Research Article

Comparison of an AI-Based Controller for a Positive Output Superlift DC-DC Converter

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Abstract: DC-DC converters have emerged as crucial components in various industrial applications and form an integral part of power supplies based on switch-mode. Solar energy has garnered increasing significance owing to the scarcity of non-renewable fuels and its abundant availability. Photovoltaic (PV) technology, characterized by the arrangement of numerous series and parallel-connected PV cells within modules, generates DC output. Consequently, the demand for DC-DC converters has risen to elevate voltage to desired levels and optimize solar power output. While conventional boost converters have gained prominence, they exhibit limited gain and introduce voltage ripples, necessitating the addition of filters. This, however, results in increased system size and cost. To address these challenges, this paper introduces a topology for DC-DC conversion that is based on the voltage lift technique, which is capable of geometrically progressing voltage enhancement. Closed-loop control becomes indispensable to enhance system efficiency and stability. This paper employs optimized proportional-integral controllers and intelligent controllers like fuzzy logic and artificial neural networks to precisely regulate the positive output converters. With these controllers' use, the system's dynamic response has been improved.

Keywords: DC-DC Converters, Photovoltaic (PV), Positive Output Super Lift Luo Converters, Artificial Neural Network

Introduction

Nowadays, DC-DC converters are an integral part of various power electronic-based applications. Due to the diminishing of fossil fuels, renewable energy sources are gaining importance, especially solar. Also, for charging and bidirectional flow of power in electric vehicles, DC-DC converters are employed. However, the performance of conventional DC-DC converters such as buck, boost,buck-boost, Cuk, and zeta (Athikkal et al., 2017) is satisfactory. However, these have limitations like limited voltage transfer gain and ripples in the output as a result of parasitic elements (Kwasinski, 2009), which affect the application's performance. In order to overcome this, Luo developed converters based on the voltage lift technique in seven series. This series of converter voltage gain enhancement is based on the arithmetic progression. There is another series voltage lift converter based on geometric progression, known as the positive super lift Luo converter. These converters have more voltage transfer gain, and the effect of the parasitic elements is reduced. These superlift converters (Luo, 2001) are further divided into five main series depending upon the placement of the switching device and have different numbers of capacitors and inductors. These five series are the main series, additional series, enhanced series, Re-enhanced series, and multi-enhanced series of converters. These five series are further categorised as elementary circuits, re-lift circuits, triple-lift circuits, and so on, and termed as n = 1,2,3, respectively (Lin Luo and Ye, 2003). This type of converter is finding application in solar-powered systems where it is required to boost the voltage (Dasari and Immanuel, 2018) in vehicular technology to charge the batteries, and hence reduces the charging time, high voltage DC transmission, traction systems, etc. The main series converter up to the order n = 2 is presented in this paper. Controllers like proportional, integral, and fuzzy, artificial intelligence are employed, and comparative analysis by altering duty cycles is done.

Closed-loop control of the converters is preferred because of the more stable response and self-adaptability (Biswal, 2012) of the system. Various control techniques suited well for converters like PI, fractional order partial control, sliding mode control, fuzzy control, artificial neural network control, etc. Each controller has its own implications, and artificial neural control is applied in this paper.

Materials and Methods

The performance of DC-DC converters is impacted by their inherent resistance of inductors and capacitors, i.e., the parasitic elements which produce the ripples in the output parameter (Banaei and Sani, 2018). The series of the converter eradicates the effect of the parasitic element. To acquire the optimum performance, closed-loop control techniques like Proportional Integral, Fuzzy, and Artificial Neural Network are implemented. To optimise the performance of the controller, the particle swarm optimization technique is implemented. Photovoltaic system voltage needs to be boosted while feeding to the grid or when used for the charging of electric vehicles and many other photovoltaic applications. DC-DC Boost converters (Forouzesh et al., 2017) and positive output superlift converters are applied for this purpose, and an artificial intelligence technique for tracking the maximum power is employed, and their performance is compared.

