Intelligent control solutions for enhancing dual-fold Luo converter efficiency in EVs

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ABSTRACT

This research proposes the design and application of a smart controller for a dual-fold Luo converter tailored specifically for E-vehicle applications. The dual-fold Luo converter, known for its ability to efficiently step up and step down voltage levels with reduced components, is augmented with a smart control strategy to enhance its performance in the context of electric vehicles. The smart controller utilizes advanced techniques, such as artificial neural networks or fuzzy logic, to adaptively regulate the converter's operation, thereby improving efficiency, transient response, and overall reliability. By leveraging real-time data from the E-vehicle system, the controller dynamically adjusts key parameters to optimize performance under varying load and operating conditions. Key design considerations include the selection and training of the smart controller to achieve desired voltage regulation, efficiency, and robustness in the face of uncertainties inherent in E-vehicle operation. The proposed design methodology is validated through simulation studies, demonstrating superior performance compared to conventional control techniques. The results illustrate the efficacy of the smart controller in enhancing the dynamic response of the dual-fold Luo converter, making it a promising solution for E-vehicle power management systems. This research contributes to the advancement of power electronics in electric transportation, facilitating the development of more efficient and reliable E-vehicle systems in the pursuit of sustainable mobility.

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1. INTRODUCTION

The rapid advancement of electric vehicles (EVs) has highlighted the critical role of power electronics converters in their performance and efficiency [1]. Among these converters, the Luo converter stands out for its ability to efficiently step up or step down voltage levels with reduced components, making it an attractive choice for E-vehicle applications [2]. However, optimizing the control of the dual-fold Luo converter to meet the stringent requirements of electric vehicles remains a significant challenge.

Traditional control techniques, while effective to some extent, often struggle to adapt to the dynamic and nonlinear nature of E-vehicle operation [3]. As a result, there is a growing interest in leveraging smart control strategies to enhance the performance of the dual-fold Luo converter in E-vehicle applications. This introduction sets out to explore the rationale behind incorporating smart control techniques, such as neural networks, fuzzy logic, and adaptive control, into the design of the dual-fold Luo converter for E-vehicle systems [4]. By harnessing the power of artificial intelligence and advanced control algorithms, smart controllers can dynamically adjust key parameters of the converter in real-time, enabling optimized performance under varying operating conditions [5].

The primary objective of this research is to review existing literature on smart control strategies applied to power electronic converters in electric vehicles, with a particular focus on the dual-fold Luo converter. This review will offer insights into the strengths and limitations of various smart control techniques and assess their applicability to E-vehicle systems. This study seeks to propose a novel smart controller design tailored specifically for the dual-fold Luo converter in E-vehicle applications. By drawing upon the principles of neural networks, fuzzy logic, or other smart control methodologies, the proposed controller aims to optimize voltage regulation, efficiency, and transient response, thereby improving overall converter performance.

This research evaluates the effectiveness of our proposed smart controller through comprehensive simulation studies and experimental validation where feasible. The controller aims to outperform conventional control methods in E-vehicle power management systems, potentially offering significant improvements in efficiency and reliability. Our work with smart controllers in dual-fold Luo converters represents a promising step forward in electric vehicle technology. By leveraging artificial intelligence, we're working toward more efficient and sustainable transportation solutions.

Previous research has explored various DC to DC converter topologies for industrial applications. The research documented in [6], which describes a modified Luo converter to improve the charging capabilities of electric vehicles (EVs), is particularly interesting. Their approach focused on two main objectives: simplifying discontinuous conduction mode (DCM) selection processes by reducing sensor requirements, improving power quality while maintaining stable current and voltage levels. Their modified Luo converter achieved notable results in voltage gain through optimized voltage conversion ratios. The charging system proved particularly effective at maintaining battery current within specified parameters across various operating conditions. However, the study revealed some limitations: cost efficiency remained a challenge, higher than desired harmonic content in the output, and room for improvement in overall system optimization.

An innovative converter design for electric vehicle (EV) applications, the super-lift buck converter (SLBC), was implemented [7]. This design combines the advantages of the conventional super-lift Luo topology with those of a buck converter. The primary motivation behind developing this converter was to enhance voltage gain while providing two outputs—one step-up and one step-down—from a single input. Another key benefit is improved power efficiency without the need for additional transformer circuits. The converter's efficiency was evaluated based on loss, root-mean-square (RMS) values, and inductor currents. The SLBC's low conduction loss, high voltage gain, and simple control architecture are among its primary advantages.

