Double Output Positive Conversion Path Re-Lift Luo Converter Performance with Intelligent Control Strategies

D. Thaniga[1], Dr. S. Padma[2], Dr. R. Kannan[3]

[1]Research Scholar, Department of Electrical Engineering, Annamalai University, Annamalainagar, Tamil Nadu, India
[2,3]Associate Professor, Department of Electrical Engineering, Annamalai University, Annamalainagar, Tamil Nadu, India

KEYWORDS
Luo Converter, DOPCPRL, PI Controller, Fuzzy Logic controller, Neuro controller

ABSTRACT
This study investigates double-output DC-DC Luo converters as a cost-effective, high-power-density solution for generating positive and negative output voltages from a single positive input source, addressing the increasing demand for such converters in modern electronics. The research focuses on the development and comparison of control strategies for a Double Output Positive Conversion Path Re-lift (DOPCPRL) Luo Converter. Specifically, Proportional-Integral and fuzzy logic controllers are designed and implemented to regulate the output voltage under varying input voltage and load conditions. Performance evaluation through simulation demonstrates the superior performance of the fuzzy logic controller and neural network controllers compared to the traditional PI controller, highlighting its effectiveness in maintaining stable and accurate output voltage regulation. The results underscore the potential of intelligent control techniques for enhancing the performance of Luo converters in demanding applications.

1. INTRODUCTION

The electronics industry's relentless pursuit of miniaturization and increased performance has fueled the demand for DC-DC converters capable of handling higher voltages and power densities [1-3]. Traditional converter topologies often fall short of these requirements, necessitating the exploration of innovative circuit architectures. Double-output DC-DC converters, particularly those based on the Luo converter topology, have emerged as a promising solution [4]. These converters utilize a single switch to generate both positive and negative output voltages, offering a cost-effective and efficient approach to power conversion [6]. Luo converters distinguish themselves through their modular design, which facilitates scalability and enhances fault tolerance. This inherent modularity makes them well-suited for a wide range of applications, including renewable energy systems, motor drives, and high-voltage direct current transmission [7-8]. Furthermore, the Luo converter's ability to provide both step-up and step-down DC-DC conversion expands its versatility and applicability. The increasing need for mirror-symmetrical dual output voltages in applications such as operational amplifiers, computer peripherals, differential servomotor drives, and medical devices further underscores the significance of Luo converters [9-11]. These devices require precise and balanced positive and negative voltages, a requirement efficiently met by the dual-output configuration of Luo converters. Recent research and development efforts have focused on optimizing the performance of Luo converters, particularly in terms of efficiency, power density, and cost-effectiveness [12-13]. The fundamental Luo converter circuit serves as a basis for several derived topologies, including self-lift, re-lift, and multiple-lift circuits. Each variation offers unique performance characteristics and trade-offs, allowing for tailored solutions to specific application requirements [14-17]. Further investigation into the operating principles, control strategies, and comparative performance analysis of these variations will be crucial in realizing the full potential of Luo converters and shaping the future of power conversion systems.

2. DOUBLE OUTPUT POSITIVE CONVERSION PATH RE-LIFT (DOPCPRL) LUO CONVERTER

Figure 1 shows the circuit of re-lift circuit derived from self-lift circuit. The positive conversion path consists of a pump circuit S-L_1-D_0-C_1 and a filter C_2- L_2-C_O and a lift circuit D_1-C_2-D_3-L_3-D_2-C_3. The negative conversion path consists of a pump circuit S-L_{11}-D_{10}-C_{11} and a "Π"-type filter C_{11}-L_{12}-C_{10} and a lift circuit D_{11}-C_{12}-L_{13}-D_{22}-C_{13}-D_{12}. The equivalent circuit during switch-on is shown in Figure 2a, and the equivalent circuit during switch-off in Figure 2b. The voltage across inductors L_1 and L_3 is equal to V_I during switch-on, and –(V_{C1} – V_I) during switch-off.

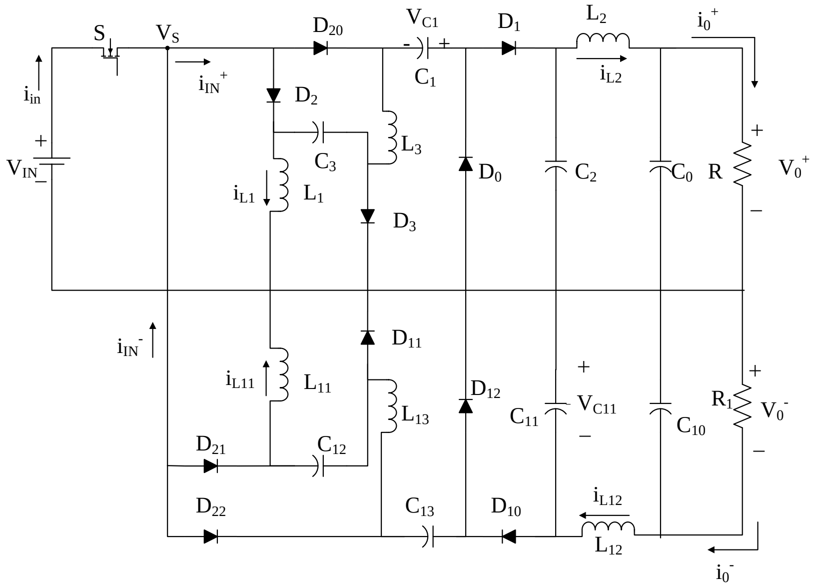
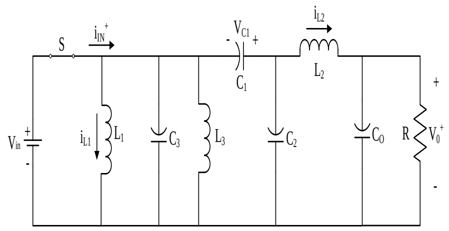
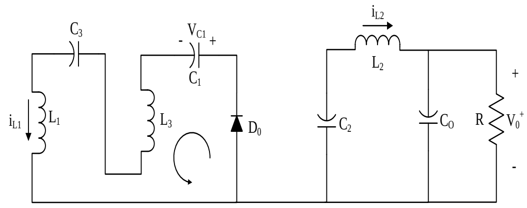


