

Analysis of High-Performance Step-Down DC to DC Converter Design Based on Zero Voltage Switching with Pulse Width Modulation Technique for Electric Vehicles

Hnin Wint War Nyo, Hla Myo Tun, Lei Lei Yin Win, Thanda Win, Ei Ei Khin, Mya Mya Aye and Devasis Pradhan

Abstract—The paper mainly focuses on analyzing high-performance step-down DC to DC converter based on zero voltage switching with pulse width modulation technique for electric vehicles. In this paper, PI, fuzzy PI, and adaptive network-based fuzzy inference system (ANFIS) control methods are applied to the phase shift full-bridge (PSFB) zero voltage switching (ZVS) converter for auxiliary components in electric vehicles. The robust analysis of three control methods is compared by using the AC small-signal mathematical model. Traditional PI control uses specific mathematical equations with errors and derivatives. Fuzzy PI control utilizes fuzzy logic rules with linguistic variables such as high, medium, and low. ANFIS combines fuzzy logic and neural networks to capture both benefits. The three control designs' switching losses and load changes are analyzed and implemented with the MATLAB/SIMULINK Software platform. From the simulation results, traditional PI control works with 92% efficiency. Fuzzy PI control and ANFIS work with 93% efficiency at full load capacity.

Index Terms—DC to DC Converter, Electric Vehicles, High-Performance Step Down Converter, Pulse Width Modulation, Zero Voltage Switching.

I. INTRODUCTION

THE topologies are important in converter design with requirements. There have two sides in isolated converter such as primary side and secondary side. Phase shift full bridge and LLC resonant are more utilized for the primary side in EV. PSFB has more advantages than LLC in wide conversion range, easily synchronization, easy to parallel for current sharing. The PSFB (Phase Shift Full Bridge) converter consists of a full-bridge topology with two additional features: phase shifting and soft switching. The phase shifting can control the power flow of the converter as design requirements. The PSFB converter uses soft switching techniques, such as zero-voltage switching (ZVS) and zero-current switching (ZCS), to minimize switching losses and improve efficiency [1]-[6]. These techniques allow the converter to operate at higher frequencies, reducing the size and weight of the magnetic components. Overall, the

PSFB converter is a popular choice for high-power applications due to its high efficiency, compact size, and ability to handle high power levels. In secondary side, full bridge rectification, center-tapped rectification and current doubler rectification are popular in converter [7-9].

The control system with converter is one of the important converter design. There are basically open-loop and closed-loop control system. Open-loop control with ZVS-PSFB DC-DC isolated buck converter works with fixed duty cycles and phase shift for switching signals without considering actual operating conditions. Closed-loop control with converter can adjust the phase shift and duty cycle to maintain desired output and stability. Nowadays, researchers have been improving converter efficiency by using famous and robust controller such as PID, Fuzzy and ANFIS. AC small signal analysis helps transfer function and optimize control gains for converter's stability and efficiency [10-13].

AC small signal analysis helps small-signal transfer functions, stability and dynamic response for converter. This analysis starts by linearizing the nonlinear converter model around the steady-state conditions operating point. It can identify deviations from the steady-state values. It makes ensures the system remain stable under small perturbations. It can optimize converter's design parameters such as control loop gain for desired efficiency and transient response [14-16].

There are various techniques to achieve ZVS and ZCS for minimizing losses in switches. ZVS makes the voltage across switch ensure zero when it turns on or off. ZVS can be achieved by using resonant circuits for ensuring zero transition in voltage waveform. Auxiliary switches and phase shift control such as push pull converter and full bridge converter adjusts time during switch transition and makes ZVS to operate. Snubber circuits such as RC snubbers prevent voltage spikes and enable ZVS by absorbing residual energy. ZCS makes the current through a switch ensure zero during switching on or off. ZCS can be achieved by using current mode control and similar techniques like ZVS.

While ZVS focuses on minimizing voltage-related switching losses, ZCS targets reducing current-related losses. Both techniques are critical for high-efficiency and reliable power conversion systems. ZVS targets reducing switching losses about voltage while ZCS aims reducing losses about current.

The paper organized as follows. Section II presents the

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operation of PSFB ZVS DC-DC converter. Section III mentions the analysis on closed loop system with pi control. Section IV highlights the analysis on closed loop system with fuzzy PI control. Section V focuses on the determination of the exact fuzzy output and setting fuzzy control rules. Section VI gives the design of Sugeno adaptive network based fuzzy inference system PID controller. Section VII emphasizes on the discussions and conclusion of the study.

II. OPERATION OF PSFB ZVS DC-DC CONVERTER

The traditional full-bridge converter is improved with PSFB ZVS topologies. The converter with PSFB reduces switching losses and improves efficiency by controlling the two legs of the bridge. ZVS ensures switch to be turned on and off. PSFB ZVS DC-DC converter is suitable for reducing switching losses in high-frequency.

