Power Factor Correction and Power Quality Improvement in BLDC Motor Drive fed from SEPIC Converter Using Fuzzy Logic Controller

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***Abstract*—** In this paper, a (PF) Power factor correction and power quality (PQ) improvement is the main concern for BLDC motor drive fed from a SEPIC Converter using a FLC controller is proposed [2], [4], [10]. BLDC motor drives employ a DBR followed by a high-value DC-link capacitor, resulting in poor power factor, increased current harmonics, and degraded power quality at the utility interface [1], [2], [9]. To overcome these limitations, a SEPIC converter is integrated between the rectifier and the voltage source inverter (VSI) to regulate the DC-link voltage and shape the input current [1], [4], [5], [10]. The proposed system utilizes both PI and FLC controllers for converter control and speed regulation. The performance of the controllers is assessed in terms of power factor, THD, dynamic response, and speed regulation capability [5], [8], [9]. Simulation results demonstrate that the FLC provides superior performance compared to the traditional PI controller by achieving near-unity power factor, significantly reducing input current THD, minimizing steady-state error, and improving transient response under varying operating conditions [6], [7].

Keywords - Diode Bridge Rectifier (DBR), Direct Current (DC) , Brushless DC (BLDC), Proportional Integral (PI), Fuzzy Logic Controller (FLC), Total Harmonic Distortion (THD), Power Factor (PF), Power Quality (PQ).

I. INTRODUCTION

Brushless DC (BLDC) motors have found extensive application in the past few years in both industrial and domestic applications. Because of their high efficiency, small size and reliable speed-to-torque performance, they are popular in electric vehicles, robotics, aerospace engineering, medical devices and green drive systems [1], [2], [9]. The main advantage that characterizes a BLDC motor is the electronic switching mechanisms. They replace entirely the physical commutators of traditional brushed models. This means no mechanical friction and drastically less maintenance needs and an overall operational lifespan of the hardware [9], [11].

Despite these benefits, traditional BLDC motor drives have power quality difficulties when coupled to an AC utility source. The front-end stage of a BLDC motor drive is typically made up of a DBR and a big DC-link capacitor. Although this setup is simple and inexpensive, it uses significantly distorted current from the utility source [1], [2], [9], [10]. The charging and discharging of the DC-link capacitor concentrate current pulses around voltage peaks, resulting in a low power factor and an increase in a Total Harmonic Distortion (THD). As a result, the drive fails to meet international harmonic standards like IEC 61000-3-2 and drastically degrades power quality [1], [5], [8], [9].

BLDC motors offer very high reliability, high efficiency and high functional performance, in industrial and home applications [1], [2], [9]. Conventional BLDC motor drives, however, are frequently used with this leads to a low power factor and important harmonic distortion if a Diode bridge is used, Rectifiers and DC link capacitors [1], [2], [9], [10].

To overcome these issues, a SEPIC converter-based methodology of the Power Factor Correction (PFC) is shown as the SEPIC converter in DCM current shape, removes harmonics, and results in a near-unity power factor [1], [4], [5], [10].

Furthermore, the an FLC is also implemented to improve the voltage regulation, speed control and improve the responsiveness as compared to customary PI controllers [6], [7].

As a result, the proposed FLC- controlled SEPIC-fed BLDC motor drive has less THD and better power quality. Efficiency and long-term reliability, making it a candidate for many advanced motor drive applications [5] - [8].

However, in this paper, a BLDC drive fed by a SEPIC converter using an FLC and a PI Controller is analyzed, and the results are simulated using MATLAB/Simulink software. In PI controlled SEPIC converter THD value at the input side is slightly high and PF is also poor as compared with Fuzzy Logic Controller (FLC) [6], [7].

II. OPERATION OF SEPIC CONVERTER

Figure-1 shows the traditional SEPIC converter basic circuit arrangement. Whereas this converter is the most popular for DC-DC because it is capable of stepping up and stepping down the input voltage with a non-inverting output voltage. A SEPIC converter's intermediate energy storage stage consists of two inductors and a capacitor. The linked capacitors and two inductors in this setup allow the converter to transmit energy from the input to the output by varying the duty cycle of the switches (often a MOSFET) and the output capacitor [1], [2], [4], [5], [10], [12].