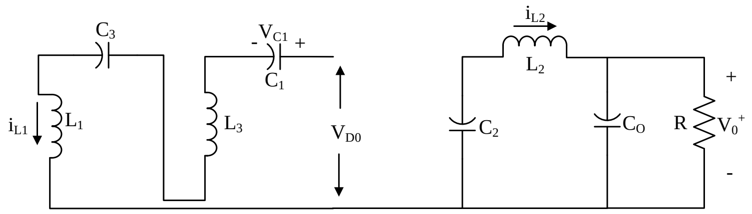
Figure 1. Double output re-lift Luo converter



(a) Switch-on state



(b) Switch-off state



(c) Discontinuous mode

Figure 2. Equivalent circuits of double output re-lift Luo circuit (positive conversion path)
(a) Switch-on state (b) Switch-off state (c) Discontinuous mode

$$V_{C1} = \frac{1+k}{1-k} V_I \text{ and } V_O = V_{CO} = V_{C2} = V_I + V_{C1} = \frac{2}{1-k} V_I$$

Thus,

$$V_{O+} = \frac{2}{1-k} V_I$$

and

$$I_{O+} = \frac{1-k}{2} I_{I+}$$

The other relations are

$$I_{I+} = k i_{I+} \quad i_{I+} = I_{L1} + I_{L3} + i_{C3-on} + i_{C1-on} \quad i_{C1-off} = \frac{k}{1-k} i_{C1-on}$$

and

$$I_{L1} = I_{L3} = i_{C1-off} = i_{C3-off} = \frac{k}{2} i_{I+} = \frac{1}{2} I_{I+}$$

The voltage transfer gain in continuous mode is

$$M_{R+} = \frac{V_{O+}}{V_I} = \frac{2}{1-k}$$

This mode of operation typically occurs at light loads or high switching frequencies. The equivalent circuit in DCM differs from the continuous conduction mode during the portion of the off-state where the inductor current is zero. A detailed analysis of the DCM operation requires considering the specific time intervals within the switching cycle where the inductor current is zero. This analysis can reveal the impact of DCM on the converter's efficiency and output voltage regulation.

2.1 Modelling of Double Output Re-Lift Luo Converter

To study the behaviour of any system, modelling and simulation are very essential. State-space analysis is a popular and useful approach for modelling any non-linear and time variant system. The state model of a system consists of the state equation $\dot{X} = AX(t) + BU(t)$ and output equation $Y = CX(t) + DU(t)$

where, X(t) is the state vector of order n x 1, U(t) is the input vector of order m x 1, Y is the output vector of order p x 1, A is the system matrix of order n x n, B is the input matrix of order n x m, C is the output matrix of order p x n, D is the transmission matrix of order p x m, [n is the order of the system, m is the number of inputs and p is the number of outputs]

The state variables for positive conversion path are assumed to be

$X_1=i_{L1}$ $X_2=V_{C3}$ $X_3=i_{L3}$ $X_4=V_{C1}$ $X_5=V_{C2}$ $X_6=i_{L2}$ $X_7=V_{C0}$
$U=V_{in}$ $Y=V_0$

Using the equivalent circuit for the switch – on period of positive conversion path of the chosen circuit as in Fig. 2(a), the state space model for mode 1 is

$$A_{11} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C} & 0 & \frac{1}{C_1} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & \frac{1}{L_2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad B_{11} = \begin{bmatrix} \frac{1}{L_1} \\ 1 \\ \frac{1}{L_3} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$C_{11} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{RC_0} \end{bmatrix}$$

$$D_{11} = [0]$$

Using the equivalent circuit for the switch – off period of the circuit as in Fig. 2(b), the state model for mode 2 is

$$A_{21} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_3} & 0 & \frac{1}{C_3} & 0 & \frac{1}{C_3} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{L_2} & 0 & \frac{1}{L_2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{C_0} & 0 \end{bmatrix} \quad B_{21} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$C_{21} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{RC_0} \end{bmatrix}$$

$$D_{21} = [0]$$

$$D_{22} = [0]$$

The state space models for the chosen Luo converters needed for the development of conventional and intelligent controllers

3. DESIGN OF CONVERTERS

3.1. Design of Conventional Controller

Proportional-Integral controllers have been a cornerstone of industrial process control for decades. Their widespread adoption stems from a combination of straightforward design and effective performance characteristics, particularly for slow-responding processes. PI controllers typically exhibit low percentage overshoot and short settling times in such applications, contributing to stable and efficient control [18].