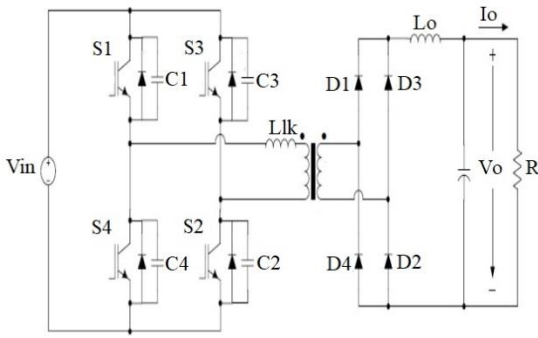


Fig. 1. PSFB ZVS DC-DC converter.

TABLE I
PARAMETERS OF COMPONENTS IN CIRCUIT

Symbol	Quantity	Value
V_{in}	Input Voltage	350 V -400 V -410V
V_{out}	Output Voltage	10 V -12 V -15V
I_{out}	Output Current	50 A
n (Np/Ns)	Effective Turns Ratio	11.2
f_s	Switching Frequency	100k Hz
L_{lk}	Leakage Inductor	10 μ H
L	Filter Inductor	5.3 μ H
C	Filter Capacitor	347 μ F
R_d	Damping Resistor	0.0319
R_{out}	Load	0.24
P_{out}	Output Power	600 W

Figure 2 shows the AC small signal of PSFB ZVS DC-DC converter with effective phase shift D_{eff} and effective turns ratio n .

$$D_{eff} = \frac{V_0}{V_{in}} n \quad (1)$$

The open loop transfer function of AC small signal model of PSFB ZVS DC-DC converter is as follows.

$$G_{vd}(s) = \frac{\frac{V_{in}}{n}}{s^2 LC + s \frac{L}{R_{out}} + R_d C_f \frac{\ddot{\theta}}{\dot{\theta}} + \frac{R_d}{R_{out}} + 1} \quad (2)$$

The parameters are substituted from Table 1.

$$G_{vd}(s) = \frac{35.71}{2.776' 10^{-9} s^2 + 4.44' 10^{-5} s + 1.133} \quad (3)$$

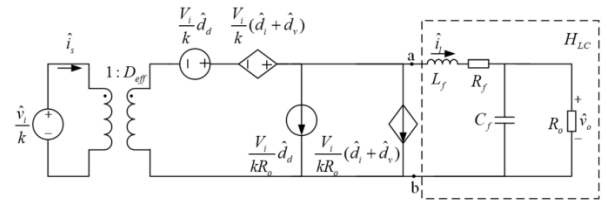
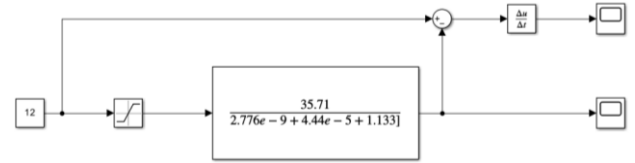
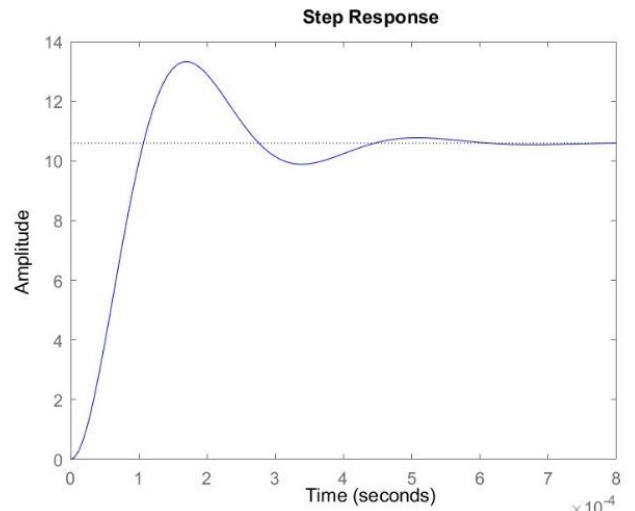


Fig. 2. AC small-signal model of PSFB ZVS DC-DC Converter with Effective Phase Shift [1]

The simulation results of the opened-loop system are as shown in Figure 3. The steady state error -9.6 with traditional turns ratio. Maximum deviation change rate is 12.9×10^4 and minimum deviation change rate is -3.3×10^4 . Although the open loop system acquires around 12V with effective turns ratio, the accuracy and stability cannot be guaranteed if the load or situation changes. Therefore, the closed loop system is needed to offer robust control and better performance although it gets more complex and requires more components.



