Neuro Fuzzy Controller for Positive Output KY Boost Converter to Reduce Output Voltage Ripple

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Abstract—KY boost converter is a recently invented in DC-DC converter topology by K. I. Hwu and Y. T. Yau. This converter operates in continuous conduction mode with low output voltage ripple in the order of few mV, fast transient response and settling time yielding larger voltage conversion ratio. In this work, Neuro Fuzzy control technique is proposed to reduce the output voltage ripple and to achieve fast settling time. The digitally simulated results are obtained using MATLAB/Simulink with reduced voltage ripple in the order of μV along with fast settling time. The proposed controller is devised with a microcontroller which is embedded with Neuro Fuzzy algorithm to regulate the output voltage of the converter and the experimental result has validated the simulation result.

Index Terms—DC-DC converter, KY boost converter, Neuro Fuzzy, voltage ripple reduction.

I. INTRODUCTION

Advent of communication and computing gadgets such as Personal Digital Assistant (PDA), MPEG etc., necessitate the boosted output voltage for specific input voltage. For such applications, the designer has to be precise in considering the voltage ripple content, settling time and load transient response of the converter. Conventional non-isolated DC - DC boosting converters tend to cause large output voltage ripples. This can be overcome by using Equivalent Series Resistant (ESR) Capacitor [1] or by adding an inductance – capacitance (LC) filter [2]. However the operation of the converter under Continuous Conduction Mode (CCM) [3]–[9] leads to good load transient response by holding the right – hand zero in the transfer function for that mode which is complicated in practice. DC-DC converters are controlled using various techniques like coupling inductors [3], voltage control techniques [4]–[9], sliding mode converter [10] and loop bandwidth control [11] to reduce output voltage ripples. It is evident that these converters [3]–[9] has one right – half plane zero with CCM

mode produces very good transient response which is difficult to achieve.

The KY boost converter [12]–[15] which is a recent development proposed by K. I. Hwu and Y. T. Yau operates in CCM while keeping the output current non-pulsating leading to reduced voltage stress across the output capacitor resulting low output voltage ripples in the order of few mV. In distinct with the non-isolated voltage boosting converters, KY boost converter produces a very good transient response in the order of few ms similar to Synchronous Rectified (SR) buck converter.

In this paper Neuro Fuzzy control technique is employed to control the output voltage of the KY boost converter. The performance parameters are estimated in time domain.

The converter along with Adaptive Neuro Fuzzy Inference System (ANFIS) is designed in the MATLAB Simulink model and the simulated results exhibit a reduction in output voltage ripple from existing ripple of mV to μV with rapid settling time. The hardware implementation of the proposed system for the KY boost converter and the experimental results are discussed in following sections.

II. PROPOSED CONTROLLER SYSTEM

The proposed Neuro Fuzzy Controller for voltage regulation of Positive output KY boost converter is depicted by the block diagram in following Fig 1.
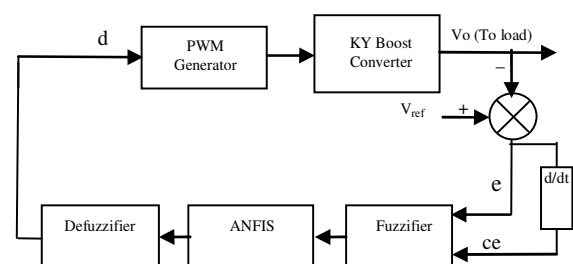

Fig. 1. Neuro Fuzzy controlled Positive output KY Boost Converter block diagram.

The main blocks of the proposed system are Positive

output KY boost converter, comparator and Neuro Fuzzy controller and Pulse Width Modulation (PWM) generator. The comparator compares the output voltage (V_o) of the converter with reference voltage (V_{ref}) and yield the error (e) signal. The change of error with respect to time (ce) is calibrated. The error and change in error are fed as input to the Neuro Fuzzy controller. The output of Neuro Fuzzy is duty cycle (d), which is fed to PWM generator to produce switching signal which drives the KY boost converter. The following section describe the functioning of the KY boost converter and the design of proposed Neuro Fuzzy controller along with the output obtained through simulation and experimental results.