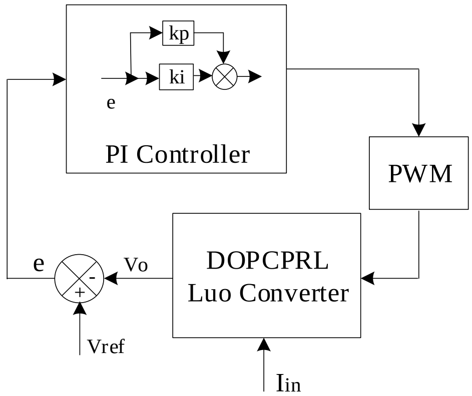


Figure 3. Structure of PI controller

A key advantage of PI controllers lies in the intuitive physical interpretation of their three adjustable parameters: proportional gain, integral gain, and setpoint. This inherent transparency simplifies the tuning process, enabling operators to achieve desired performance even through empirical methods like trial and error [19]. These tuning rules offer practical guidelines based on readily obtainable process characteristics, further enhancing the usability and effectiveness of PI control in diverse industrial settings [20-21]. The PI controller's differential equation is as follows: The overall control action m(t) can be expressed as:

$$m(t) = K_P e(t) + K_i \int_0^t e(t)dt \quad (1)$$

In the s-domain, this can be expressed as:

$$M(s) = \left(K_P + \frac{K_i}{s} \right).E(s)$$

Increasing the proportional gain (K_p) generally leads to a faster system response, albeit with an increased propensity for overshoot. While a higher K_p reduces the steady-state error, it does not eliminate it entirely. Conversely, increasing the integral gain (K_i) drives the steady-state error towards zero, but simultaneously increases the risk of instability. Consequently, integral control is never implemented in isolation, but rather in conjunction with proportional control. Figure 3 presents the block diagram illustrating the PI control scheme for the Luo converter. In this specific implementation, the PI controller parameters are set as follows: proportional gain (Kp) = 0.505, integral time constant (T_i) = 191.01, and integral gain (K_i) = 2643.9. These values have been determined through a suitable tuning method to achieve the desired performance characteristics for the converter system. Further analysis and experimentation may be necessary to optimize these parameters for specific operating conditions and performance requirements.

3.3. Design of Fuzzy logic Controller

Fuzzy logic Controller offer a powerful mechanism for translating human-understandable linguistic control strategies into automated control action [22]. This is achieved through the rule base, which defines the relationships between linguistic input and output variables. Fuzzy logic, the underlying principle of FLCs, provides a robust framework for deriving definitive conclusions from imprecise, uncertain, or ambiguous information, making it well-suited for complex or poorly defined systems [23].

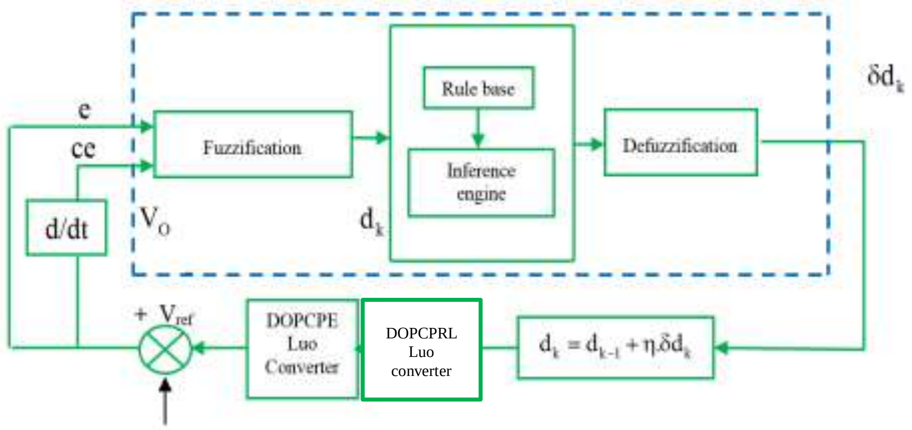


Figure 4. Fuzzy logic controller for Luo converter

The FLC architecture comprises the components are Fuzzification Unit, Fuzzy Inference Engine, Knowledge Base, Defuzzification Unit. Compared to traditional control methodologies, FLCs present several advantages like, Simplified Design, Cost-Effectiveness, Robustness to Uncertainty. Figure 4 illustrates the specific FLC implementation employed for the Luo converters considered in this study. The figure details the chosen membership functions, fuzzy rules, and defuzzification method used to achieve the desired control performance. A comprehensive analysis of the FLC design and its impact on the converter's performance is presented in subsequent sections. While fuzzy logic operates on linguistic variables and rules, it seamlessly integrates with real-world systems by accepting crisp numerical data as inputs. These crisp inputs, typically obtained from sensors or other instrumentation, are then fuzzified, or transformed into linguistic representations, within the fuzzy logic system.