An interleaved Luo converter was developed [8] to enhance the power charging capacity of electric vehicle systems while reducing associated costs. The main purpose of this converter was to decrease current stress and switching conduction losses through the integration of the low output and input current ripples. In order to provide a constant and ripple-free voltage for electric vehicle systems [9] upgraded Luo DC to DC converter is designed. In many cases, the Luo converter will reduce parasitic effects and output ripples. Since it permitted greater power density and reduced harmonic distortions, it was more suited for use in EV systems. To improve the efficiency of electric vehicle systems used the voltage lift method is used to create a new design for a multi-port Luo converter [10]. The overall system behavior was assessed by analyzing transient responses, such as settling time and overshoot. Various operating modes were considered for state-space analysis to ensure efficient load power regulation.

By choosing the converter mode that accounts for the main factors of minimized harmonics and enhanced power factor, an optimal regulating technique for improving power factor quality is created [11]. Additionally, the stability of the mechanism has been validated using state space averaging (SSA) modeling. For more voltage gain with reduced power consumption, a flyback converter is designed [12]. Reducing conduction loss, cost consumption, and switching voltage stress to an optimal level was the major objective of this endeavor. At this point, the converter's output has been managed using a guaranteed supply voltage. Optimized power conversion progression by implementing an adaptive controlling system with the modified Luo converter architecture is produced [13]. Improving power transfer gain efficiency whilst decreasing induction losses and output ripples was the main objective of this effort. Additionally, it takes advantage of the best features of both flyback and Luo converter designs, resulting in an enhanced output gain, a simple design, and reduced cost consumption. In their groundbreaking work [14] used a state space averaging DC to DC converter designed to generate a voltage devoid of ripple. The objective of this research was to enhance the voltage transfer gain of the power management system.

A negative output Luo converter that can enhance the efficiency of electric vehicle power transfer and voltage output is proposed [15]. Efficiently controlling motor speeds in response to changing irradiances was the primary goal of this converter. Then, the input voltage, duty ratio, switching frequency, and current ripples were the most important parameters that determined the converter's output. In this instance, the continuous conduction approach resulted in the higher voltage gain. A device known as a single-ended primary inductor converter (SEPIC) was proposed [16] to enhance the efficiency and transfer capacities of electric vehicle power conversion. The converter's strong step-up static gain was its defining characteristic; it allowed it to boost motor performance when operating on a constant DC voltage. In order to increase the input voltage in this system without changing the frequencies, a high-frequency transformer circuitry was utilized.

In order to improve the performance of EV systems, a high-gain interleaved boost converter is suggested [17]. A control method that centered on the radial basis function network (RBFN) was used to maximize the amount of electricity extracted from the solar PV installations. Subsequently, semiconductor devices employed the interleaving method to mitigate voltage stress and current ripples. Brushless DC (BLDC) motors boost solar PV systems' power generation efficiency, which in turn enhances EV systems' efficiency [18]. Reduced losses, assured energy efficiency, and low maintenance costs are the main advantages of using BLDC motors in electric vehicle applications that have been detailed in this work.

The BLDC motor in electric vehicle systems is controlled by the chaotic-based synchronization method implemented [19]. The optimal values for the model's coefficients were found by means of an optimization procedure based on the artificial bee colony (ABC). This regulating technology performance has also been determined using stability analysis and error values. Reduced steady-state error, settling, and overshoot times were some of the advantages of this effort. But it comes with the downsides of more complicated algorithms and less efficient performance. The main research contribution of the work includes:

- Development of a smart controller for the dual-fold Luo converter – proposed an intelligent control strategy utilizing artificial neural networks (ANNs) to enhance the performance of the converter in E-vehicle applications.
- Real-time adaptive control – implementing a control mechanism that dynamically adjusts key parameters based on real-time data from the E-Vehicle system, ensuring optimal performance under varying load and operating conditions.
- Enhanced performance metrics – improving the efficiency, transient response, and overall reliability of the dual-fold Luo converter compared to conventional control techniques.
- Validation through simulation studies – demonstrating the effectiveness of the proposed smart control strategy through simulation, showcasing superior performance in terms of dynamic response and efficiency.
- An attempt has been made in this work to design and simulate PI, neural network controller, and fuzzy logic controller for regulating the output voltage for a positive output dual-fold Luo converter.

2. DUAL FOLD LUO (DFLUO) CONVERTER

The dual-fold Luo (DFLuo) converter offers an elegant solution for generating a regulated DC output from unstable DC power sources. This specialized Luo converter variant achieves power control through dynamic gain adjustment, primarily serving to boost the voltage delivered to the load. The basic circuit configuration is illustrated in Figure 1.