III. POSITIVE OUTPUT KY BOOST CONVERTER

The KY boost converter as shown in the following Fig. 2 is a combination of KY converter with SR boost converter.
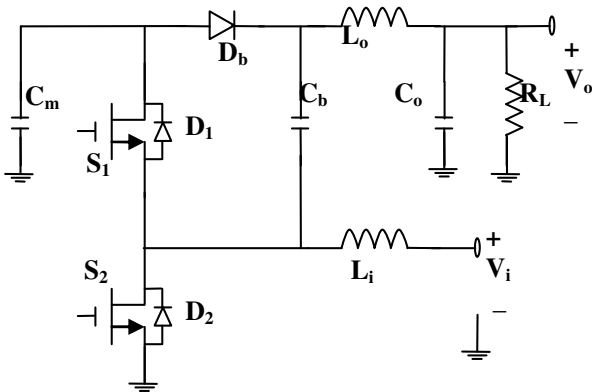

Fig. 2. KY boost converter.

The KY boost converter is a non-isolated converter and operates in CCM with voltage conversion ratio of 1 plus d, where d is the duty cycle produced by the controller, which is a time variant. It possesses inductors both in input and output sections, so that the output current ripples are very small, leading to low output voltage ripple around 300 mV. It is a combination of KY converter section combined with SR boost converter in which KY converter consist of two switches S_1, S_2, diode D_b, energy transferring capacitor C_b, output inductor L_o and output capacitor C_o. The input of KY converter is replaced by buffer capacitor C_m in KY boost converter. The SR boost converter comprises two switches S_1 and S_2 with input inductor L_1 and the output of SR boost converter is replaced by buffer capacitor C_m. Hence C_m is a buffer between KY converter and SR boost converter forming the KY boost converter. This converter operates in CCM with two switches. Hence there are two modes of operation represented by mode 1 and mode 2.

The mode 1 operation of KY boost converter is depicted by the Fig. 3. In this mode the negative terminal of C_b is grounded leading to forward biasing of D_b as it is turned ON by switching ON switch S_2 and turning OFF switch S_1. Hence C_m is discharged and C_b is charged and the voltage across L_i is v_i there by magnetizing L_i and L_o is demagnetized. The current through C_o is the difference between current through L_o and current through R_L, and the current flowing through C_m is the sum of $-i_{Cb}$ and $-i_{Lo}$ which is represented by the differential equations as given by (1).

The mode 2 operation of KY boost converter is depicted by the Fig. 4. In this mode D_b is reverse biased as it is turned OFF by switching ON switch S_1 and turning OFF switch S_2. Hence C_m is charged and C_b is discharged and the voltage across L_i is the difference between v_{Cm} and v_i, there by demagnetizing L_i and L_o is magnetized as the voltage across this inductor is the difference between v_o and $2v_{Cm}$. The current through C_o is the difference between current through L_o and current through R_L, and the current flowing through C_m is the difference between i_{Li} and i_{Lo} which is represented by the differential equations as given by (2):