(a)



(b)

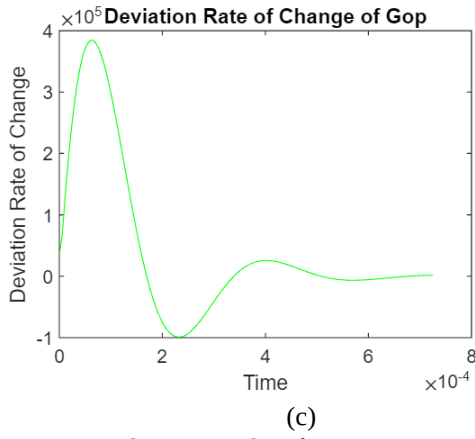


Fig. 3. Simulation Results of Open Loop Control System (a) Open Loop Control of Small Signal System, (b) Step Response of Output Voltage, (c) Deviation Rate of Change of Output Voltage

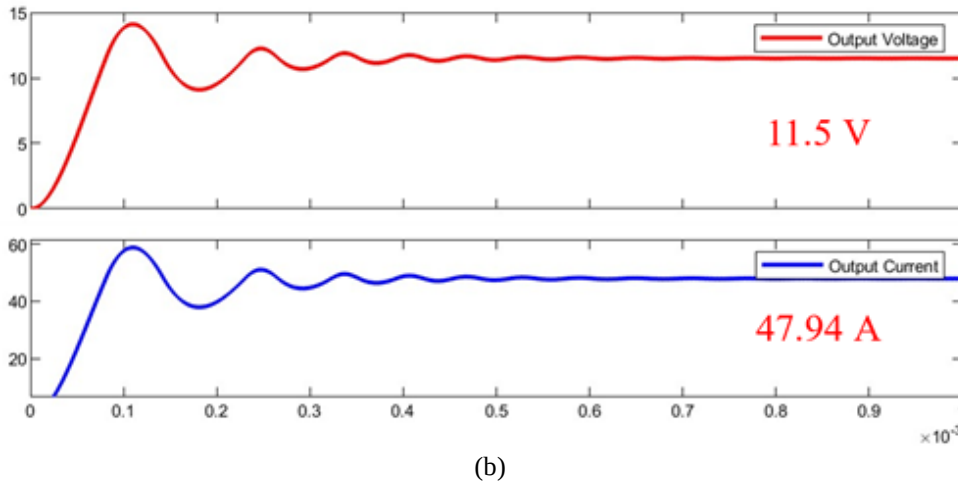
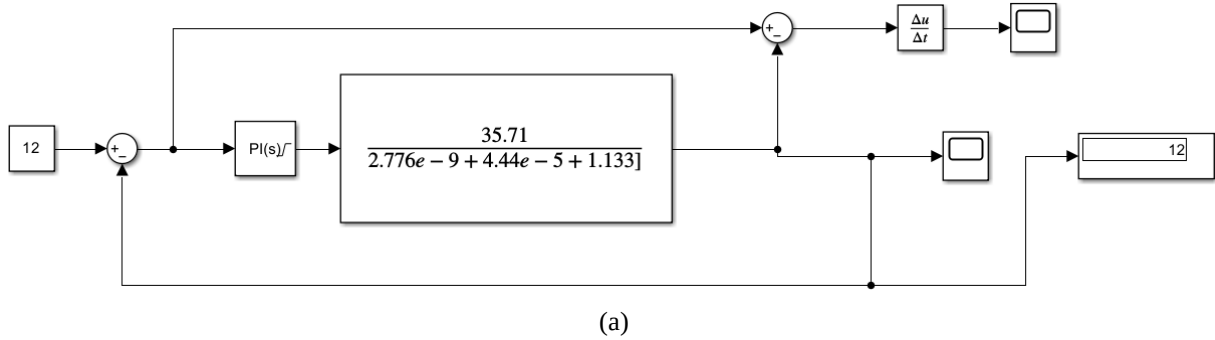


Fig. 4. Simulation Results from PI Controller (a) Closed Loop PI Control of Small Signal System, (b) Waveforms of ZVS PSFB DC-DC Converter with PI Controller

IV. ANALYSIS ON CLOSED LOOP SYSTEM WITH FUZZY PI CONTROL

Fuzzy PI controller works with control rules. There are two types of fuzzy model such as Mamdani and Sugeno. In this paper, Sugeno model is adopted for no requirement defuzzification step and can simply applied in real-world applications. Two fuzzy controllers for each P and I gain are used to tune easily. The input variables range such as deviation K_e , deviation rate of change K_{ec} and output variable range such as control signal to PI initial gains are set in fuzzy.

A. Fuzzification

The fuzzy sets are defined as seven such as Negative Big, Negative Medium by using membership functions

III. ANALYSIS ON CLOSED LOOP SYSTEM WITH PI CONTROL

In PI controller, choosing gains is one of the most important designs. K_p gain determines the current error and corresponds to stability and speed. If K_p gain becomes higher, the speed of response becomes quick. However, it leads instability if K_p gain is too high. K_i gain helps steady state error correction. These gains are adjusted for tuning the controller to meet the system requirements. There are tuning methods such as Ziegler-Nichols, Trial and error, manual tuning and auto tuning methods. In this paper, manual tuning is applied to implement gains. K_i is set as zero and K_p is increased until oscillation starts and it is noted as 150. K_p is set as 15. The simulation results are shown in Figure 4. The output voltage is 11.5 and the output current is 47.93A. The efficiency is 92% at full load.