3.3. Design of Neuro Controller

Artificial neural networks, possessing inherent capabilities for real-time learning, parallel computation, and self-organization, present a compelling approach to pattern classification and control. These characteristics make ANNs particularly well-suited for addressing complex, non-linear control problems, leveraging their learning and generalization abilities [24]. This work employs an ANN-based controller for regulating a Double Output Positive Conversion Path re-lift Luo converter. In contrast to many feed-forward neural network applications that rely on offline training with pre-collected datasets, this implementation utilizes online training with the standard backpropagation algorithm. Each online training epoch involves forward propagation of the input vector through the ANN to compute the output. This output is then compared with a reference value to determine the training error [25]. The artificial neural network controller is trained using a backpropagation algorithm to minimize the error between the desired output voltage and the actual output voltage of the Luo converter. This iterative training process involves presenting the network with a set of input-output pairs, calculating the error, and adjusting the network weights to reduce the error. This process is repeated for all training patterns, ensuring accurate mapping and generalization across the desired operating range of the converter. The ANN architecture employed in this study consists of an input layer, five hidden layers, and an output layer.

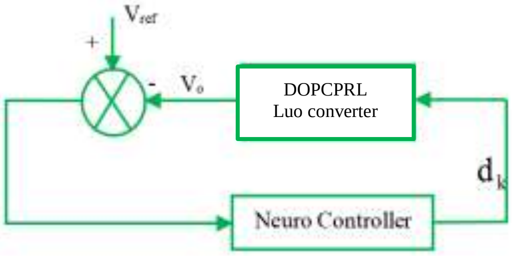
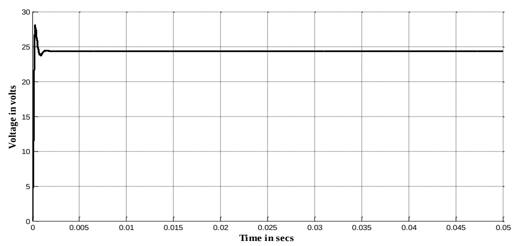


Figure 5. Neuro controller for Luo converter

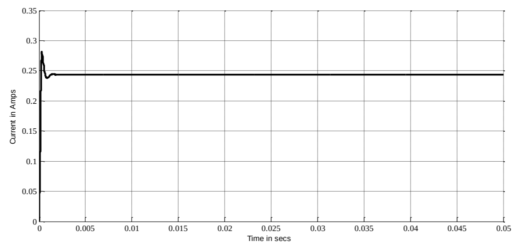
The input to the neural controller is the output voltage error, calculated as the difference between the measured output voltage of the Luo converter under supply and/or load disturbances and the desired output voltage setpoint [25]. The controller's output is the updated duty ratio, which is subsequently used to modulate the switching devices of the converter and regulate the output voltage. Figure 5 provides a visual representation of the neuro-control scheme implemented for the DOPCPRL Luo converter, illustrating the signal flow and control loop. This online training approach allows the neural network controller to adapt to real-time operating conditions and variations in the converter's dynamics. This adaptability leads to improved performance and robustness compared to traditional control methods, which may not be as effective in handling unpredictable disturbances or parameter variations.

4. SIMULATION RESULTS AND DISCUSSION

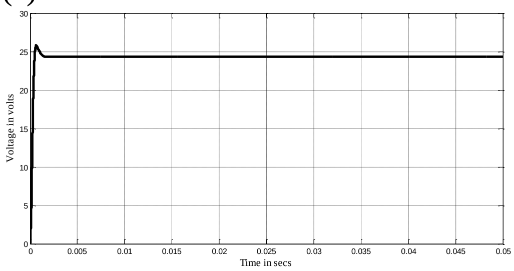
This section presents a comparative analysis of proportional-integral, fuzzy logic and neural network controllers implemented for with Double Output Positive Conversion Path re-lift Luo converters. Performance evaluation focuses on the transient response characteristics of the closed loop during start-up, particularly examining the output voltage and current waveforms. Figures 6 and 7 present the closed-loop output voltage and current transient responses of the DOPCPRL Luo converter under three different control strategies: PI, fuzzy logic, and neural network. Qualitative analysis reveals distinct performance characteristics for each controller. While all achieve satisfactory transient responses, the PI controller exhibits slight overshoot with minor oscillations as shown in Figures 6(a) and 7(a), whereas the fuzzy logic (Figure 6(b) and 7(b)) and neural network controllers responses (6(c) and 7(c)) demonstrate smoother, overshoot-free responses. Quantitative analysis of settling times reveals the neuro controller as the fastest, followed by the fuzzy controller, and lastly, the PI controller. These differences are attributed to the inherent characteristics of each control strategy. The PI controller's higher gain and faster response result in a shorter settling time but at the cost of a small overshoot. The fuzzy logic and neural network controllers, with their nonlinear control capabilities and adaptive nature, offer smoother responses but with longer settling times. The PI controller's faster rise time further emphasizes its aggressive control, contributing to a shorter settling time but increased susceptibility to overshoots. This analysis highlights the trade-offs between settling time, overshoot, and control complexity. The optimal controller selection depends on the specific application requirements. Further research on robustness and dynamic performance under varying loads is needed for a more comprehensive evaluation.