$$\begin{cases} L_i \dfrac{\partial iLi}{\partial t} = vi, \\[2mm] L_o \dfrac{\partial iLo}{\partial t} = vcm - vo, \\[2mm] C_o \dfrac{\partial vo}{\partial t} = iLo - \dfrac{vo}{RL}, \\[2mm] C_m \dfrac{\partial vcm}{\partial t} = -icb - iLo. \end{cases} \qquad (1)$$
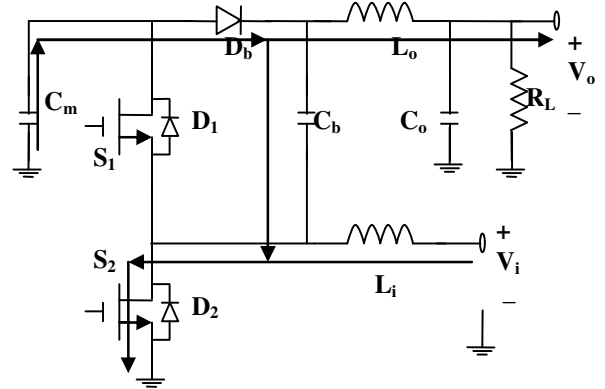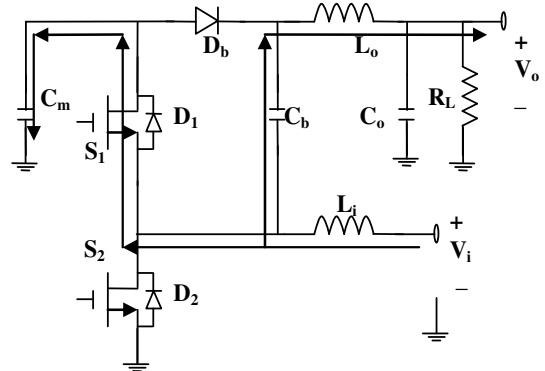

Fig. 3. KY boost converter mode 1 operation.

Fig. 4. KY boost converter mode 2 operation.

$$\begin{cases} L_i \dfrac{\partial iLi}{\partial t} = vi - vcm, \\[2mm] L_o \dfrac{\partial iLo}{\partial t} = 2vcm - vo, \\[2mm] C_o \dfrac{\partial vo}{\partial t} = iLo - \dfrac{vo}{RL}, \\[2mm] C_m \dfrac{\partial vcm}{\partial t} = iLi - iLo. \end{cases} \qquad (2)$$

The average value of voltage or current can be obtained from (3), where the variable x is a time varying quantity and

represents voltage or current

$$\langle x \rangle = \frac{1}{Ts} \int_0^{Ts} x d\tau .$$ (3)

The averaged equations are obtained from (1)-(3) and represented by (4):

$$\begin{cases} Li \frac{\partial \langle iLi \rangle}{\partial t} = \langle vi \rangle - (1-d) \langle vcm \rangle, \\ Lo \frac{\partial \langle iLo \rangle}{\partial t} = (2-d) \langle vcm \rangle - \langle vo \rangle, \\ Co \frac{\partial \langle vo \rangle}{\partial t} = \langle iLo \rangle - \frac{\langle vo \rangle}{RL}, \\ Cm \frac{\partial \langle vcm \rangle}{\partial t} = -\langle iLo \rangle + (1-d) \langle iLi \rangle - d \langle icb \rangle, \end{cases}$$ (4)

where d is the duty cycle of PWM signal of switch S_2. The voltage conversion ratio of the KY boost converter obtained is given by (5)

$$\frac{Vo}{Vi} = \frac{2-d}{1-d}.$$ (5)

The specification of KY boost converter which we have taken in to account is depicted by the following Table I. We have considered the following specifications to simulate the results of the proposed control technique.

TABLE I. SPECIFICATIONS OF KY BOOST CONVERTER.

Parameter	Symbol	Value	Unit
Input voltage	V_i	12	V
Rated output voltage	V_o	36	V
Rated load current	I_o	2.5	A
Output and Input Inductance	L_o, L_i	15	µH
Buffer capacitance	C_m	1000	µF
Energy transferring capacitor	C_b	680	µF
Output capacitor	C_o	470	µF
Load resistor	R_L	14.4	Ω
Switching frequency	f_s	195	kHz

IV. NEURO FUZZY CONTROLLER MODELING

Adaptive Neuro Fuzzy Inference System (ANFIS) is the implementation of neural network architecture [16] in the inference engine of a Fuzzy controller. Figure 5 shows the proposed controller for KY boost converter with ANFIS controller [17]–[19] for a reference output voltage of 36 V. The input to ANFIS controller is error (e) in output voltage and change in error (ce); the output of the controller is duty cycle (d) which is fed to the PWM generation block whose switching frequency is 195 kHz and the output of which is the control signal (c) fed as switching signal for switch S_2 of the KY boost converter. The output voltage V_L and output current I_L values are stored in the MATLAB workspace by the sink "itr" as shown in the Fig. 4.