shown in Figure 5. The membership function range is taken as $[-6, 6]$. The E_e is set to $X_e \in [-0.58, 13]$ and E_{ec} is set $X_{ec} \in [-3.3 \times 10^4, 12.9 \times 10^4]$. Fuzzy quantification factor for E_e and E_{ec} are set as 0.46 and 4.6×10^{-5} from the following equations.

$$K_e = \frac{|M|_{\max}}{|X_e|_{\max}} \quad (4)$$

$$K_{ec} = \frac{|M|_{\max}}{|X_{ec}|_{\max}} \quad (5)$$

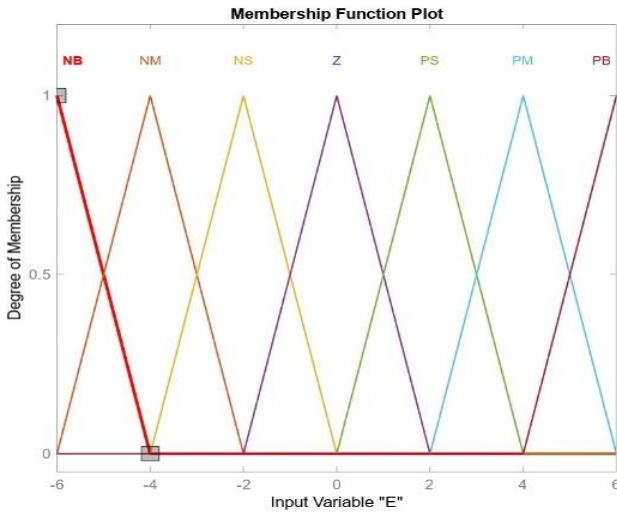


Fig. 5. Membership Function of Fuzzy Variables

V. DETERMINATION OF THE EXACT FUZZY OUTPUT AND SETTING FUZZY CONTROL RULES

Separate fuzzy output ranges for seven memberships are defined as $Y_p \in [-537, 537]$, $Y_i \in [-53.7, 53.7]$.

ΔK_p : {NB = -537, NM = -400, NS = -200, Z = 0, PS = 200, PM = 400, PB = 537}

ΔK_i : {NB = -53.7, NM = -40, NS = -20, Z = 0, PS = 20, PM = 40, PB = 53.7}

TABLE II
FUZZY CONTROL RULES FOR ΔK_p

ΔK_p	K_e						
K_{ec}	NB	NM	NS	Z	PS	PM	PB
NB	-537	-537	-537	-400	-400	0	0
NM	-537	-537	-400	-400	-200	0	0
NS	-400	-400	-200	-200	0	200	200
Z	-400	-200	-200	0	200	200	400
PS	-200	-200	0	200	200	400	400
PM	0	0	400	400	400	537	537
PB	0	0	200	400	537	537	537

TABLE III
FUZZY CONTROL RULES FOR ΔK_i

ΔK_i	K_e						
K_{ec}	NB	NM	NS	Z	PS	PM	PB
NB	53.7	53.7	40	40	20	0	0
NM	53.7	40	40	40	20	0	0
NS	40	40	40	20	0	-20	-40
Z	40	20	20	0	-20	-40	-40
PS	20	20	0	-20	-20	-40	-40
PM	0	0	-20	-40	-40	-40	-53.7
PB	0	-20	-20	-40	-40	-53.7	-53.7

The output surfaces of ΔK_p and ΔK_i of Fuzzy PI Controller are as shown in Figure 6. The intensity of the color values of ΔK_p shows the range of values in the specific rule base systems. If the light color mentions the wide range of the values and the high intensity color expresses the less values in error values.

The results of Fuzzy PI controller with ZVS PSFB converter are as shown in Figure 7. The output voltage is 11.59 and the output current is 48.31A. The efficiency is 93% at full load. The value of ΔK_i is only changed in the limited range of error values in the stability output voltage for the practical applications.

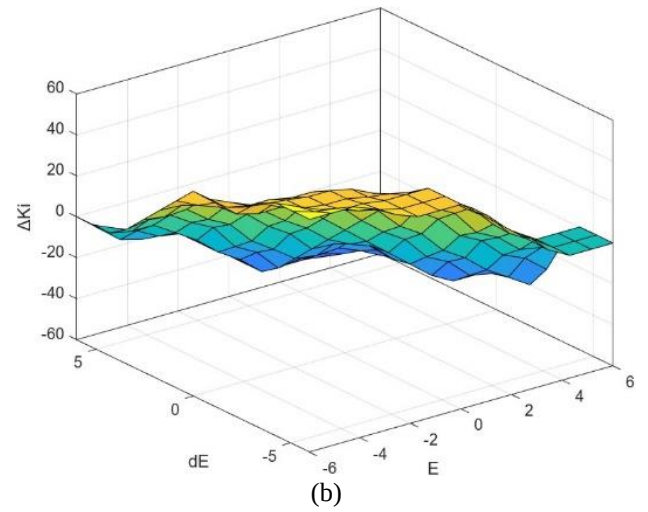
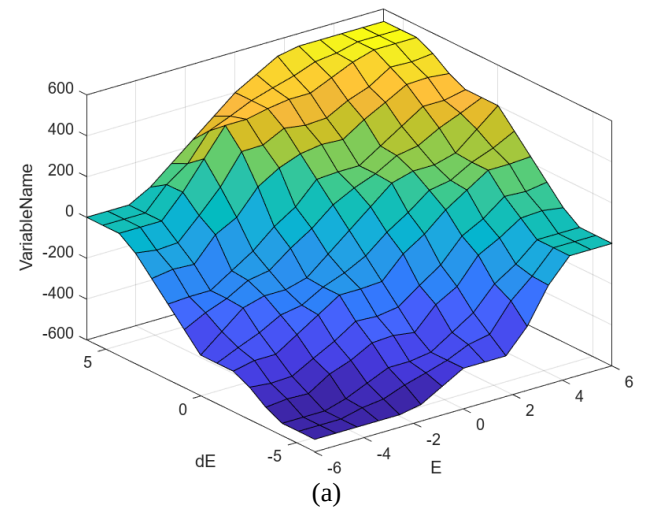