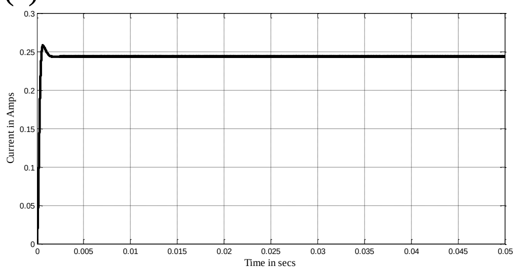
(a) PI Controller



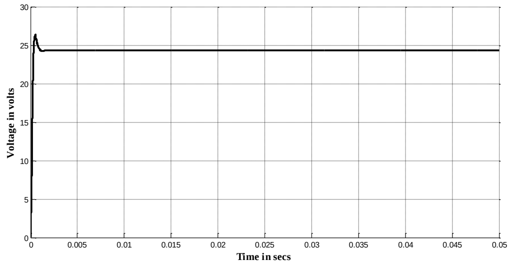
(a) PI Controller



(b) Fuzzy Logic Controller

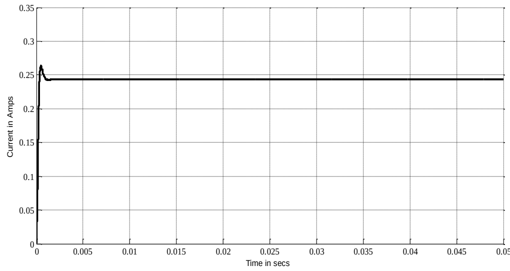


(b) Fuzzy Logic Controller



(c) Neuro Controller

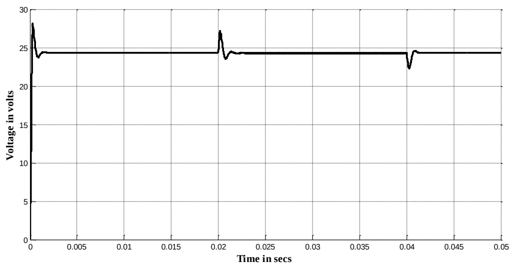
Figure 6. Start-up transient in output voltage



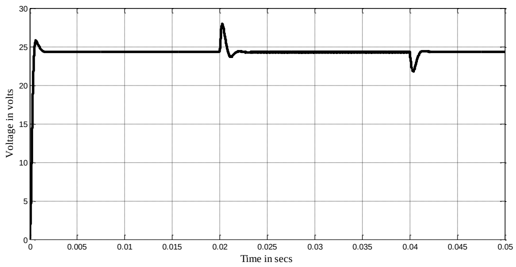
(c) Neuro Controller

Figure 7. Start-up transient in output current

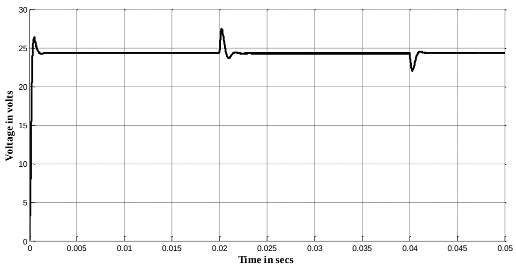
Figures 8 and 9 illustrate the closed-loop output voltage and current responses of the DOPCPRL Luo converter under sudden line voltage disturbances (±25% step change in input voltage). The dynamic performance of three controllers was analyzed. Transient line disturbances resulted in comparable peak overshoots in both output voltage and current for all controllers. However, the neural network controller exhibited superior performance (Figures 8(c) and 9(c)), likely due to its adaptive learning-based architecture. While the PI controller, with fixed gains, may struggle under changing input voltage (Figures 8(a) and 9(a)), the fuzzy logic controller, though capable of handling nonlinearities, may not match the neural network's adaptability (Figures 8(b) and 9(b)). Further analysis of transient response characteristics (rise time, settling time, steady-state error) would enable a more quantitative comparison. Quantifying these metrics would facilitate a more informed controller selection for applications with expected line voltage fluctuations. Studying controller robustness under various disturbance variables and frequencies would provide a more comprehensive understanding of their dynamic performance.