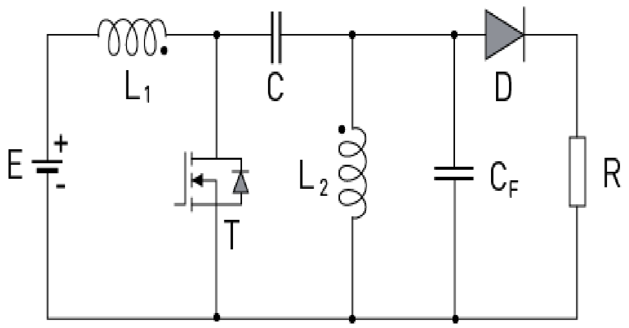

Figure 1 : Conventional SEPIC converter

Figure 2: During the switch's on state, energy will be stored in both inductors, and the capacitor is charged [1], [4], [10], [12].

Figure 3: At the instant t_{off} , when the switch is turned off, the inductor's stored energy is delivered to the output capacitor and load. The voltage at the output side is controlled for a continuous energy transfer process, and based on the switch's ON and OFF time period, resulted output voltage may be larger or smaller than the input voltage [1], [4], [5], [10].

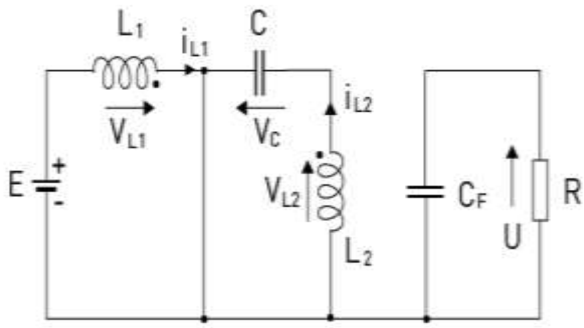

Figure 2: The SEPIC converter circuit diagram – interval t_{ON}

In a steady state, the average voltage across the inductors is zero, whereas across the capacitor is the same as the DC voltage source.

Figure-2 depicts the SEPIC converter's equivalent network during the on time.

$$V_{L1} = -E \quad \ldots\ldots Eq..[1]$$

$$V_{L2} = -V_C = -E \quad \ldots\ldots Eq..[2]$$

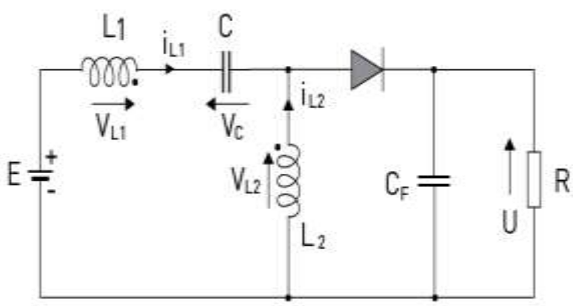

Figure 3: The SEPIC converter circuit network – interval t_{OFF}

The above Figure-3 shows the SEPIC converter's equivalent network during the t_{off} phase. At that instant (t_{off}) of the switch , the voltage across the inductors L1 and L2 are:

$$V_{L2} = U \quad \ldots Eq\ldots[3]$$
$$V_{L1} = U + V_C - E = U \quad \ldots Eq\ldots[4]$$

III. FUZZY LOGIC CONTROLLER (FLC)

An FLC is adopted to regulate the duty cycle of the SEPIC converter. Unlike traditional PI controllers, the FLC does not require an accurate mathematical model of the system and can effectively handle nonlinear characteristics and parameter fluctuations [6], [7].

The controller processes the voltage error signal and also the change in error signal using linguistic rules to generate an appropriate control signal. This intelligent control strategy provides faster dynamic response, improved voltage regulation, lower overshoot, and better disturbance rejection [3], [5], [9].

Error (e) = $V_{ref} - V_o$ ………Eq..[5]

Change in Error (Δe) = e(k) − e(k−1) …Eq..[6]

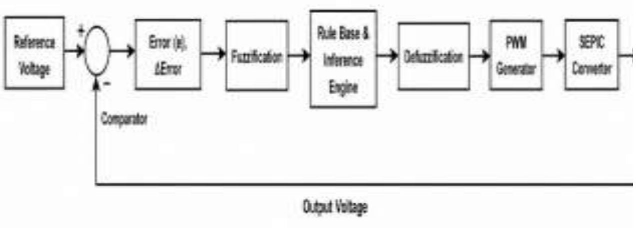

Figure 4: Block Diagram of FL Control Structure

The FLC consists of four main parts:

a) Fuzzification
b) Rule-based
c) Inference engine
d) Defuzzification

a) Fuzzification :

It is the first stage of the FLC. It converts the numerical values of the input variables, namely the error signal and the change in error signal, into linguistic terms such as Negative Large (NL), and Zero (ZE) etc., as shown in table-1. This conversion allows the controller to process information in a way that resembles human reasoning [6].