The KY boost converter realized in Simulink model is depicted by Fig. 6, whose input is PWM output control signal (c) fed as switching pulse (M) to the switch S_2 and the output voltage (V_L) and output current (I_L) are taken as

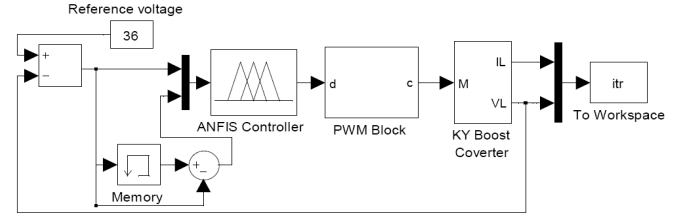output to the MATLAB workspace.

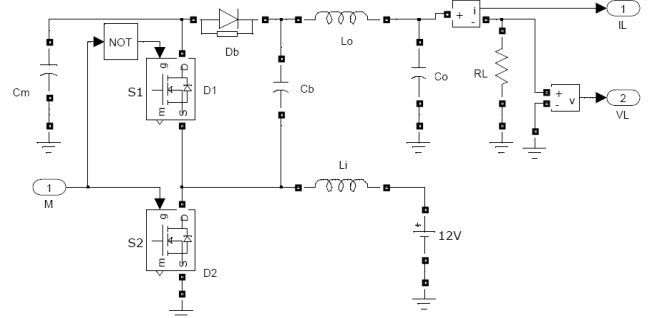Fig. 5. ANFIS Control of KY Boost converter Simulink model.

Fig. 6. KY boost converter Simulink structure.

Figure 7 shows the PWM control signal generation block which generates control signal (c) from the duty cycle (d) obtained from ANFIS controller with a switching frequency of 195 kHz.
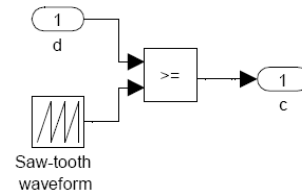

Fig. 7. PWM block with 195 kHz switching frequency.

Figure 8 shows a general block diagram of ANFIS controller, where the Neural network is implemented in the rule base of the Fuzzy controller and Fig. 9 describes the general structure of a five layer four rule base ANFIS algorithm using first order Sugeno type Fuzzy - Neural network architecture with two input functions and one output function, whose input function is classified with 7 membership functions implemented during the creation of rule base.

The ANFIS structure [20] comprises three distinct layers namely input layer (Layer I); hidden layer (Layer II to Layer IV) and output layer (Layer V). The input layer namely Layer I consists of input membership functions X_1 and X_2 which transmit the input signal for classification through membership functions into fuzzy linguistic variables in Layer II. In this article ANFIS controller input variables are chosen as output voltage error (e) and change in error (ce); fed as input variables X_1 and X_2 respectively. The layer II consists of 14 nodes, as each input is classified into 7 membership functions to convert to fuzzy linguistic variables. The layer III comprises of 49 nodes, each node representing a fuzzy rule, denoted as rule layer whose function is to multiply the input signal and is denoted by the symbol Π in Fig. 9. Layer IV consist of output membership functions comprising 49 nodes termed as sigmoidal layer whose node consist of nonlinear mapping imposing bounds

on the signal to enhance the stability of the system. The output layer denoted by Layer V consists of output function represented by the symbol C in Fig. 9 which sums all the signals to acquire final inferred result.
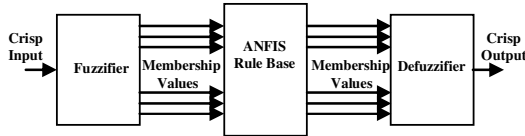