Positive Output Superlift DC-DC Converter

These voltage changers are essential in various industrial applications involving power conversion, photovoltaic systems, and electric vehicles (Camara et al., 2009) Several topologies exist for these converters, with the buck, boost, and buck-boost being common ones. Although these converters are widely used, they face limitations in voltage transfer gain caused by parasitic elements, leading to output ripples. To reduce these ripples, additional filter components are required, which increase the size of the converters; however, today there is a growing demand for compact switched-mode power supplies. To address these issues, an alternative is the use of converters based on the voltage lift technique. This technique, commonly used in analog circuits, involves charging a capacitor at one stage to boost the voltage level (Han et al., 2018) and then using that boosted voltage at another stage. In voltage lift converters, the voltage is increased using an arithmetic progression, whereas super lift converters increase voltage through a geometric progression (Athikkal et al., 2018).

These converters are further dismented as Deepa et al. (2017):

- Main series: Single semiconductor toggle, n coil, 2 n condenser (3 n-1) diodes for n stages
- Additional series: Comprises one solid state device, n coils, 2 (n+1) condensers, 3 n+1 diodes for n stages
- Enhanced series: One solid state device, n coils,4 n condenser (5 n-1) diodes for n stages
- Re-enhanced series one solid state device, n coils, 6 n condensors (7 n-1) diodes for n stage
- Multi-enhanced series of converters: It has *j* times enhanced series with one semiconductor device, n inductors,2 (1+j) n condensors [(3+2j) n-1] diodes for n stages

Each of the series converters is further divided as elementary, relift, triple lift, quadruple, and so on, and named as n = 1,2,3.

In this paper, the elementary and re-lift topology of the DC-DC converter is analyzed (Dasari and Immanuel, 2018).

Elementary Main Series Positive Output Superlift

The elementary main series converter is shown in Fig. 1.

The circuit consists of one switching device, either MOSFET or IGBT, which are preferred nowadays, two diodes, two capacitors, and an inductor (Manikandan and Vadivel, 2013).

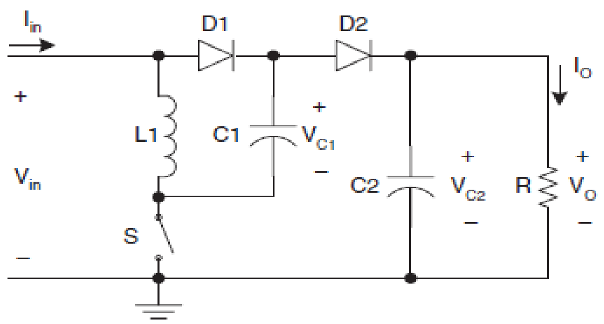

Fig. 1: Elementary main series converter

When the switch is turned on, the current goes through L, and the capacitor is charged to the voltage VC1. The voltage across the capacitor and current in the inductor increase as the input voltage increases during the turn-on time of the switch. Figure 2 shows the turn time of the During the turn-off time of the switch, current through the coil decreases, and the voltage reaches –(V0-2Vin). Switch-off mode is shown in Figure 3.

The voltage transfer gain is given by:

$$G = \frac{Vo}{Vin} = \frac{2-k}{1-k} \quad (1)$$

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Output voltage ripple is given by:

$$\Delta vo = \frac{\Delta Q}{C2} = \frac{Io(1-k)T}{C2} = \frac{1-k}{fC2}\frac{V0}{R} \quad (2)$$

Re-Lift Main Series Positive Output Superlift Converter

The re-lift circuitry of the main series is shown in Figure 4.

The circuit contains one switching device, three inductors, five diodes, and four capacitors.

As the switch changes to the active state, C1 is charged to Vin, and the potential across C2 is Vin, which can be found by Equation 1. The potential across C3 is also Vin, and the current through the coil increases. The turn-on mode is shown in Figure 5 (Navamani et al., 2015).

As the device is turned off, the current flowing through the inductor decreases with voltage –(V0-2Vi).