Symbol	Meaning
NL	Negative Large
NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PL	Positive Large

Table 1: Linguistic Variables

b) Rule Base :

It consists a set of IF–THEN rules that define the controller's response for different combinations of input conditions. These rules are developed from expert knowledge and system behavior. i.e., IF Error is Positive Small (PS) AND Change in Error is Negative Small (NS) THEN Output is Positive Medium (PM) shown in table-2. This means the converter should slightly increase its duty cycle to restore the desired voltage [6].

Error / ΔError	NL	NS	ZE	PS	PL
NL	NL	NL	NM	NS	ZE
NS	NL	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PL
PL	ZE	PS	PM	PL	PL

Table 2: Sample Fuzzy Rule Matrix

c) Inference Engine:

It acts as the decision-making unit of the controller. It evaluates the fuzzified inputs using the rules stored in the rule base and determines the most appropriate control action. The output is generated by combining the results of all active rules. i.e., If the error belongs to PS with a membership value of 0.7 and to PM with a membership value of 0.3, the inference engine activates both rules and combines their outputs to determine the final controller response [6], [11].

d) Defuzzification :

Defuzzification converts the fuzzy output into a precise numerical value. This crisp value is used as the PWM duty cycle to control the SEPIC converter. i.e., If the fuzzy output is Positive-Medium (PM), the defuzzification process may produce a duty cycle of 0.65 (65%). The PWM generator then uses this value to switch the converter and regulate the output voltage [6].

IV. BLDC MOTOR DRIVE WITH SEPIC CONVERTER USING PI CONTROLLER

The traditional closed loop control system with a PI controller based BLDC motor drive with a SEPIC converter is employed to enhance the input power factor and to regulate the DC-linked voltage [1], [2], [4], [10] - [12]. The SEPIC converter acts as a PF correction stage by controlling the duty cycle (switching period) of the converter with the PI controller [1], [2], [4].

The PI controller parallels the reference voltage with the measured output voltage all the time and gives an error signal [1], [2], [11], [12]. It sets the PWM duty cycle according to the proportional and integral gains to maintain the output voltage constant as shown in Figure- 5 below.

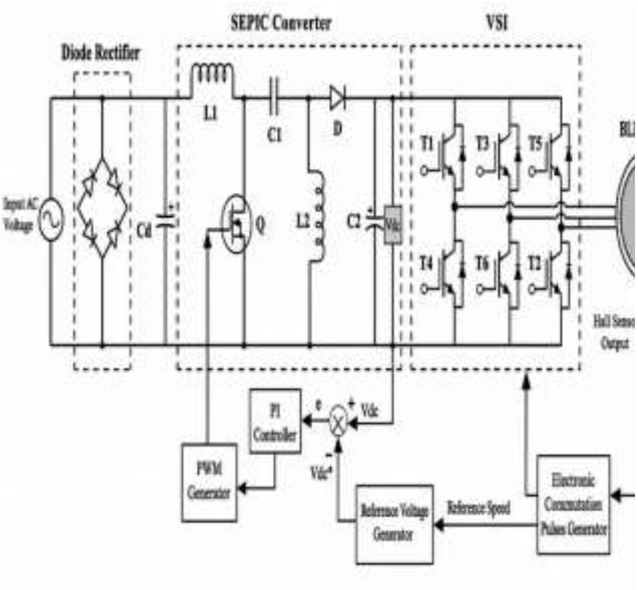

Figure 5: BLDC drive with SEPIC converter using PI Controller

The PI controller achieves satisfactory steady-state performance and has simple implementation but fails to perform under nonlinear mode of operation and sudden load variations resulting in increased overshoot, longer settling time and reduced dynamic response. This scheme gives THD value 4.87% and PF approximately 0.97 as shown in Figure-6.