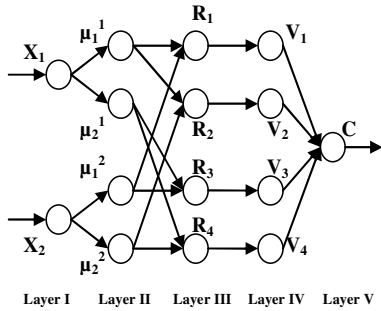Fig. 8. Neuro Fuzzy System general block diagram.

Fig. 9. Neuro Fuzzy architecture for mamdani model.

The ANFIS controller implemented in this article is of the model described as above whose fuzzifier section comprise the input signals error *(e)* and change in error signal *(ce)* whose membership functions are selected as Gaussian membership function and are classified into seven functions namely Negative Big (NB); Negative Medium (NM); Negative Small (NS); Zero (ZE); Positive Small (PS); Positive Medium (PM) and Positive Big (PB). The defuzzifier section comprises the output signal which is the duty cycle *(d)* is considered as linear signal in ANFIS model with the classification of membership functions as assumed above. The membership function plots for the input variables e and ce are shown by the figures Fig. 10 and Fig. 11 respectively.
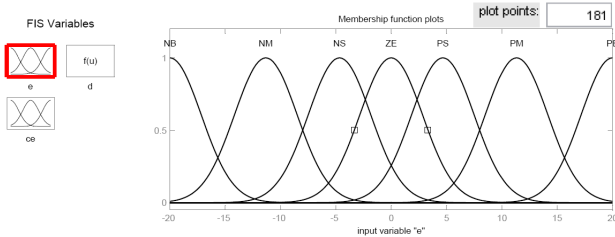

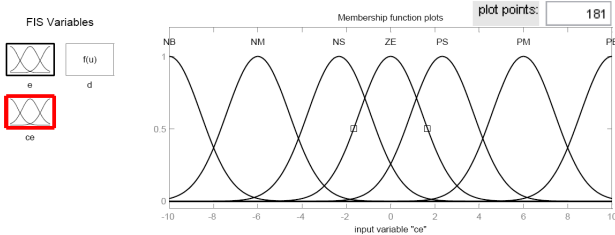Fig. 10. Membership function view for error signal.

Fig. 11. Membership function view for change in error signal.

The input membership functions are mapped to the output membership function by 49 rules through grid partitioning method using FIS generator in MATLAB Simulink® ANFIS trainer and the ANFIS rule base model is portrayed by the Fig. 12.

The data sets to train ANFIS is obtained from workspace from the PID controller model in which data's namely output voltage error (e), rate of change of error (ce) and the corresponding duty cycle (d) are obtained by executing the PID controller model. The ANFIS model is trained with data sets obtained from the workspace by loading the data into ANFIS trainer and the data is then trained through back propagation technique for 50 epochs for minimum error tolerance. It is found that the error minimizes at epoch 33 during training and it is constant as depicted by Fig. 13.
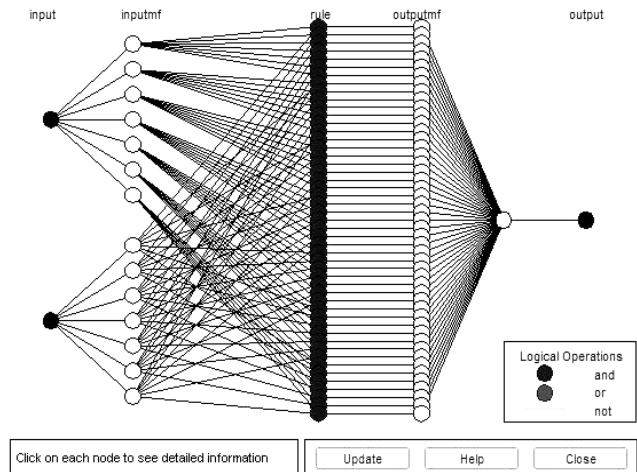

