Case 3
The DC-link voltage of the three-leg VSI for conventional PI and proposed fuzzy controller shown in Figure 5.28 are obtained for the simulation time from 0 sec to 0.3 sec. From the Figure 5.28, it is found that the DC-link voltage gets settled at 0.04 sec for PI controller whereas for fuzzy controller it gets settled at 0.025 sec. To run the motor at the desired speed, the DC-link voltage of 332.89 V is maintained at the three-leg VSI.

![Graphs showing DC-link voltage, power factor, source current, and current THD](image)

(a) Source voltage  (c) Power factor of Input AC source
(b) Source current  (d) Current THD of the AC source

**Figure 5.30** Source voltage, current, power factor and current THD of the AC source in case 3

Similarly, the DC-link current waveforms for conventional PI and proposed fuzzy controller are shown in Figure 5.29. From the inspection of figure, it is evident that the rise time in current has been reduced significantly in fuzzy control scheme when compared with conventional PI controller. From the comparison, one can observe that the fuzzy based speed control scheme instantly responds in terms of rise time deviations and settling time difference in both DC-link voltage and in motor speed than the PI controller. The Figure 5.30 (a) - (d) shows the Source voltage, Source current, power factor of input AC source and current THD of the AC source, respectively.
5.3.4 Case 4: BLDC Motor under 3000 rpm

The proposed system is also tested by setting the motor speed as 3000 rpm.

Figure 5.31 BLDC motor stator voltage for all the three phases in Case 4
(a) Stator current for R phase

(b) Stator current for Y phase

(c) Stator current for B phase

Figure 5.32 BLDC motor stator current for all the three phases in Case 4
Figure 5.31 and Figure 5.32 shows the stator voltage and stator current waveforms for the three phases (R, Y and B) respectively. The stator voltage of the three phases is noted for the simulation time from 0 sec to 0.3 sec. Similarly, the three phase stator current waveforms (R, Y and B) for this case are obtained for the simulation time between 0.2 sec and 0.3 sec.

The electromagnetic torque waveform of the BLDC motor, for PI and fuzzy controller is shown in Figure 5.33. From the given Figure 5.33, it is observed that the torque rise time has been considerably reduced in fuzzy controller when compared with PI controller. Figure 5.34 depicts the BLDC motor speed for conventional PI and proposed fuzzy based speed control scheme.

From the Figure 5.34, it is found that the speed of the motor for conventional controller gets settled at 0.035 sec whereas fuzzy controller approach gets settled at 0.025 sec. After 0.025 sec the speed remains constant at 3000 rpm throughout the simulation time of 0.3 sec.
Figure 5.34 Speed of the BLDC motor for Case 4

Figure 5.35 DC-link voltage of the VSI for Case 4

Figure 5.35 represents the DC-link voltage of the three-leg VSI for conventional PI and proposed fuzzy controller for the simulation time from 0 sec to 0.3 sec. From the Figure 5.35, it is found that the DC-link voltage gets settled at 0.035 sec for PI controller whereas for fuzzy controller it gets settled at 0.025 sec. The DC-link voltage of 392.38 V is maintained at the three-leg VSI. Similarly, the DC-link current waveforms for conventional PI and proposed fuzzy controller are shown in Figure 5.36. From the inspection of figure, it is revealed that the current rise time has been reduced significantly in fuzzy control scheme when compared with PI controller.
From the comparison, it is found that the fuzzy control scheme instantly responds in terms of rise time deviations and settling time difference in both DC-link voltage and in motor speed than the PI controller. The Figure 5.37 (a) - (d) shows the source voltage, source current, power factor of input AC source and Current THD of the AC source respectively.

Figure 5.37  Source voltage, current, power factor and current THD of the AC source in case 5
5.3.5 Case 5: BLDC Motor with fuzzy controller under dynamic load conditions

The final analysis is made to show the performance of the BLDC motor with fuzzy control approach under dynamic load condition. For this analysis the motor speed is chosen as 3000 rpm.