Fig. 6. Output Surfaces of the Coefficient for Fuzzy PI Controller (a) Output surfaces of ΔK_p , (b) Output surfaces of ΔK_i

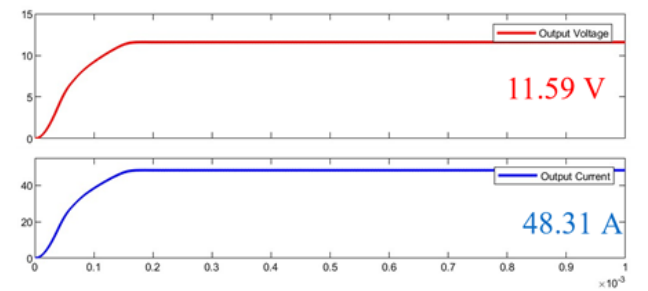


Fig. 7. Waveforms of ZVS PSFB DC-DC Converter with Fuzzy PI controller

VI. DESIGN OF SUGENO ADAPTIVE NETWORK BASED FUZZY INFERENCE SYSTEM PID CONTROLLER

ANFIS PID controller has neural network and uses a learning algorithm for training fuzzy control rules as sample data. While fuzzy logic relies on manually rules and membership, ANFIS automatically adjust fuzzy rules and membership from training fuzzy. As a result, ANFIS can offer more flexible and adaptable without experiences. The output surfaces of ΔK_p and ΔK_i are as shown in Figure 8.

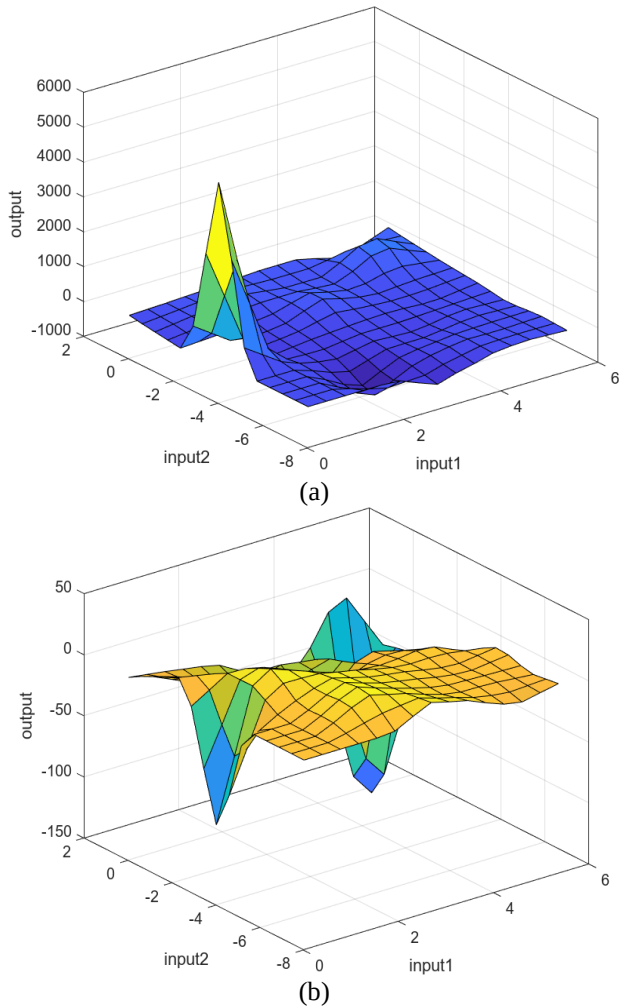


Fig. 8. Output surfaces of the coefficient for ANFIS PI Controller (a) Output surfaces of ΔK_p , (b) Output surfaces of ΔK_i

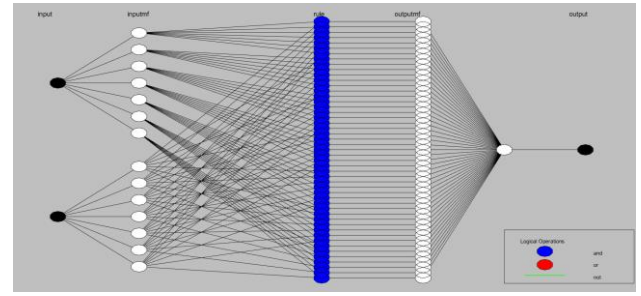


Fig. 9. ANFIS Control Network

Figure 10 shows that simulation of fuzzy PID and ANFIS control. The input port 1 is reference voltage 12 V and the input port 2 is feedback from output voltage. The output port 3 is output voltage.