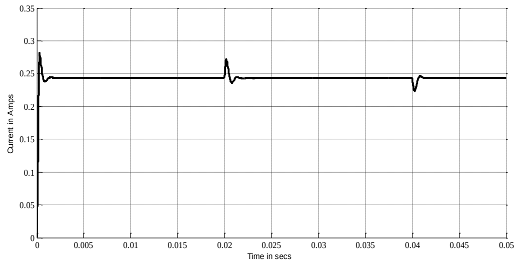
(a) PI Controller



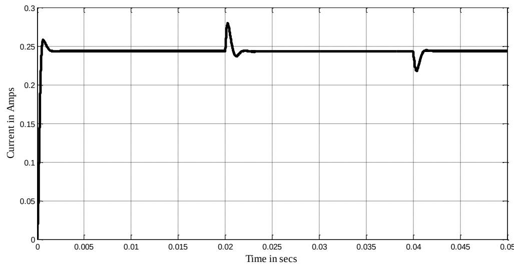
(b) Fuzzy Logic Controller



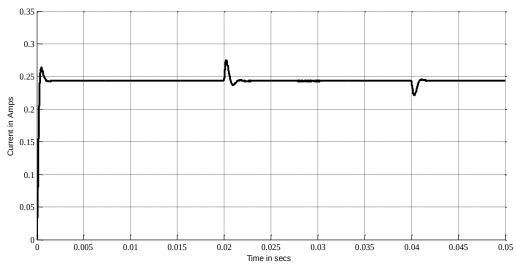
(c) Neuro Controller



(a) PI Controller



(b) Fuzzy Logic Controller

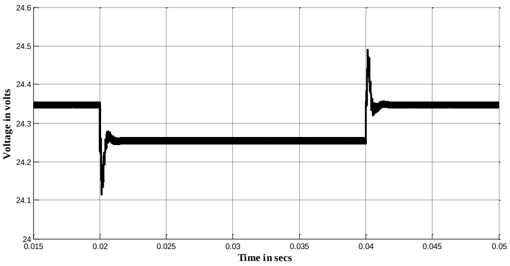


(c) Neuro Controller

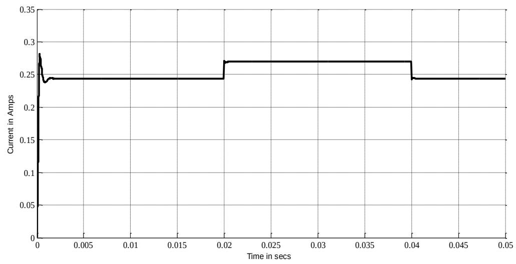
Figure 8. Output voltage with sudden line disturbances of 25% of rated supply

Figure 9. Output current with sudden line disturbances of 25% of rated supply

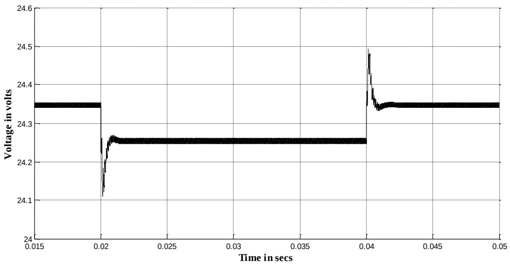
Figures 10 and 11 depict the dynamic response of the DOPCPRL Luo converter under sudden load disturbances (±10% step change in load resistance). The transient responses of the output voltage and current with PI controller is shown in Figures 10(a) and 11(a), the transient responses of the output voltage and current with fuzzy controller is shown in Figures 10(b) and 11(b) and similarly the responses with neuro controller is shown in Figures 10(c) and 11(c) respectively. All three controllers exhibited comparable peak overshoots in both output voltage and current. However, consistent with previous analyses, the neural network controller demonstrated significantly faster settling times, indicating superior dynamic performance and robustness under load fluctuations.



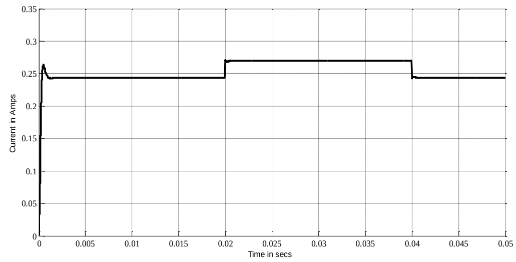
(a) PI Controller



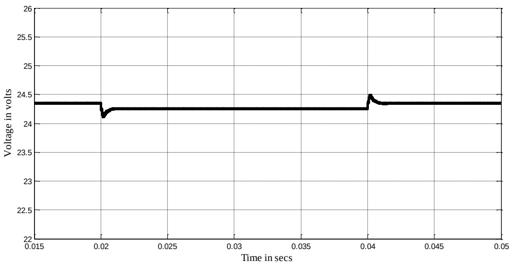
(a) PI Controller



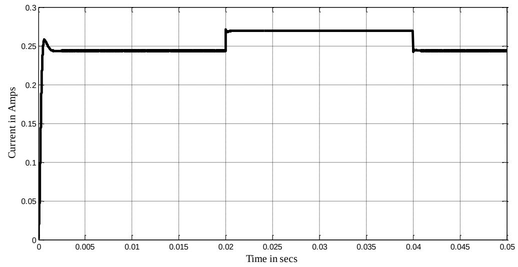
(b) Fuzzy Logic Controller



(b) Fuzzy Logic Controller



(c) Neuro Controller



(c) Neuro Controller

Figure 10. Output voltage with sudden load disturbances of 10% of rated load

Figure 11. Output current with sudden load disturbances of 10% of rated load

Table 1. Performance evaluation of controllers for double output positive conversion path re-lift Luo converter using MATLAB simulation

Controllers	Start-up transient					Supply increase 25%		Supply decrease 25%		Load increase 10%		Load decrease 10%	
	Delay time (ms)	Rise time (ms)	Peak over shoot (%)	Peak time (ms)	Settling time (ms)	Peak over shoot (%)	Settling Time (ms)	Peak over shoot (%)	Settling Time (ms)	Peak over shoot (%)	Settling Time (ms)	Peak over shoot (%)	Settling time (ms)
PI	0.13	0.19	17.04	0.29	2.5	16.62	3.66	9.17	2.32	2.09	3.19	2.5	2.35
FUZZY	0.22	0.38	9.79	0.63	1.8	13.2	2.62	7.12	2.02	2.04	2.7	2.08	1.58
NEURO	0.15	0.27	7.2	0.51	1.38	12.97	2.59	7.9	1.95	0.45	1.08	0.45	1.47