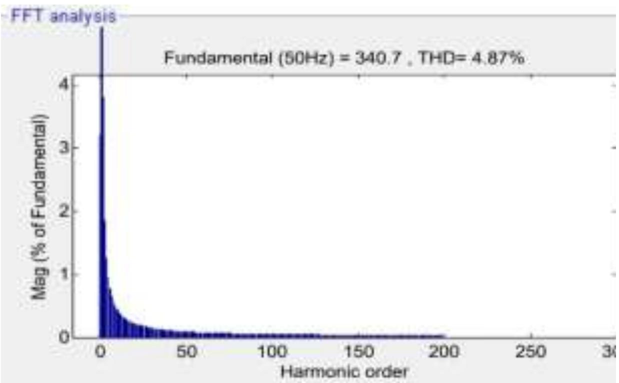

Figure 6: THD value with SEPIC converter using PI Controller

V. BLDC Motor drive with SEPIC converter using Fuzzy Logic controller (FLC)

The proposed BLDC motor drive with SEPIC converter using FLC provides better performance than the traditional PI controller. The FLC decides the converter duty cycle through fuzzy rules, which are based on the voltage error and its rate of change, and where as FLC doesn't need an accurate mathematical model [6].

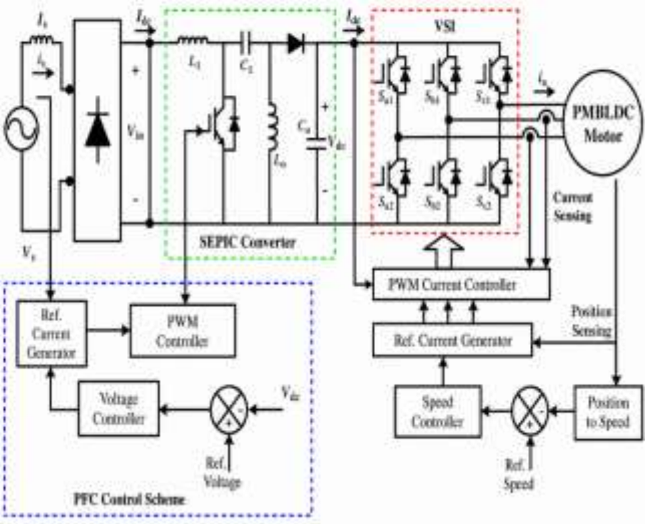

Figure 7: BLDC drive with SEPIC converter using Fuzzy Logic Controller

This intelligent control method is more effective in dealing with the nonlinear characteristics and sudden load changes. Therefore the system has faster voltage regulation, less overshoot, shorter settling time and improved input PF and THD. These improvements increase the overall efficiency, stability and reliability of the BLDC motor drive and render FLC-based approach more suitable for modern high performance applications [6], [7].Block representation is shown in figure-7.

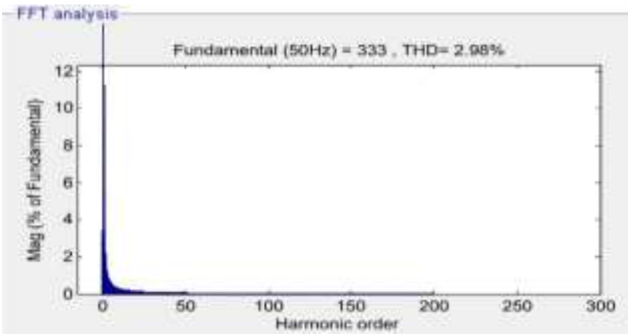

Figure 8: THD value with SEPIC converter using FLC controller

The proposed scheme with FLC gives THD value 2.98% and PF approximate unity as shown in figure-8. Therefore, from this analysis it is clear that by using THD value is reduced and PF is also improved as compared with PI Controller and also FLC does not require an accurate mathematical model for control.

VI. Results and Conclusion

a) Simulation Model:

The proposed system is performed using MATLAB software. Use of the FLC incorporate with the SEPIC converter will reduce the THD value as per the IEC standard and also improve PF. The simulated circuit is shown in Figure-8, and the results of the graphical representation of PF using FLC and PI are shown in Figures- 9 and 10 respectively. THD value reduced to 4.87% to 2.98% by using FLC and PF approximately equal to unity.