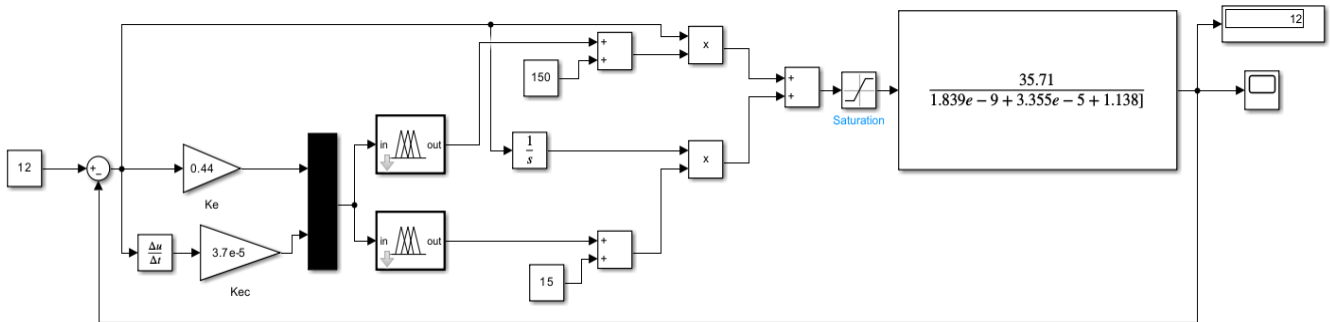


Fig. 10. Simulation model of the Fuzzy PID control (/the ANF PID control)

The results of ANFIS PI controller with ZVS PSFB converter are as shown in Figure 11. The output voltage is 11.59 and the output current is 48.31A. The efficiency is 93% at full load.