Table 1 summarizes the overall performance evaluation, confirming the neural network controller's superior performance across multiple metrics. Its faster settling time highlights its ability to rapidly adapt to load changes, crucial for maintaining stable and reliable converter operation. This table compares the performance of three controllers PI, Fuzzy, and Neuro in a double output positive conversion path re-lift Luo converter system, focusing on start-up transient behavior and responses to supply and load disturbances. The start-up transient performance is evaluated using metrics such as delay time, rise time, peak overshoot, peak time, and settling time. The Neuro controller outperforms the others with the lowest delay time (0.15 ms), rise time (0.27 ms), peak overshoot (7.2%), peak time (0.51 ms), and settling time (1.38 ms). In contrast, the PI controller has the highest peak overshoot (17.04%) and the slowest settling time (2.5 ms), while the Fuzzy controller shows intermediate performance. For disturbance responses, including 25% supply increases and decreases and 10% load changes, the NEURO controller consistently demonstrates superior performance with the lowest peak overshoots and fastest settling times, followed by the Fuzzy controller, which shows moderate improvements over the PI controller. The PI controller, being simpler, exhibits higher overshoots and slower stabilization in all scenarios. Overall, the analysis highlights the significant advantages of advanced controllers like Neuro and Fuzzy in achieving better dynamic performance compared to the traditional PI controller.

5. CONCLUSION

This study comprehensively analyzed the performance of a DOPCPRL Luo converter, focusing on the development and comparison of three control strategies: PI, fuzzy logic, and neural network. The primary goal was output voltage regulation, ensuring stability despite input voltage and load fluctuations. Extensive simulations demonstrated the neural network controller's superior performance in robust and stable output voltage regulation, outperforming the PI and fuzzy logic controllers in dynamic response and adaptability to disturbances. While the PI controller offered the fastest response in certain scenarios, it exhibited overshoots and oscillations. The fuzzy logic controller provided a smoother response but with slower settling times. The neural network controller's adaptive learning capability proved crucial for maintaining optimal performance under various perturbations, making it promising for real-world applications with unpredictable fluctuations. Future research could involve experimental validation on a physical prototype, optimizing the neural network architecture and training algorithms, and exploring advanced control techniques like adaptive neuro-fuzzy inference systems for enhanced robustness and efficiency.

REFERENCES

[1] B. L. Narasimharaju, V. V. Prahlad, U. R. Reddy, K. V. Babu, and P. Srinivasan, “Optimized Dual Active Bridge bi-directional DC-DC converter for UPS application,” in *proc. IEEE International Conf. on Power Elect., Drives and Energy Systems (PEDES)*, pp. 1–6, Dec. 2014, doi: 10.1109/pedes.2014.7042117.

[2] J. Chen, M.K. Nguyen, Z. Yao, C. Wang, L. Gao, and G. Hu, “DC-DC converters for transportation electrification: Topologies, control, and future challenges,” *IEEE Electrif. Mag.*, vol. 9, no. 2, pp. 10–22, Jun. 2021, doi: 10.1109/mele.2021.3070934.

[3] J. Shi, E. Soenen, A. S. Roth, Y.-C. Hsu, and M. Kinyua, “Practical Considerations for a Digital Inductive-Switching DC/DC Converter With Direct Battery Connect in Deep Sub-Micron CMOS,” *IEEE J. Solid-State Circuits*, vol. 47, no. 8, pp. 1946–1959, Jul. 2012, doi: 10.1109/jssc.2012.2196318.

[4] K. Park and Z. Chen, “A Double Uneven Power Converter-Based DC–DC Converter for High-Power DC Grid Systems,” *IEEE Trans. Ind. Electron.*, vol. 62, no. 12, pp. 7599–7608, Jul. 2015, doi: 10.1109/tie.2015.2458301.

[5] F. L. Luo and H. Ye, “DC/DC Conversion Technique and Twelve Series Luo-converters,” in *Elsevier eBooks*, 2011, pp. 265–356. doi: 10.1016/b978-0-12-382036-5.00014-8.

[6] M. A. Perez, S. Ceballos, G. Konstantinou, J. Pou, and R. P. Aguilera, “Modular Multilevel Converters: Recent Achievements and Challenges,” *IEEE open J. Ind. Electron.*, vol. 2, pp. 224–239, Jan. 2021, doi: 10.1109/ojies.2021.3060791.

[7] M. Wu, J. Zhao, and Z. Yuan, “Power Bidirectional Flow Converter Based on Linear Phase Shift Transformer,” in *proc. IOP Conf. Series Earth and Environ. Sci.*, vol. 651, no. 2, p. 022014, Feb. 2021, doi: 10.1088/1755-1315/651/2/022014.

[8] A. Poorfakhraei, M. Narimani, and A. Emadi, “A Review of Multilevel Inverter Topologies in Electric Vehicles: Current Status and Future Trends,” *IEEE Open J. of Power Elect.*, vol. 2, pp. 155–170, Jan. 2021, doi: 10.1109/ojpel.2021.3063550.