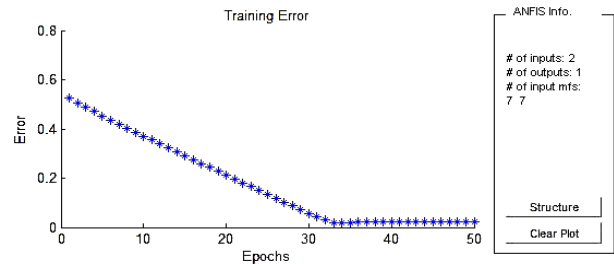Fig. 12. ANFIS rule base model structure.

Fig. 13. ANFIS training output.

The final ANFIS rule base surface view after training is depicted by the Fig.14 as given below.
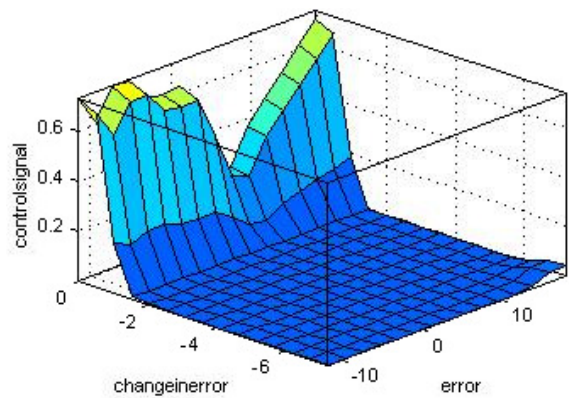

Fig. 14. ANFIS rule base surface view.

V. SIMULATION RESULTS

The results of the KY boost converter with input voltage 12 V; rated output voltage of 36 V and load current 2.5 A

simulated with MATLAB Simulink R2011a is shown by the following figures from Fig. 15 to Fig. 17.

Figure 15 depicts the output voltage waveform of existing PID controller [12], [13] and proposed Neuro Fuzzy controller for a time period of 0.1 second. It is evident that the overshoot in PID output is reduced in Neuro Fuzzy controller output and the settling time of the output voltage is reduced to greater extent by the proposed controller and the measured settling time is 15 ms.

Figure 16 shows simulation result of the output voltage ripple for the proposed ANFIS controller in the time period of 0.3259 s to 0.3261 s. It clearly shows that the output ripple for an output voltage of 36 V is about 610 µV which ranges from 36.00025 V to 36.00086 V.
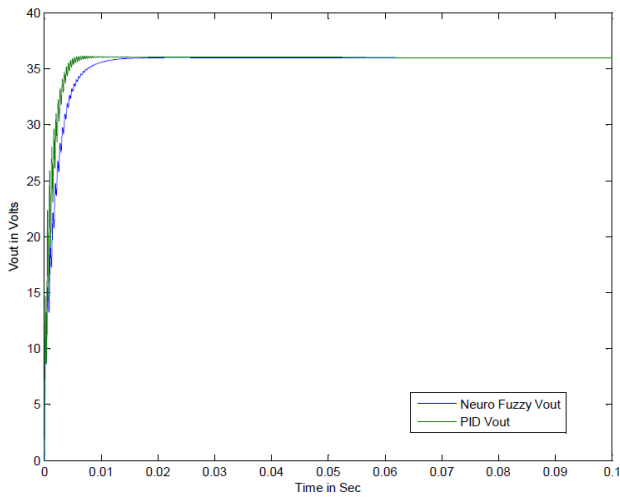