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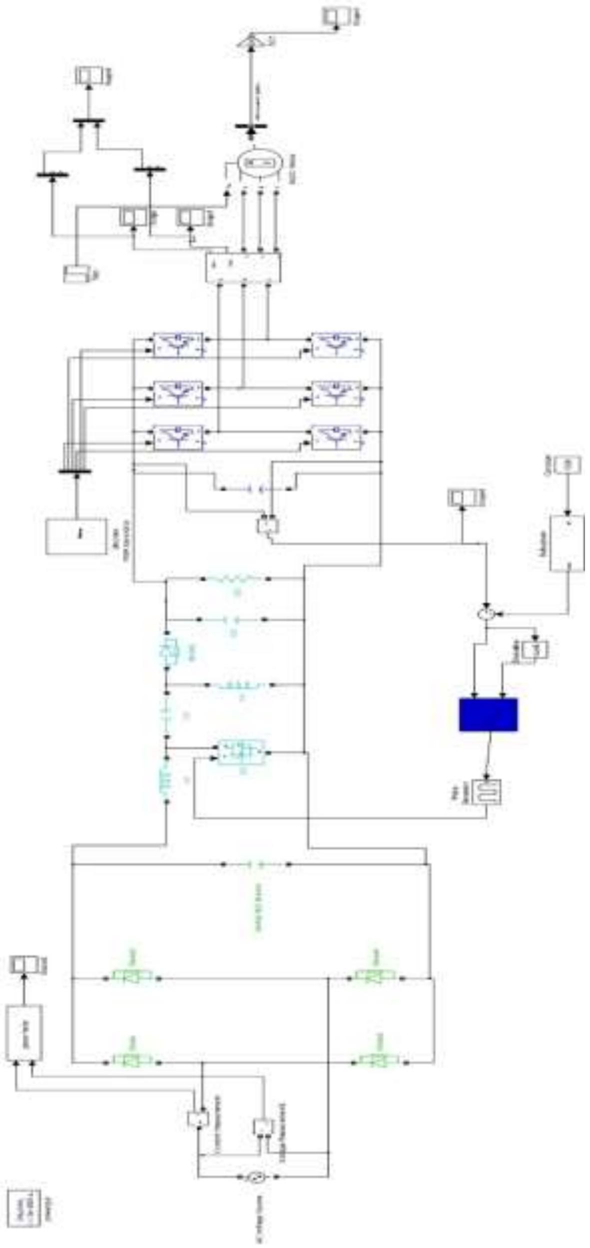

Figure 9: Simulink model of BLDC motor with SEPIC converter using FLC controller

The above Figure-9 is the proposed drive with SEPIC converted by using Fuzzy logic controller is performed using MATLAB/Simulink Software .

b) Results:

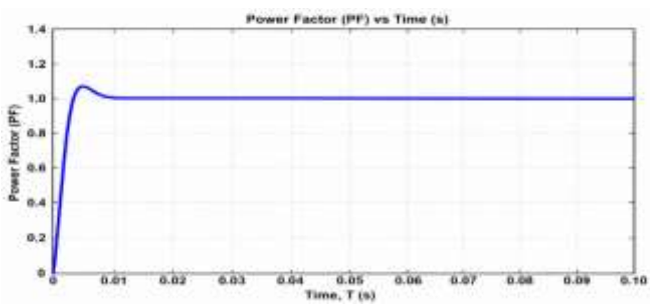

Figure 10: Power factor (PF) Vs Time, T (s) using Fuzzy Controller

The waveform in Figure-10, is the power factor plot of the proposed system using FLC. Through which it is observed that it is clear from the above waveform that the power factor increases rapidly and then remains constant at around 1.0 (unity) with a slight overshoot during start-up due to the startup charging of the SEPIC converter energy storage elements and the initial action of the fuzzy logic controller. The overshoot quickly diminishes (0.003 sec), and the power factor settles to unity within a very short time (0.007 sec), indicating stable and effective control performance.

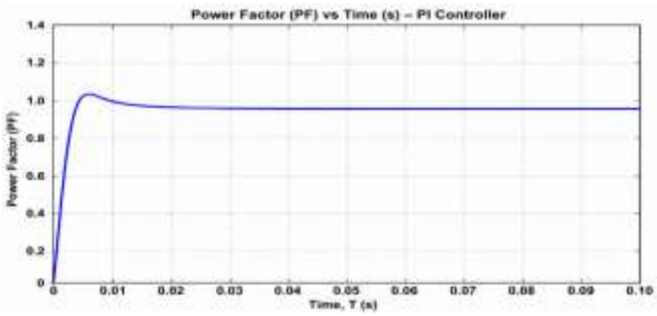

Figure 11: Power factor (PF) Vs Time, T (s) using PI Controller

The waveform in figure-11, shows how Power Factor (PF) changes with respect to time in the case of SEPIC converter fed BLDC motor drive using PI control. This rise of power factor ends in a very short span of time (0.006 sec) and the power factor gets stabilized to almost a constant value which is near about 0.97.