[9] F. L. Luo, “Double-output Luo converters, an advanced voltage-lift technique,” in *proc. Elect. Power Appl.*, vol. 147, no. 6, p. 469, Jan. 2000, doi: 10.1049/ip-epa:20000622.

[10] A. R. Alonso, J. Sebastian, D. G. Lamar, M. M. Hernando, and A. Vazquez, “An overall study of a Dual Active Bridge for bidirectional DC/DC conversion,” in *proc 2010 IEEE Energy Conv. Congress and Expo.*, pp. 1129–1135, Sep. 2010, doi: 10.1109/ecce.2010.5617847.

[11] Z. Ye, “Dual Half-Bridge DC–DC Converter With Wide-Range ZVS and Zero Circulating Current,” *IEEE Trans. on Power Elect.*, vol. 28, no. 7, pp. 3276–3286, Nov. 2012, doi: 10.1109/tpel.2012.2228278.

[12] F. L. Luo, “Positive output Luo converters: voltage lift technique,” in *proc. Elect. Power Appl.*, vol. 146, no. 4, p. 415, Jan. 1999, doi: 10.1049/ip-epa:19990291.

[13] D. M. Giuliano, M. E. D’Asaro, J. Zwart, and D. J. Perreault, “Miniaturized Low-Voltage Power Converters With Fast Dynamic Response,” *IEEE J. of Emer. and Selected Topics in Power Elect.*, vol. 2, no. 3, pp. 395–405, Jun. 2014, doi: 10.1109/jestpe.2014.2331671.

[14] M. A. Khan, A. Ahmed, I. Husain, Y. Sozer, and M. Badawy, “Performance Analysis of Bidirectional DC–DC Converters for Electric Vehicles,” *IEEE Trans. on Ind. Appl.*, vol. 51, no. 4, pp. 3442–3452, Jan. 2015, doi: 10.1109/tia.2015.2388862.

[15] N. Gupta *et al.*, “Novel Non-Isolated Quad-Switched Inductor Double-Switch Converter for DC Microgrid Application,” in *proc. 2022 IEEE Int. Conf. on Environ. and Elect. Eng. and 2022 IEEE Ind. and Comm. Power Syst. Europe (EEEIC /*

I&Amp;CPS Europe), Jun. 2020, doi: 10.1109/eeeic/icpseurope49358.2020.9160839.

[16] K. Pavithra, H. Pooja, D. Tamilselvan, and T. D. Sudhakar, "Solar power based positive output super-lift Luo converter using fuzzy logic controller," *J. of Phy. Conf. Series*, vol. 2040, no. 1, p. 012034, Oct. 2021, doi: 10.1088/1742-6596/2040/1/012034.

[17] N. F. L. Luo, "Luo-Converters, a series of new DC-DC step-up (boost) conversion circuits," in *proc. of Second Int. Conf. on Power Elect. and Drive Syst.*, vol. 2, pp. 882–888, Nov. 2002, doi: 10.1109/peds.1997.627511.

[18] A. Balestrino, A. Caiti, V. Calabro, E. Crisostomi, and A. Landi, "From Basic to Advanced PI Controllers: A Complexity vs. Performance Comparison," in *InTech eBooks*, 2011. doi: 10.5772/19390.

[19] N. Rezazadeh, "Laser tracker adaptive tuning," *arXiv (Cornell University)*, Jan. 2020, doi: 10.48550/arxiv.2002.03533.

[20] A. O'Dwyer, "A Summary of PI and PID Controller Tuning Rules for Processes with Time Delay. Part 1: PI Controller Tuning Rules," in *proc. IFAC Volumes*, vol. 33, no. 4, pp. 159–164, Apr. 2000, doi: 10.1016/s1474-6670(17)38237-x.

[21] F. G. Shinskey, *Process Control Systems: Application, Design, and Tuning*. McGraw-Hill Professional Publishing, 1996.

[22] C. C. Lee, "Fuzzy logic in control systems: fuzzy logic controller. I," *IEEE Trans. on Syst. Man and Cyber.*, vol. 20, no. 2, pp. 404–418, Jan. 1990, doi: 10.1109/21.52551.

[23] S. Rajurkar and N. K. Verma, "Developing deep fuzzy network with Takagi Sugeno fuzzy inference system," in *proc. 2022 IEEE Int. Conf. on Fuz. Syst. (FUZZ-IEEE)*, pp. 1–6, Jul. 2017, doi: 10.1109/fuzz-ieee.2017.8015718.

[24] A. Basheer and M. Hajmeer, "Artificial neural networks: fundamentals, computing, design, and application," *J. of Microbio. Methods*, vol. 43, no. 1, pp. 3–31, Dec. 2000, doi: 10.1016/s0167-7012(00)00201-3.

[25] A. Borzooy, S. A. Khajehoddin, M. Karimi-Ghartemani, and M. Ebrahimi, "Alternative Control Approach to Achieve Fast Load-Transient Responses in DC–DC Converters," *IEEE Trans. on Ind. Elect.*, vol. 68, no. 12, pp. 12668–12678, Dec. 2020, doi: 10.1109/tie.2020.3040675.