For designing the DFLuo converter, several key parameters must be carefully considered. The inductors L_1 and L_2 are particularly crucial, and their values can be determined using (1).

$$L_{1,}L_2 = \max(d) \times \left(\frac{min(V_{in})}{\Delta I_o \times f_s}\right) \quad (1)$$

Here, ΔI_0 represents load current variation, Ts is the sampling period, d denotes duty cycle, and V_{in} is input voltage. The load current variation at the output can be calculated as (2).

$$\Delta I_o = I_o \frac{(V_o \times T_h)}{min(V_{in})} \quad (2)$$

Where V_o represents the desired output voltage and L indicates the ripple current threshold at the output. The relationship between output voltage and switching duty cycle as (3).

$$V_o = V_{in} \left(\frac{4-d}{1-d}\right) \quad (3)$$

During switch-on periods, the capacitor supplies the output current while the inductor charges. For a comprehensive analysis, we can calculate the RMS currents at both input and output: Input RMS current as (4) and (5).

$$I_{CO}(RMS) = I_o\sqrt{\left(\frac{(V_o+V_D)}{\min(V_{in})}\right)} \quad (4)$$

$$I_{Cin}(RMS) = \frac{\Delta I_o}{\sqrt{\varphi}} \quad (5)$$

Where V_f represents the voltage drop across diodes D1 through D4, and n indicates the number of switching events. Finally, the output capacitance can be determined using (6).

$$C_o = \frac{I_o \times d}{V_r X_a X f_s} \quad (6)$$

Where Xα represents the half-cycle impedance rate in duty cycle d, V_r is the ripple voltage, and X_{fs} denotes the impedance at switching frequency.

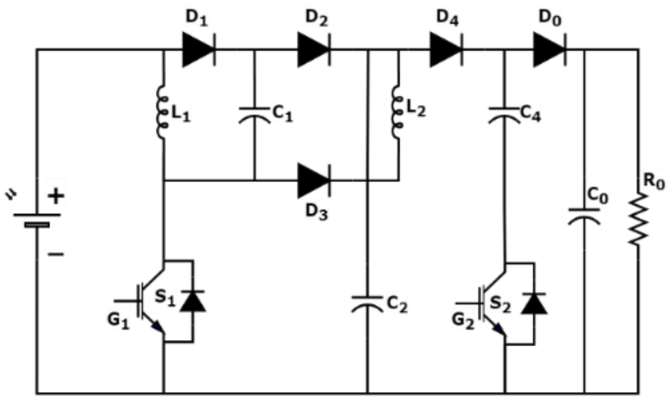


Figure 1. Schematic representation of DF Luo DC to DC converter

3. DESIGN OF PI CONTROLLER

Among the various feedback control systems used in engineering, the proportional-integral (PI) controller stands out [20]. A PI controller calculates and applies a corrective action to minimize the deviation of the process variable from a set point. The PI controller operates based on two distinct parameters: proportional and integral values.

In a proportional controller, the measured process variable is compared to the set value, generating an error variable. This error is then multiplied by a constant gain and sent to the system. While this improves time responsiveness, it introduces an offset relative to the target value.

So, to improve on this, an integrated controller that eliminates the offset was implemented. In most cases, an integral controller with proportional which is also called as proportional integral is employed. The system is fed the total of the errors multiplied by the proportional constant and the integral of the errors.

The gain of a proportional controller is K_p whereas the gain of an integral controller is K_i.

$$u_c = K_p e + K_i \int_0^t edt \quad (7)$$

In this work, a PI controller is employed for the designed converter to regulate the output voltage at a specified value despite fluctuations in the load, set point, noise effects, modeling error, or component variations. If the gains K_p and Ki are calculated correctly, the PI controller will be operated effectively. The main goal is to tune the controller. There are methods for fine-tuning the settings. Ziegler Nicholas tunneling is a popular tuning method, although it is a complicated process.

4. FUZZY LOGIC CONTROLLER

Fuzzy logic controllers (FLCs) are widely used in the control of DC-DC converters due to their ability to effectively handle nonlinearities, imprecise modeling, and variable operating conditions [21]. The following section explains the implementation steps for the FLC application to DC-DC converter control:

i) System modeling: Before implementing an FLC, a mathematical model of the DC-DC converter must be developed. This model defines three key parameters—input voltage, output voltage, and control input duty cycle. Although the model is often simplified due to the nonlinear nature of DC-DC converters, it serves as the foundation for designing the FLC.

ii) Fuzzy input variables: FLCs require input variables that represent the converter's current operating conditions. Common input variables for DC-DC converters include the error between the desired and measured output voltage, the rate of change of error (to account for dynamic behavior), and possibly input voltage or load current. These variables are fuzzified, meaning they are mapped to fuzzy sets using membership functions to capture imprecision, as shown in Figure 2.

iii) Fuzzy rules: The control rules for an FLC are typically expressed in the form of "if-then" statements, connecting fuzzy input variables to fuzzy output variables. These rules are derived from the knowledge and expertise of the control system designer and often take the form of linguistic rules. For example, "If the error is large and the change in error is increasing, then increase the duty cycle".