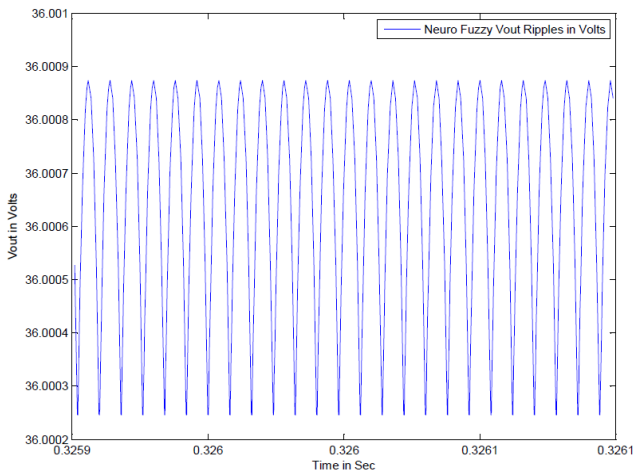Fig. 15. Output Voltage waveform of PID and Neuro Fuzzy controlled KY Boost converter.

Fig. 16. Output Voltage Ripple waveform of Neuro Fuzzy controlled KY boost converter.

Figure 17 shows the output current ripple waveform of proposed Neuro Fuzzy controller output for a time period of 0.0224 s to 0.0225 s which shows 100 µA ripple current in the simulation result.

Figure 18 shows the output current waveform of existing PID controller and proposed Neuro Fuzzy controller output for a time period of 0.1 s. It shows the reduction in overshoot and settling time of the output current in the proposed ANFIS controller output current waveform.
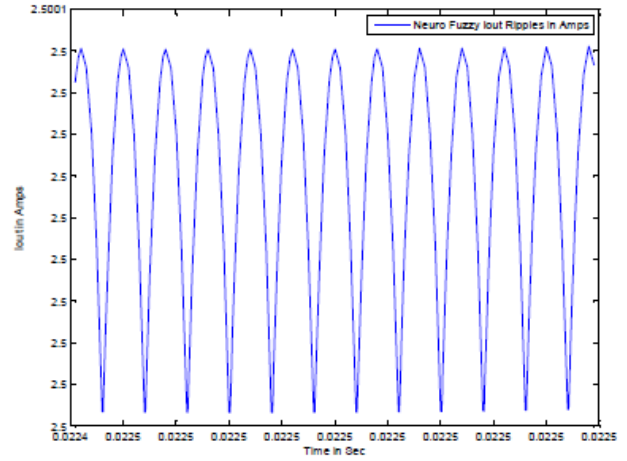

Fig. 17. Output Current ripple waveform of Neuro Fuzzy controlled KY Boost converter.
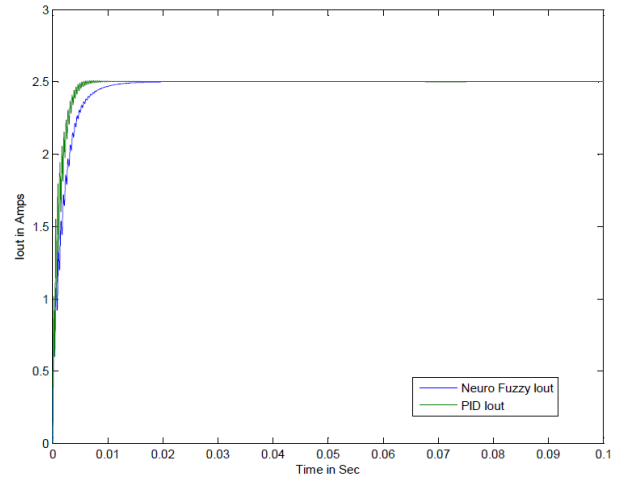

Fig. 18. Output Current waveform of PID and Neuro Fuzzy controlled KY Boost converter.