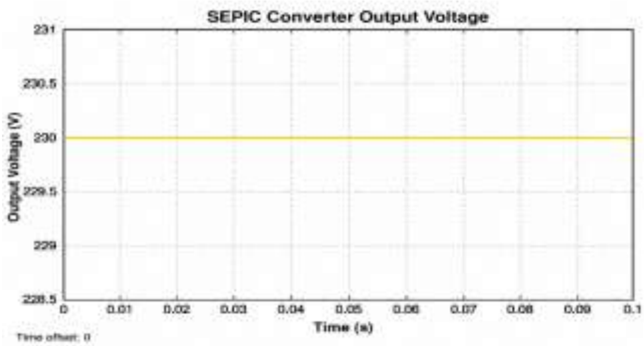

Figure 12: Voltage V_o (volts) Vs Time, T (s) of SEPIC output voltage

The waveform in Figure-12, illustrates the output voltage of the SEPIC converter over a 0.1-second time interval. The data indicates a stable steady-state response, with the converter effectively regulating the output to a

nominal value of 230 V. The steady-state voltage ripple is minimal and well-contained, restricted to a narrow operational band between 228.5 V and 231 V. Overall, this transient response demonstrates the converter's robust regulation capability and low steady-state error.

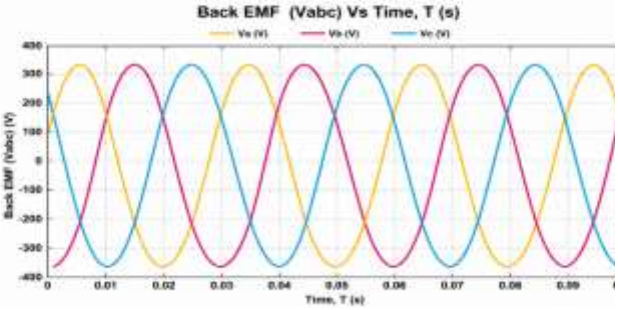

Figure 13: Back EMF(V_{abc}) Vs Time, T (s) using Fuzzy Controller

The waveform in Figure-13,The inverter is operated on the basis of the Sinusoidal Pulse Width Modulation (SPWM) produced by the PWM controller. Therefore, three sinusoidal voltages with a 120° phase shift between each other are generated at the output of the inverter. Such voltages are supplied to the motor stator windings to create a rotating magnetic field. As can be seen from the waveform, the three-phase voltages are balanced and symmetrical with constant amplitude.

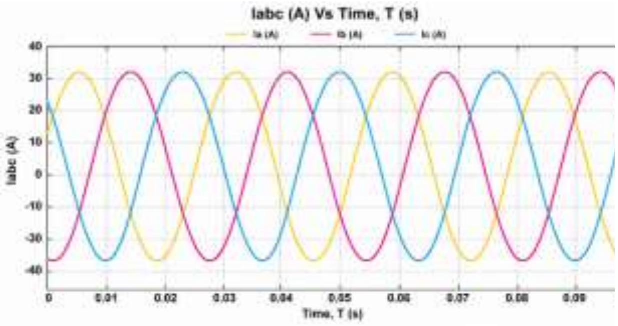

Figure 14: Stator Currrent, (I_{abc}) Vs Time, T (s) using Fuzzy Controller

The waveform in Figure-14, The three-phase currents are sinusoidal in nature and are displaced by 120° electrical phase difference from each other. These balanced currents produce a rotating magnetic field in the motor, resulting in smooth torque production and stable speed operation. It is visibly observed that the stator currents are balanced and maintain a nearly constant amplitude of approximately ±33 A throughout the simulation period.

c) Conclusion:

The Power Factor (PF) characteristics of the FLC and PI Controllers imply successful power factor compensation in the SEPIC converter-fed BLDC motor drive. Nevertheless, the FLC out performs the traditional PI Controller in terms of handling its dynamic characteristics.

According to the obtained simulation results, the steady-state value of the Power Factor for the PI Controller is equal to about 0.97 with the relatively small transient overshoot and a somewhat extended settling time.

Meanwhile, the FLC is capable of achieving unity power factor (PF ≈ 1.0) much faster and with smaller steady-state oscillations.

Whereas, the PI controller manages to maintain a THD of 4.87%, which is below the IEEE - 519 standard permissible limit of 5%. Nevertheless, the harmonic spectrum consists of higher-order harmonic components. On the other hand, the FLC helps to bring down the THD to 2.98%. This shows that the harmonic distortion has been greatly reduced.

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