iv) Fuzzy inference: Using the present input data, the fuzzy inference engine evaluates the fuzzy rules. It computes the degree to which every rule is satisfied (firing strength) and combines these degrees using fuzzy logic operators (e.g., max-min) to determine the fuzzy output.

v) Fuzzy output variables: The fuzzy output variables represent the control actions to be taken. One of the most common output variables in DC to DC converters is the duty cycle change, sometimes called delta duty cycle. The fuzzy output is computed based on the firing strengths of the rules.

vi) Defuzzification: The fuzzy output needs to be defuzzied to obtain a crisp regulator signal, which is the actual variation in duty cycle applied to the converter. Common defuzzification methods include centroid, mean of maximum, or weighted average.

Using FLCs for DC to DC converter control can lead to robust and adaptive control strategies that perform well under varying operating conditions and system uncertainties [22]. FLCs are useful in power electronics and control systems because of their ability to tolerate disturbances such as sudden changes in load, input voltage variations, and other disturbances.

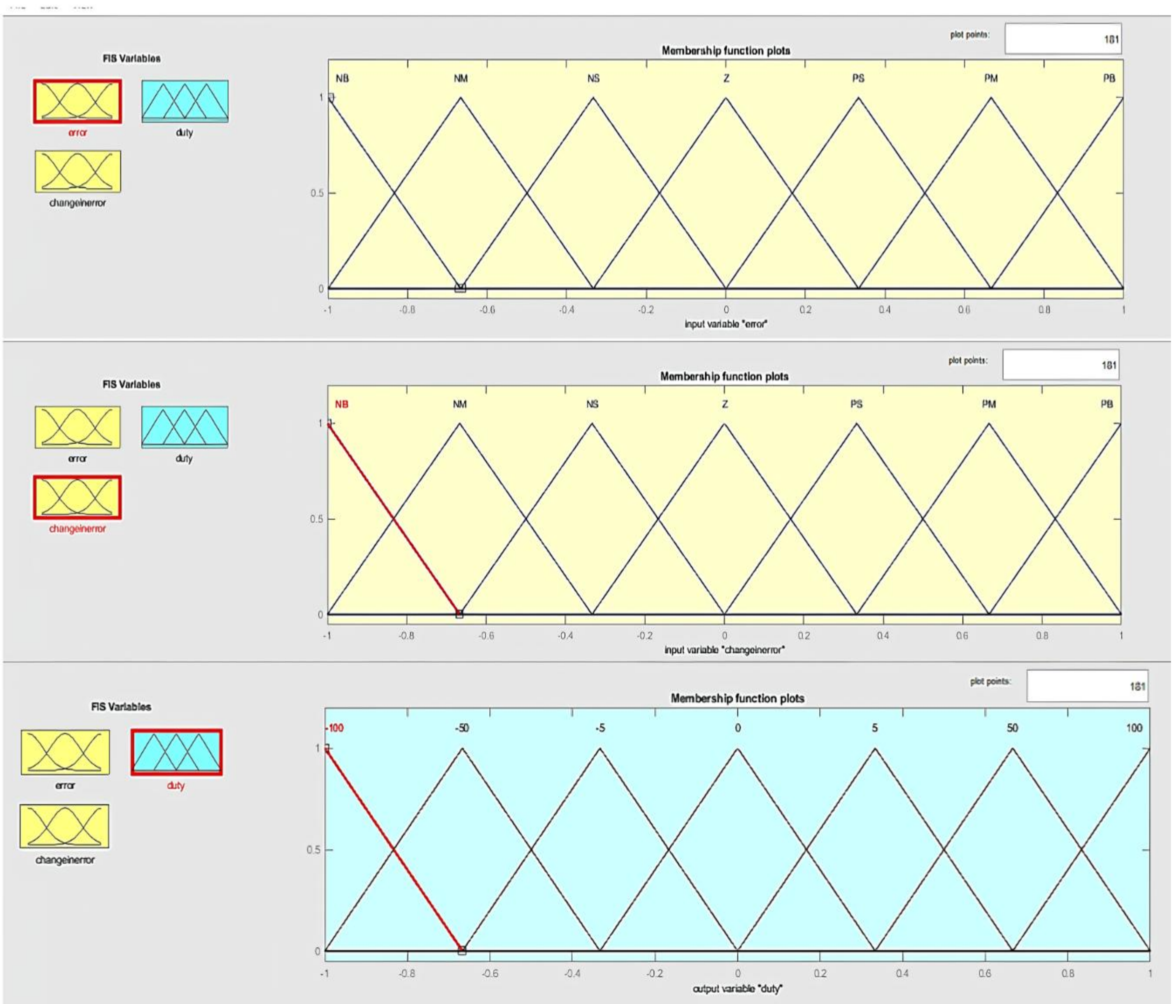


Figure 2. Fuzzy input variable (error, change in error) and output membership function duty ratio

5. NEURAL NETWORK CONTROL

To operate the converter in a closed-loop configuration, in the field of power electronic converter control, various controllers are gaining popularity, including proportional-integral, sliding mode, fractional-order, and artificial intelligence-based controllers. Among artificial control approaches, neural network control is widely used due to its rapid responsiveness and precision [23].