VI. HARDWARE IMPLEMENTATION

The hardware implementation for the proposed ANFIS controlled KY boost converter with the specifications mentioned in Table 1 is shown in Fig. 19.
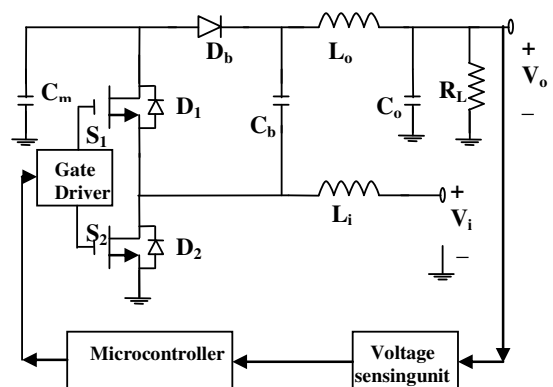

Fig. 19. Hardware implementation of Neuro Fuzzy controlled KY boost converter.

The output of the KY boost converter is sensed by the voltage sensing unit by a potential divider and this analog signal is converter into digital signal by an analog-to-digital converter from which current output voltage is calibrated by the microcontroller which estimates the error and change in

error from which it implements the Neuro Fuzzy control algorithm and produce corresponding duty cycle from which PWM signal is generated which controls the switching action of the KY boost converter.
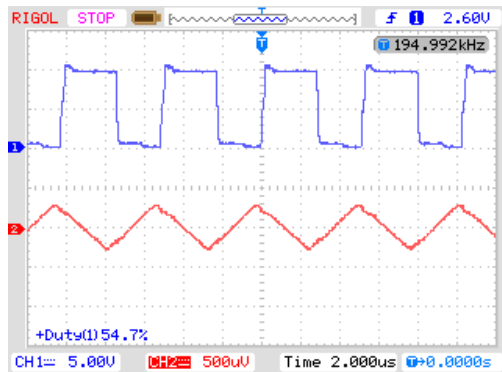

Fig. 20. Output Voltage Ripple waveform of Neuro Fuzzy controlled KY boost converter.

Figure 20 shows the output voltage ripple waveform of proposed Neuro Fuzzy controller output in hardware realization. The ripple is around 500 µV in the hardware output shown in channel 2 waveform with switching frequency of 195 kHz for a corresponding duty cycle of 54.7% for PWM switching signal shown by channel 1 as shown in the output picture.
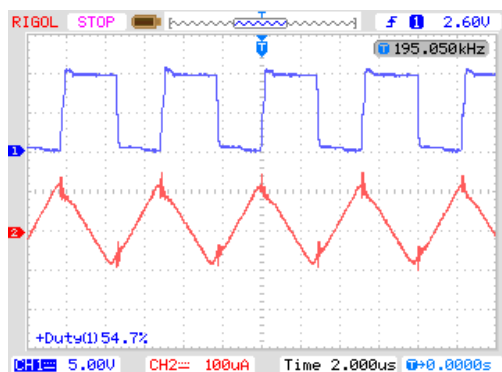

Fig. 21. Output Current Ripple waveform of Neuro Fuzzy controlled KY boost converter.

Figure 21 shows the output current ripple waveform of proposed Neuro Fuzzy controller output in hardware realization. The ripple is around 200 µA in the hardware output shown in channel 2 waveform with switching frequency of 195 kHz.

VII. CONCLUSIONS

In this paper a Neuro Fuzzy controller is employed to improve the performance of positive output KY boost converter and the results of the controller illustrate decrease in overshoot, reduce in settling time and decrease in output voltage ripple. The back propagation technique is implemented for training the ANFIS controller with the results obtained from the resulting values of the PID controller. The resulting output values of the proposed Neuro Fuzzy controller are compared with the existing controller output in the following Table II. The minimization of output voltage ripple from 200 mV of existing PID controller to 500 µV in the proposed Neuro Fuzzy controller is validated through hardware output. Further improvements

in KY boost converter output can be achieved by implementing various optimization techniques in the controller.

TABLE II. COMPARISON OF EXISTING AND PROPOSED CONTROLLER OUTPUT.

Parameter	Existing PID controller	Proposed Neuro Fuzzy controller
Settling time	65 ms	15 ms
Output voltage ripple	200 mV	500 µV

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