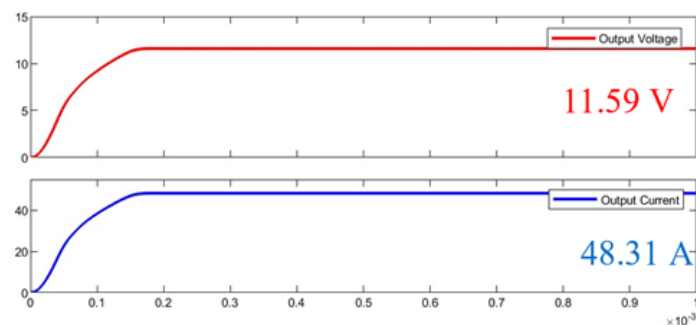


Fig. 11. Waveforms of ZVS PSFB DC-DC Converter with ANFIS PI controller

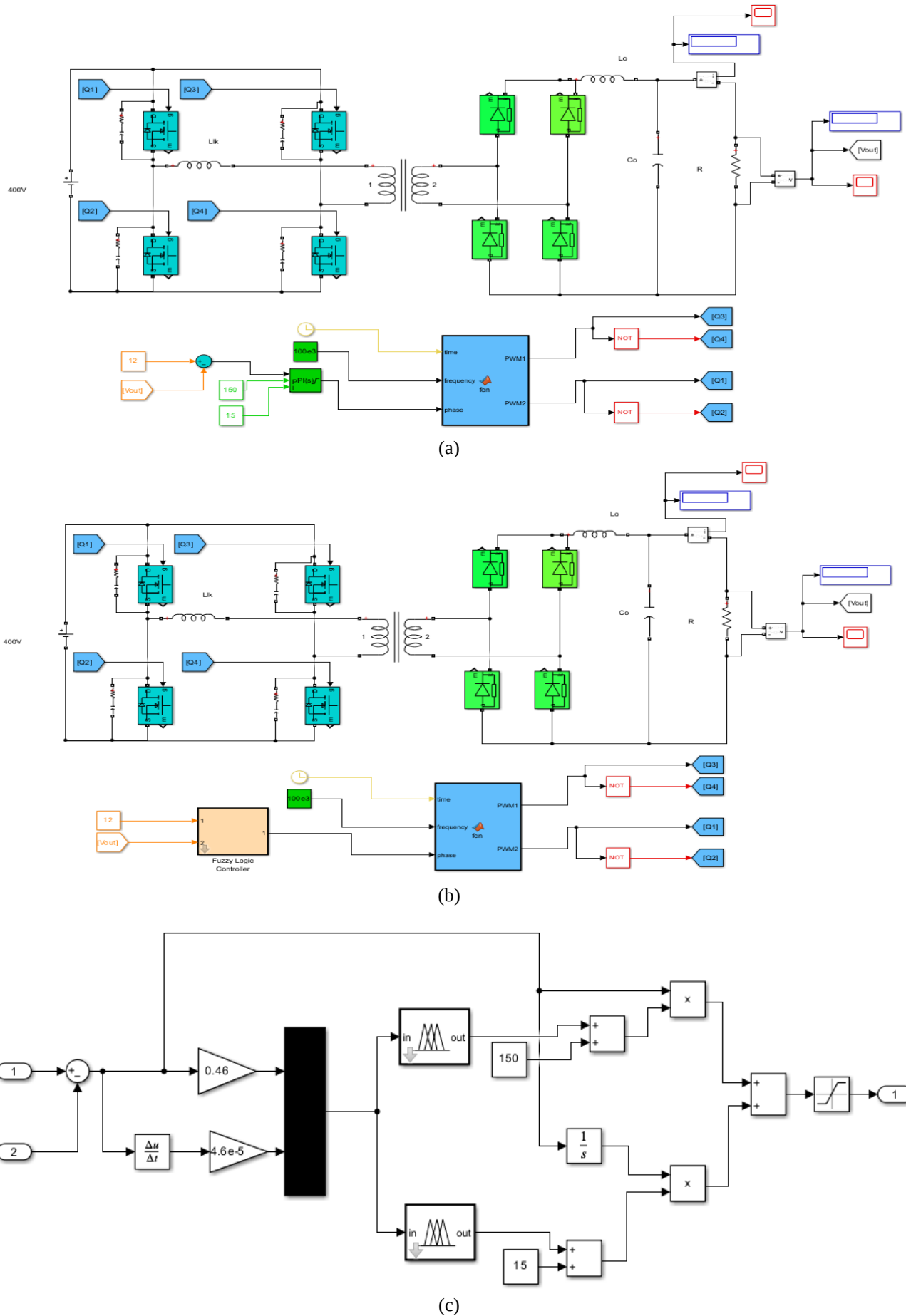


Fig. 12. Circuit Model of ZVS-PSFB DC-DC converter with Controller (a) Overall Circuit model of PI Closed Loop Control System, (b) Overall Circuit model of Fuzzy /ANFIS PI Closed Loop Control System, (c) Fuzzy PI (ANFIS PI) Control System

TABLE IV
PERFORMANCE TABLE

Parameters	PI Controller	Fuzzy PI Controller	ANFIS PI Controller
Output Voltage	11.5 V	11.59 V	11.59 V
Output Current	47.93 A	48.31 A	48.31 A
Output Power	551 W	559 W	559 W
Efficiency	92%	93%	93%
Steady State Time	0.7 ms	0.8 ms	0.8ms
Switching Losses	More than other methods	Less than PI Controller	Less than PI Controller
Control Strategy	Simple	Complex	Complex

Table IV gives the performance comparison between different analyses on various parameters for the study.

VII. HARDWARE TESTING RESULTS

Fig.13 shows the electric vehicle interior light being powered by the push-pull converter during the experimental testing. The light is connected to the converter's DC output, demonstrating the converter's ability to provide a stable and consistent voltage to a real-world load. In this setup, the push-pull converter is supplying the necessary power for the car interior light, which is typically designed to operate on a low-voltage DC supply. The successful operation of the light indicates that the converter is delivering the required voltage and current, and that its output is stable and suitable for powering small electrical loads. This also serves to validate the converter's performance under practical conditions, as the interior light is a common load in automotive applications. Testing the converter with such a load helps ensure that it can reliably provide power for various devices and systems in an electric vehicle, confirming its effectiveness in real-world applications.

VIII. DISCUSSIONS

The push-pull converter demonstrated efficient operation, with an experimentally measured efficiency of 95% which is in close alignment with the simulation predictions. The results confirm that the converter operates efficiently under the given conditions, with the efficiency slightly varying due to real-world factors such as parasitic losses and non-ideal components. The push-pull converter maintained stable output voltage and exhibited effective load regulation, as shown in the experimental results. Despite variations in load, the converter was able to maintain consistent performance, with minimal voltage ripple. This confirms the converter's capability to provide reliable power to sensitive loads in practical applications.

IX. CONCLUSION

The controllers acquire 90% efficiency from my design simulation. They have their purposes for the application area. The traditional PI controller is simple to implement and it is sufficient if the system is well understood and linear such as a certain range of input voltages, load conditions, and other parameters. This controller is used in well-known and linear systems of low voltage in EVs. In this design, the fuzzy PI and ANFIS PI controller have the same result. The Fuzzy PI controller is complex to implement and it should be used for uncertain parameters.

The ANFIS PI controller is also complex like Fuzzy PI and it should be used for adaptive parameters and highly uncertain parameters. Fuzzy PI and ANFIS PI controller are suitable for energy management, battery management and electric motor control in EV. As this paper is mainly proposed for linear auxiliary components in EV, PI controller is sufficient and simple to implement although its efficiency is less.