Neural network control is inspired by the functioning of neurons in the human brain. The interconnection of neurons in the brain is referred to as a neural network, and when this concept is adapted for physical systems, it is known as an artificial neural network (ANN). This control approach falls under the category of nonlinear control, enhancing system robustness, improving efficiency, and making the system more effective [24].

A neural network consists of multiple neurons, which serve as processing units or cells. These units are interconnected through specialized links, similar to neurons in the human brain, with each connection assigned a weight. The assigned weight represents the information necessary for problem-solving.

This ANN control is becoming increasingly important in the regulating of DC to DC converters. These converters are regarded extremely nonlinear because of their fast switching frequency and the quick change in the conditions of the energy storage element. Furthermore, developing the mathematical model of this sophisticated DC to DC converter is difficult [25]. As a result, neural networks perform well for the proposed converters.

In this work, a neural network (NN) controller is implemented for the converter. The MATLAB 'nf tool' is utilized for designing the controller. To ensure optimal performance, a quasi-Newton backpropagation algorithm is applied to the ANN for weight updates.

The performance of the neural network is evaluated using the mean square error (MSE) criterion, which measures the average squared error between the desired and actual output. The block diagram of the NN-based Luo converter is presented in Figure 3.

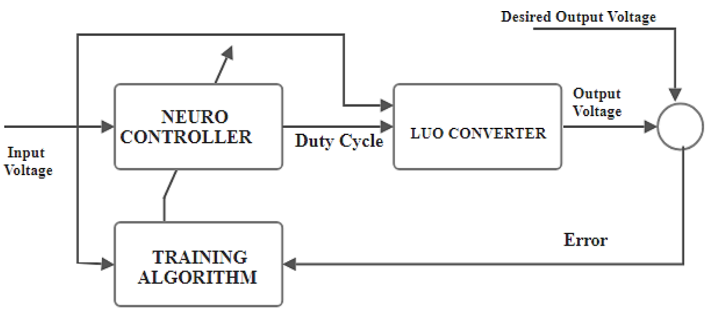


Figure 3. Block diagram NN controller-based Luo converter

6. RESULTS AND DISCUSSION

Here, a number of metrics are used to validate the modeling and comparative study of the suggested converter and regulating approaches. Voltage at output, rising and peak times, settling times, steady-state errors, and peak overshoots are all part of it. By extracting scope data from various locations of the circuit, the suggested converter and controlling architectures are validated using the MATLAB/Simulink tool for validation of the results. The DFLuo converter components values are given in the Table 1.

6.1. PI controller for DFLuo converter

The performance of the proposed converter, using the designed PI controller with values $K_p = 0.1305$ and $T_i = 0.0016$, is shown in Figures 4 and 5. For an input voltage of 100 V, the dual-fold Luo (DFLuo) converter generates an output voltage of 300 V at a duty ratio of 0.5.

Table 1. DFLuo converter components values

Converter Parameter	Specification
Input voltage	40 V
Output voltage	300 V
Duty ratio	0.3 – 0.9
Switching frequency	50 KHz
Inductor L_1& L_2	2.2 mH
Capacitor C_1, C_2 & C_3	100 µF
Capacitor C_4 & C_o	220 µF

Hence, for efficiency considerations, the proposed converter operates with minimal switching losses and optimized control parameters, contributing to improved efficiency in electric vehicle applications. Moreover, for transient response evaluation, the simulation results highlight the settling time and overshoot characteristics of the system, indicating the effectiveness of the PI controller in achieving a fast and stable response.