This section deals with analysing the performance of the motor under load condition by varying the DC-link voltage and current of the three-leg VSI.

The firing pulse for the proposed PFC cuk converter is generated by speed control scheme employed with proposed fuzzy control approach. The performance comparison of the conventional PI controller and the proposed fuzzy control scheme are also done in this section.

As said earlier, the speed of the BLDC motor is directly proportional to the DC-link voltage of the three-leg VSI. The stator voltage waveforms for the three phases R, Y and B shown in Figure 5.38 are noted for the simulation time between 0 sec and 0.3 sec.

It is observed from the figure that at 0.15 sec load of 1.5 Nm has been applied to the BLDC motor. Hence, the magnitude of the stator voltage has slightly increased in all the three phases so as to run the motor at the desired speed of 3000 rpm.
Figure 5.38 BLDC motor stator voltage for all the three phases for Case 5
Figure 5.39 BLDC motor stator current for all the three phases for Case 5
This is done by changing the DC-link voltage of the three-leg VSI. Similarly, the stator current waveforms for the three phases R, Y and B are shown in Figure 5.39 are captured for the simulation time between 0.1 sec and 0.26 sec. From the current waveforms, it is observed that the magnitude of stator currents in all the three phases has been increased at 0.15 sec due to change in load.

![Figure 5.40 Electromagnetic torque of the BLDC motor for Case 5](image)

Figure 5.40 shows the electromagnetic torque waveform obtained for conventional PI controller and proposed fuzzy controller of the BLDC motor. From the Figure 5.40 it is clear, that the rise time in torque waveform has been significantly reduced in fuzzy controller when compared with PI controller. Due to external load at 0.15 sec, the motor torque has increased at this instant and it remains constant at the same level until the simulation time of 0.3 sec to maintain the motor speed at 3000 rpm.

![Figure 5.41 Speed of the BLDC motor for Case 5](image)

Figure 5.41 Speed of the BLDC motor for Case 5
Figure 5.41 represents the speed curves of the BLDC motor for conventional PI and proposed fuzzy based speed control scheme. From above Figure 5.4, it is seen that the speed of the motor for conventional controller gets settled at 0.04 sec whereas the fuzzy controller approach gets settled 0.025 sec. It is also noticed from the same figure that the speed curve becomes unstable at 0.15 sec due to the external load. Then the speed gets stabilized after 0.17 sec for conventional PI controller whereas for fuzzy approach the speed gets stabilized at 0.16 sec. Hence from the above discussion it is revealed that the fuzzy control approach performance is superior when compared with the conventional PI controller.

![Figure 5.42 DC-link voltage of the VSI for Case 5](image1)

![Figure 5.43 DC-link current of the VSI for Case 5](image2)
The DC-link voltage and DC-link current waveforms of the three-leg VSI for conventional PI controller and proposed fuzzy controller shown in Figure 5.42 and Figure 5.43 are noted for the simulation time from 0 sec to 0.3 sec. It is observed from the voltage waveform that, the DC-link voltage gets settled at 0.04 sec for conventional PI controller whereas for fuzzy control approach the voltage gets settled at 0.02 sec. Due to load torque at 0.15 sec, the DC-link voltage has been increased at this instant and it is maintained at 425 V throughout the simulation time of 0.3 sec.

Table 5.2 Comparison between PI controller and FL controller based cuk converter fed BLDC motor

<table>
<thead>
<tr>
<th>Speed in rpm</th>
<th>V_{dc} (V)</th>
<th>I_{ds} (A)</th>
<th>Stator Voltage in V</th>
<th>Stator Current in A</th>
<th>THD %</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>E_{R}</td>
<td>E_{V}</td>
<td>E_{B}</td>
<td>I_{R}</td>
</tr>
<tr>
<td>1500</td>
<td>196.20</td>
<td>0.588</td>
<td>57.72</td>
<td>58.28</td>
<td>58.89</td>
<td>0.55</td>
</tr>
<tr>
<td>2000</td>
<td>271.31</td>
<td>0.820</td>
<td>82.34</td>
<td>81.34</td>
<td>82.44</td>
<td>0.61</td>
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<tr>
<td>2500</td>
<td>332.72</td>
<td>0.897</td>
<td>96.48</td>
<td>97.21</td>
<td>97.89</td>
<td>0.68</td>
</tr>
<tr>
<td>3000</td>
<td>392.42</td>
<td>0.989</td>
<td>115.62</td>
<td>116.02</td>
<td>115.88</td>
<td>0.77</td>
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</table>