The voltage gain is given by:

$$G = \frac{Vo}{Vin} = \left(\frac{2-k}{1-k}\right)^2 \quad (3)$$

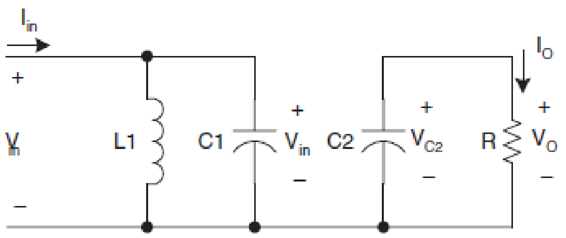

Fig. 2: Turn on the mode of the converter

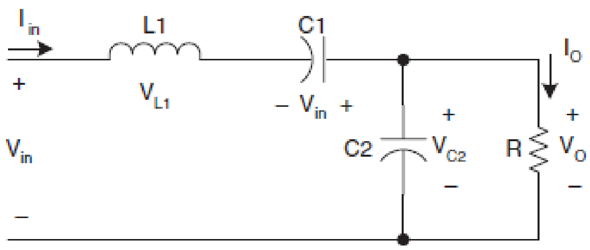

Fig. 3: Turn off time

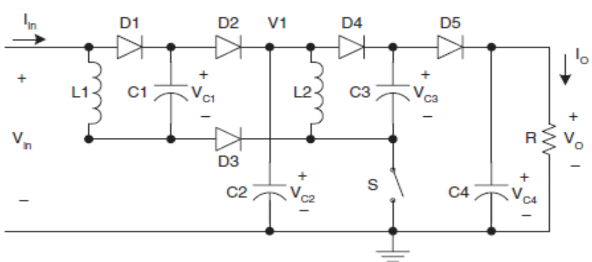

Fig. 4: Relift main series converter

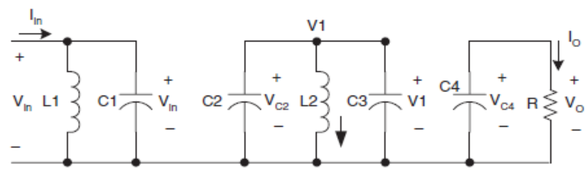

Fig. 5: Turn on the mode of the relift positive output super lift converter

Closed-loop and open-loop control can be implemented for these converters, but with feedback, it is more stable. There are various closed-loop control techniques. Artificial neural network control is applied in this paper and is described in the next session.

Converter Using PI Controller

To obtain a stable response, loop control is preferred. Conventional controllers are proportional, Proportional Integral (PI), and Proportional Integral Derivative (PID) (Han et al., 2018).

In a Proportional controller, the output is compared with the reference, and the error is then multiplied by the constant gain and finally fed to the system (Hauke, 2011). This enhances the time response, but there is an offset concerning the desired value.

So, in order to improve upon this, an integral controller was introduced, which eradicates the offset. For better results, PI is used. The sum of the error is multiplied by a proportional constant, kp, and the gain of the integral controller is termed Ki. In this work, the PI controller is used for the positive output superlift converter to maintain the output voltage of the converter at a desired value in case of any variations due to certain disturbances.

If the values of Kp and Ki are optimum, then the system works efficiently. Tuning of the controller is the major task. There are techniques available to tune the parameters. Ziegler-Nicholas tunneling is one of the common tuning methods, but it is a complex methodology. In this work, PI controllers are tuned using the Particle Swarm Optimization (PSO) technique to get the optimum values of Kp and Ki.

The PSO technique works with the target to minimise the mean square error. The error is the difference between the obtained and the desired values, and then implement it for converter control. Using MATLAB, an algorithm is implemented to obtain the optimised values of gain using PSO.

The conventional PI controller works efficiently for low-order superlift converters, but developing the mathematical model of the converter needed for the PI controller is complex.

So, to overcome these disadvantages, controllers based on intelligent techniques are more suitable. They are easy to implement and have faster dynamic response.