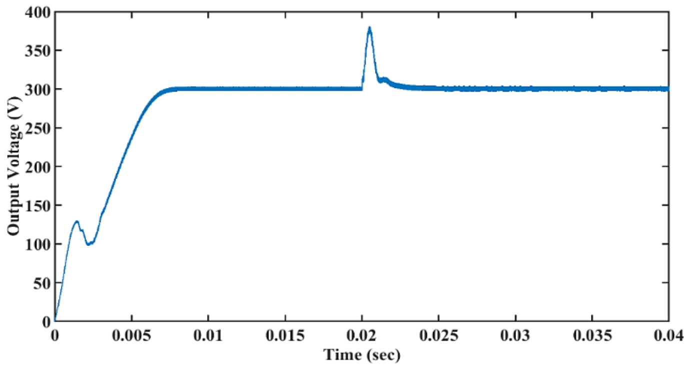


Figure 4. Voltage of PI controller-based DFLuo converter (25% input voltage variation)

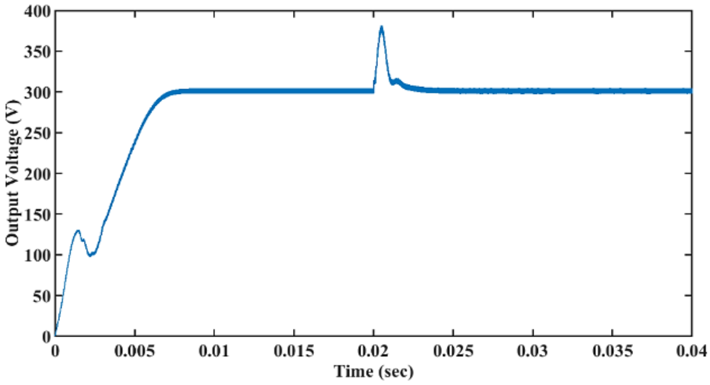


Figure 5. Voltage of PI controller-based DFLuo converter (25% load variation)

6.2. Fuzzy logic controller for DFLuo converter

For closed-loop control, many controllers are employed. The proportional integral controller works well for controlling DFLuo converters, but tweaking the parameters in higher-order systems is challenging since it needs the entire system model. This fuzzy controller was utilized to address the problem. The fuzzy controller does not need a thorough modeling of the system, but it does necessitate knowledge about the system in order to build the rules. In this research, a fuzzy controller with a DFLuo converter is used.

The fuzzy controller design approach consists of three stages: fuzzification, fuzzy rule base creation, and defuzzification. The controller has two inputs: one for errors and one for error changes. The fuzzy controller receives its error input from the optimized PI controllers, which is the voltage differential between the converter's output and a reference voltage. This smart controller's output is a duty cycle that regulates the switching device.

The seven membership functions, which are triangle functions with a range of -1 to 1, are used to identify the two inputs and outputs. For fuzzy control, the Mamdani architecture is employed, and 49 rules are generated that are inferred by the rule base using max-min composition, and for defuzzification, the center of gravity approach is used to produce the crisp value of output.

The operational results of the converter in supply and load rejection modes are presented in Figures 6 and 7. The obtained results indicate that proper control of the switching devices using the generated control pulses effectively enhances the converter's output voltage. The results further demonstrate that the implemented control strategy minimizes voltage fluctuations and improves system stability under varying load conditions. Additionally, the proposed converter exhibits a rapid transient response, with reduced overshoot and steady-state error, ensuring reliable performance. The ability to maintain a stable output voltage despite supply and load variations highlights the robustness of the proposed control mechanism, making it well-suited for electric vehicle applications.

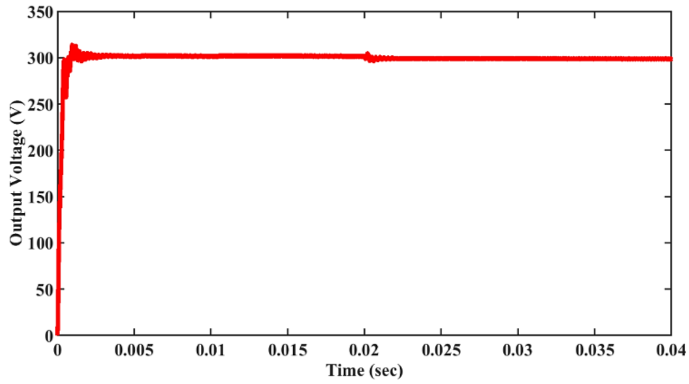


Figure 6. Voltage of FLC-based DFLuo converter (25% supply variation)

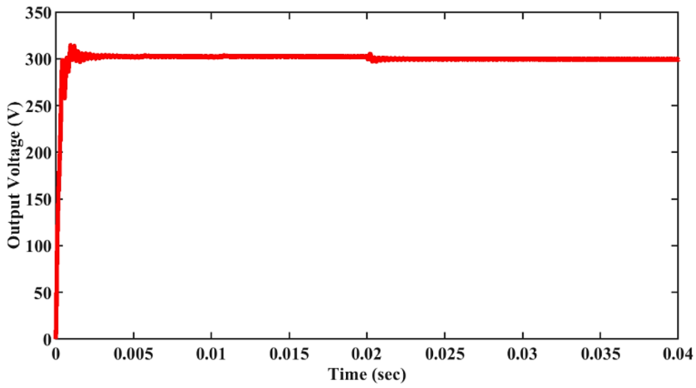


Figure 7. Voltage of FLC-based DFLuo converter (25% load variation)

6.3. Neural network controller for DFLuo converter

Artificial neural network (ANN) control was implemented for DFLuo converters using MATLAB, as in Figure 8. The controller was programmed to operate at a 50% duty ratio, and the results for output voltage under supply and load rejection modes are presented in Figures 9 and 10. The performance of the control approaches was evaluated and compared using key metrics, including overshoot, steady-state error, peak time, settling time, and rise time.