Fuzzy Logic Controller

<table>
<thead>
<tr>
<th>Speed in rpm</th>
<th>V_{dc} (V)</th>
<th>I_{ds} (A)</th>
<th>Stator Voltage in V</th>
<th>Stator Current in A</th>
<th>THD %</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>E_{R}</td>
<td>E_{V}</td>
<td>E_{B}</td>
<td>I_{R}</td>
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<td>57.72</td>
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<tr>
<td>2000</td>
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<td>0.842</td>
<td>83.08</td>
<td>82.89</td>
<td>82.79</td>
<td>0.66</td>
</tr>
<tr>
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<td>332.89</td>
<td>0.920</td>
<td>97.75</td>
<td>97.28</td>
<td>97.16</td>
<td>0.67</td>
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<tr>
<td>3000</td>
<td>392.38</td>
<td>1.153</td>
<td>116.12</td>
<td>116.14</td>
<td>115.98</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Settling Time of Speed in sec

<table>
<thead>
<tr>
<th>Speed in Rpm</th>
<th>PI controller</th>
<th>Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.070</td>
<td>0.030</td>
</tr>
<tr>
<td>2000</td>
<td>0.050</td>
<td>0.028</td>
</tr>
<tr>
<td>2500</td>
<td>0.040</td>
<td>0.025</td>
</tr>
<tr>
<td>3000</td>
<td>0.035</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Settling Time of DC Link Voltage in sec

<table>
<thead>
<tr>
<th>Speed in Rpm</th>
<th>PI controller</th>
<th>Fuzzy Controller</th>
<th>PI controller</th>
<th>Fuzzy Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.07</td>
<td>0.030</td>
<td>36.66 %</td>
<td>13.33 %</td>
</tr>
<tr>
<td>2000</td>
<td>0.05</td>
<td>0.028</td>
<td>27.50 %</td>
<td>7.50 %</td>
</tr>
<tr>
<td>2500</td>
<td>0.04</td>
<td>0.025</td>
<td>22.00 %</td>
<td>2.0 %</td>
</tr>
<tr>
<td>3000</td>
<td>0.035</td>
<td>0.025</td>
<td>16.66 %</td>
<td>0.33 %</td>
</tr>
</tbody>
</table>
It is also observed from the same figure, that the fuzzy control approach gets stabilized fast after 0.15 sec when compared with the conventional PI controller. This increase in DC-link voltage gives rise to increment in the stator voltage and stator current at the same time instant of 0.15 sec. Similarly it is also observed from the current waveform that the DC-link current has been increased at 0.15 sec due to load applied at this instant. The various parameter values obtained for performance comparison between the PI controller and FL controller based cuk converter fed BLDC motor are accordingly presented in Table 5.2. From the inspection of values in Table 5.2, it is observed that the Fuzzy Logic Controller (FLC) based cuk converter fed BLDC motor drive gives better performance than the PI Controller based BLDC drive in terms of THD, power factor, settling time of speed and DC link voltage.

5.4 SUMMARY

This chapter clearly analyzes the performance of the proposed PFC cuk converter design with BLDC motor through fuzzy logic controlling technique. The importance of using fuzzy logic controller with the proposed PFC cuk converter design is clearly explained in this chapter. The performance of the proposed fuzzy controller is validated based on the reduction of the peak over shoot and settling time difference both in DC-link voltage and in motor speed. It is observed from the simulation results that the fuzzy logic controller has offered further reduction in settling time and speed error when compared with the PI controller.