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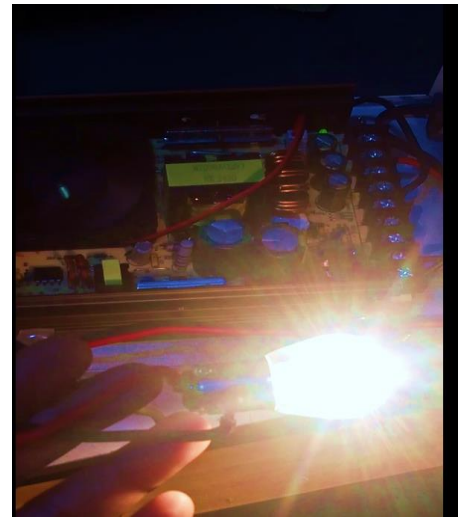


Fig.13. Hardware Testing Results

REFERENCES

- [1] Htay, A. K., Tun, H. M. T., Pradhan, D., Win, L. L. Y., Khin, E. E., & Soe, K. T. (2024). Design of Multi-Level Inverter Design for Charging Stations of Electric Vehicles. *Andalasian International Journal of Applied Science, Engineering and Technology*, 4(2), 125-136. <https://doi.org/10.25077/aijaset.v4i2.136>.
- [2] Aung, M. M., Win, S., Thar, H. A., & Tun, H. M. (2024). Implementation of Efficient Electric Vehicle Fast Charging System Using Dual Active Bridge Converter. *Andalasian International Journal of Applied Science, Engineering and Technology*, 4(3), 278-287. <https://doi.org/10.25077/aijaset.v4i3.172>.
- [3] Lin, H., Aye, K. M., Tun, H. M., Theingi, & Naing, Z. M. (2008, October). Design and construction of intelligent traffic light control system using fuzzy logic. In *AIP Conference Proceedings* (Vol. 1052, No. 1, pp. 237-239). American Institute of Physics.
- [4] Octavia, N., Maung, M. M., & Tun, H. M. (2014). Performance Evaluation of Fuzzy Logic Controller in Water Bath Temperature Control System. *International Journal of Science, Engineering and Technology Research*, 3(6), 1623-1629.
- [5] Tun, H. M., & Aung, W. (2014). Analysis of Control System for A 24V PM Brushed DC Motor Fitted with an Encoder by Supplying H-Bridge Converter. *Bahria University Journal of Information & Communication Technology*, 7(1), 54.
- [6] Nwe, M. S., & Tun, H. M. (2017). Implementation of Multisensor Data Fusion Algorithm. *International Journal of Sensors and Sensor Networks*, 5(4), 48-53.
- [7] Hlain, N., Htun, Z., & Tun, H. (2015). Design and Implementation of PC Based over Speed Violation Management for Vehicles on Highway. *International Journal of Scientific & Technology Research*, 4(7), 74-77.
- [8] Oo, K. N., Naing, Z. M., & Tun, H. M. (2014). Implementation Of Distributed Control System In Process Control Management Using MATLAB. *Int. J. Sci. Technol. Res*, 3(6), 149-154.

- [9] Paing, S. M., Mon, S. S. Y., & Tun, H. M. (2016). Design And Analysis Of Doppler Radar-Based Vehicle Speed Detection. *IJSTR*, 5(06).
- [10] Aung, N. P., Naing, Z. M., & Tun, H. M. (2016). Analysis of Time Delay Simulation in Networked Control System. *International Journal of Electronics and Communication Engineering*, 10(3), 359-364.
- [11] Khin, E. T., Myat, C., & Tun, H. M. (2015). Vehicles In Highway Communication System Using ZigBee and Bluetooth Network. *Int. Jour. Sci. Tech. Res.*, 4(6), 425-429.
- [12] Thet, W. M., Maung, M., & Tun, H. M. (2015). Real-time vehicle data logging system using GPS and GSM. *International Journal of Scientific and Technology Research*, 4(07), 44-49.
- [13] Soe, T. T., & Tun, H. M. (2014). Implementation Of Double Closed-Loop Control System For Unmanned Ground Vehicles. *international journal of scientific & technology research*, 3.
- [14] Aye, P. P., & Tun, H. M. (2018). Analysis on Control System Design of Plant Simulator for Hardware-In-The-Loop Simulation Using MATLAB. *International Journal of Sensors and Sensor Networks*, 6(1), 1-7.
- [15] Lin, K. O., Tun, H. M., Naing, Z. M., & Moe, W. K. (2015). Microcontroller based SPWM single-phase inverter for wind power application. *Int. J. Sci. Technol. Res.*, 4(8), 189-192.
- [16] Htay, Aung & Myo Tun, Hla & Lei, Lei & Khin, Ei & Pradhan, Devasis. (2024). Analysis of Step Up or Boost Converter Design for Charging Station of Electric Vehicles, *IEMTRONICS 2024* (International IOT, Electronics and Mechatronics Conference), 3rd – 5th April 2024 at Imperial College London, UK.



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