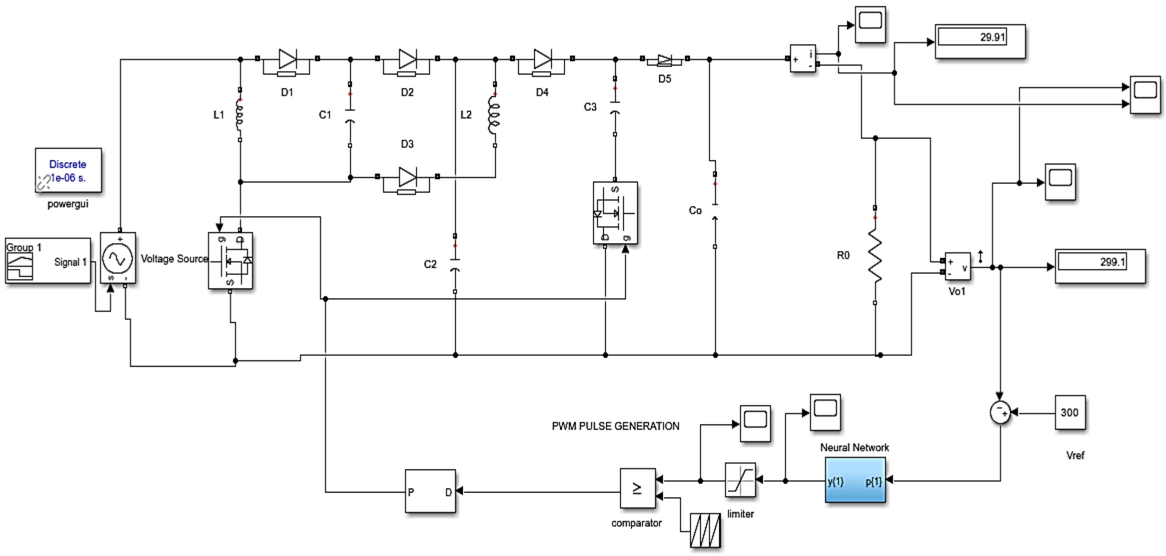


Figure 8. Simulation diagram of DF LUO converter with ANN controller

Figures 11(a), 11(b), and Figure 12, along with Table 2, compare the proposed methodologies based on time under supply rejection conditions. Lower values for these metrics indicate improved system performance. The results show that, compared to the Ziegler-Nichols PI (ZN-PI) controller, the smart controllers achieved lower rise time, peak time, and settling time. The overall response time has been significantly reduced compared to previous methods, primarily due to the efficient operation of the switching devices used in the converter circuit.

Table 2. Performance evaluation of controllers for DFLuo converter

Controllers	Rise time (msec)	Peak time (msec)	Settling time (msec)	Under a supply disturbance	
				Peak over shoot (%)	Settling time (msec)
PI	7	6.25	7.5	23.33	0.25
FLC	3	1.75	4.5	1.66	0.1
NNC	2	1	3.3	3.33	0.2

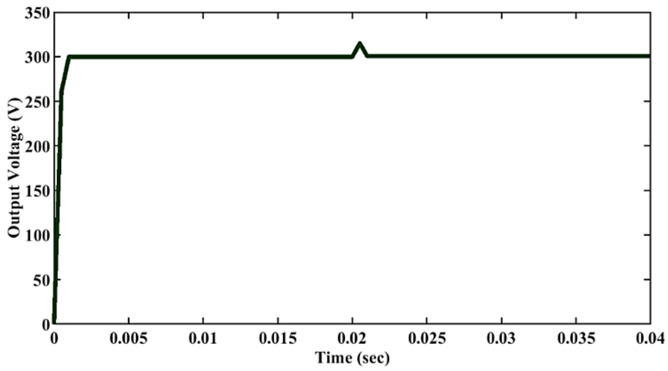


Figure 9. Voltage of NNC-based DFLuo converter (25% supply variation)