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Fuzzy Logic Controller

Due to their high switching frequency, DC-DC converters are considered highly nonlinear. So it is troublesome to obtain a mathematical model and implement a conventional controller on it. To overcome these, intelligent controllers are becoming important. The fuzzy controller is applied to the positive output superlift converter (Kwasinski, 2009).

The knowledge-based system, namely fuzzy, can solve the issue to an extent. That requires expert knowledge of the process. The concept of fuzzy is basically in terms of the belongingness of a parameter in the process. It deals with the fuzzy values instead of the crisp values.

In this, a space is defined in which inputs and outputs are defined in terms of linguistic variables, which are further defined by curves of membership function. The standard logical operations, such as AND, OR, and NOT operations, are used to find the extrema. The inputs are related to the output by forming the if-then rules in the rule base of Fuzzy. The rules are interpreted by using the Sugeno controller or Mamdani controller of Fuzzy logic and then defuzzified to obtain the crisp values.

The fuzzy logic controller has the following components, as shown in Figure 5:

1. Fuzzifier: It takes the data in the form of crisp values, converts it into linguistic variables, and defines it in terms of a membership function using the knowledge base
2. Inference engine: In a fuzzy, fuzzy input is formed and processed by the inference engine. The inference is based on the if-then rules formed on the knowledge base of the system and generates the fuzzy output. Inference can be done by using Sugeno or Mamdani-based inference systems
3. Defuzzifier: converts the fuzzy values into crisp values
4. Knowledge base: It comprises inputs, outputs, and a rule base comprising rules to interpret the relation between input and output

The duty ratio of the switch can be controlled using this controller. In this paper, a fuzzy controller, in addition to PI, is used to generate the gating pulse.

An error signal is generated after the comparison with the reference and then fed to the PI controller, which is further given to the fuzzy controller. Here, two two-input fuzzy controllers are implemented, with one as the difference between the actual and reference values obtained from the PI, commonly known as the error, and the other as the change in error. This input is received from the PI controller, which is tuned using particle Swarm Optimization.

For fewer orders, a converter with fuzzy and PI works well as it improves the dynamic response.

For higher-order systems, fuzzy is used to remove the complexity of modeling. In this paper, a fuzzy controller combined with a PI controller is implemented.

There are two inputs: the error signal tracing the output voltage and the change in error. Each input has seven triangular membership functions ranging. There are seven triangular membership functions, and depending upon these, 49 rules are framed to infer the output.

Artificial Neural Network (ANN) Control

It is always desirable to use the converter in its closed-loop control mode. There are various controllers like proportional integral, sliding mode control, and fractional order partial control, and there are also controllers based on artificial intelligence techniques (Lin et al., 2003) that are gaining great importance in the field of power electronic converter control. Due to the fast and robust response, ANN is preferred. This control is basically a replica of the functioning of neurons in the human brain. It is a cluster of neurons, similar to those found in the brain. When this network is approximated to work for physical devices, the system is termed an artificial neural network.

These schemes, which branch under nonlinear control techniques, enrich the robustness, thus increasing the efficiency of the system, making it more effective.

A general characterization of the neural network is based on the following features:

- The way of interconnecting neurons is termed its architecture
- The procedure to determine the weights is termed training of the network
- The activation function required

A neural network contains a large number of neurons, which are the processing elements called units or cells. These cells are interconnected through links similar to neurons of the brain, and each is assigned a particular weight. The weight assigned represents the information required to be solved.

This ANN control is of great importance in controlling the DC-DC converter. These converters are considered to be highly nonlinear as they have high switching frequency, and the conditions of energy storage elements also change rapidly. Due to the high switching rate of the switch in the converter, it is challenging to develop a mathematical model. So, neural networks work well for positive output superlift converters, as shown in Figure 7.

In this paper, the artificial neural network control is applied to a voltage lift-based converter. For the implementation of the controller, the NF tool of

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MATLAB is used. ANN controller uses the quasi-Newton backpropagation algorithm to optimise weights.MSE is analysed for evaluating the performance of the ANN. This work has selected the LEARNGDM learning function based on gradient descent with a learning rate of 0.01 and a momentum factor of 0.9. Figure 6 shows a block diagram of the ANN-based positive output superlift converter.