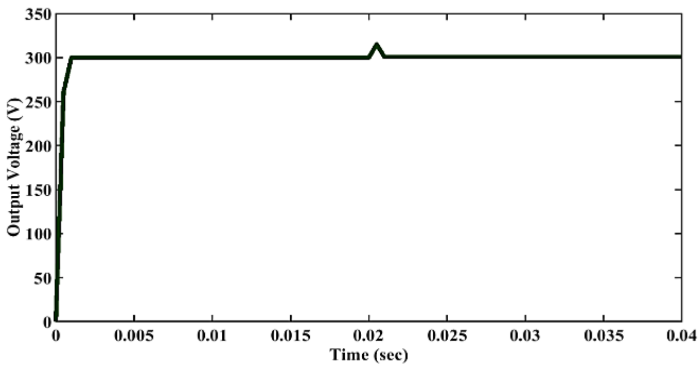
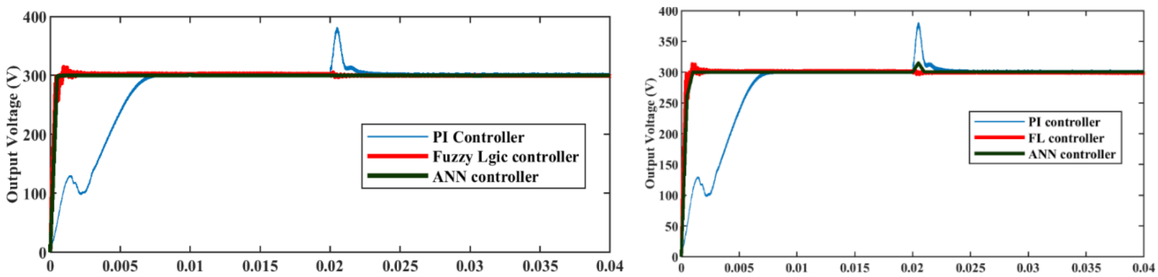


Figure 10. Voltage of NNC-based DFLuo converter (25% load variation)



(a) (b)

Figure 11. Performance of ZN-PID, FLC, and NNC for the DFLuo converter under:
(a) supply disturbance and (b) load disturbance

When all proposed controllers were compared at a 50% duty ratio, it was found that the neural controller provided the smoothest response with the shortest settling time and rise time than the other controllers. Hence, the neural controller demonstrated a significantly improved transient response, reducing overshoot and achieving faster stabilization compared to conventional controllers.

Table 3 shows the comparison of the efficiency of different DC-DC converters. The results show that the proposed DFLuo converter outperforms the other converter, with an efficiency of 95.12%. Compared to existing converters such as boost converter, cuk converter, interleaved boost converter, and interleaved cuk converter, the proposed DFLuo converter offers improvement in efficiency.

It also includes adaptive learning capability; unlike traditional controllers, the neural controller adapts to variations in operating conditions, making it more robust against disturbances in input voltage and load fluctuations. Moreover, the neural network controller has minimized steady-state error. The ANN-based controller effectively reduces steady-state error, ensuring precise voltage regulation and improved system stability.

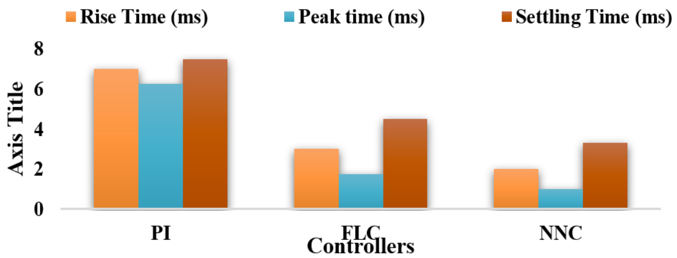


Figure 12. Comparative analysis of the performance of DFLuo converter with smart controllers

Table 3. Efficiency comparison of DC-DC converters

Controllers	Rise time (msec)
Boost converter [23]	83.95
Cuk converter [11]	84.23
Interleaved boost converter [26]	84.85
Interleaved Luo converter [6]	85.11
Proposed DFLuo converter	95.12

7. CONCLUSION

Recent advancements in power electronics have led to the innovative design of a DF Luo converter for voltage boost applications. This novel structure, with an intelligent control approach, offers several key advantages. Notably, it enables a wide voltage range while maintaining a simplified control mechanism. The design achieves higher voltage gain without relying on traditional electromagnetic components, thereby reducing conduction losses.

A comparative analysis of two smart control approaches, fuzzy logic versus neural networks, was presented to validate the performance of the converter. Both control strategies effectively maintained a stable DC voltage output, even under challenging conditions such as line fluctuations and load disturbances. The ANN controllers give a smooth response with better regulatory performance. The outcomes illustrate the suitability of the proposed system for EV applications, yielding a maximum DC output voltage of 300 V with an efficiency of 95.12 %.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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R. Ramya	✓			✓		✓	✓			✓	✓			✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [PSV], upon reasonable request.

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