When applying the backpropagation algorithm, the activation function must be differentiated. So, the differentiable activation function should be selected. The commonly used soft computing functions are logistics and sigmoid, as they are differentiable. To make learning easier, the linear output nodes are preferred. By using the linear activation function, the output range does not compress.

Therefore, for hidden layers, a bipolar sigmoid function is used, and for output (Luo, 2001), a linear activation function is applied. To determine the size of the neural network, there is no exact procedure based on the trials carried out to obtain the maximum accuracy with reduced neurons in the size of the network (Manikandan and Vadivel, 2013).

The ANN is a feed-forward network with a number of neurons in the input layer is two, in the hidden layer is 10 neurons and in the output layer, there is 1 neuron.

The converter's output voltage is fed to the optimized PI controller and then fed to the ANN block.ANN controls the duty ratio of the converter so as to provide the optimum output (Jayachandran et al., 2015).

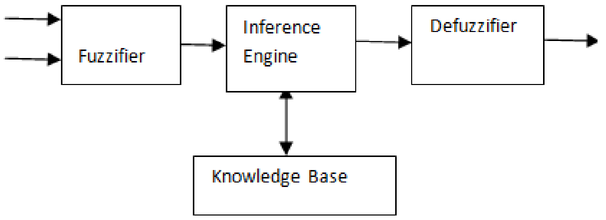

Fig. 6: Block diagram of fuzzy controller

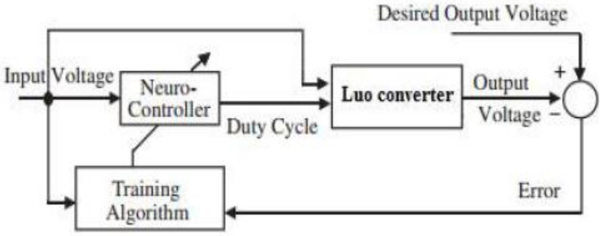

Fig. 7: Block diagram of ANN-based DC-DC converter

Results and Discussion

Performance of PI Controlled Main Series-Elementary Converter

The closed-loop control of the system is desirable to achieve a stable output and improve the dynamic response. Proportional-integral control is applied to the converter to control the duty ratio of the switch. The voltage control mode of the converter is used in the work.

The difference between the reference value and the output voltage obtained is given to the PI controller, which is tuned with the particle Swarm Optimization technique. The main task of the optimization technique is to determine the values of the constant such that the output value of the converter is kept close to the set point.

The optimization function was to be taken as:

$$F = \min MSE$$

The Program for calculating the proportional and integral constant values was developed in MATLAB. The following values chosen while applying the particle swarm optimization techniques are in Table 1.

The output of the controller is compared with the reference signal, which is the triangular waveform of high frequency and is controlled to generate the firing pulse of the switching device. The duty ratio can be controlled by controlling the modulating signal. The PI controller was applied to the main series –elementary positive output superlift converter. The load voltage, load current, and input current waveform have been plotted for different duty cycles such as k = .33,.4, and .5.the settling time has been calculated, and it was observed that it is reduced as the duty ratio is increased.

Optimized values of P&I are:

- ✓ Kp: proportional constant = .47
- ✓ Ki: integral constant: 33.3

A reduction in settling response will make the system fast and improve stability. The simulation results are shown in Figures 8-10.

As the duty cycle increases, voltage gain also increases, and the settling time decreases, as shown in Table 2.

Positive Output Superlift Converters Using Fuzzy Controller

There are different controllers used for the closed-loop control. A proportional Integral controller serves well for the control of positive output superlift converters, but for a higher order system, the tuning of the parameters is difficult as it requires the complete model of the system.

Table 1: Parameters of particle Swarm optimization

C1	1.4	win	4
C2	1.2	Population Size	20
wmax	0.9	Number of iterations	25

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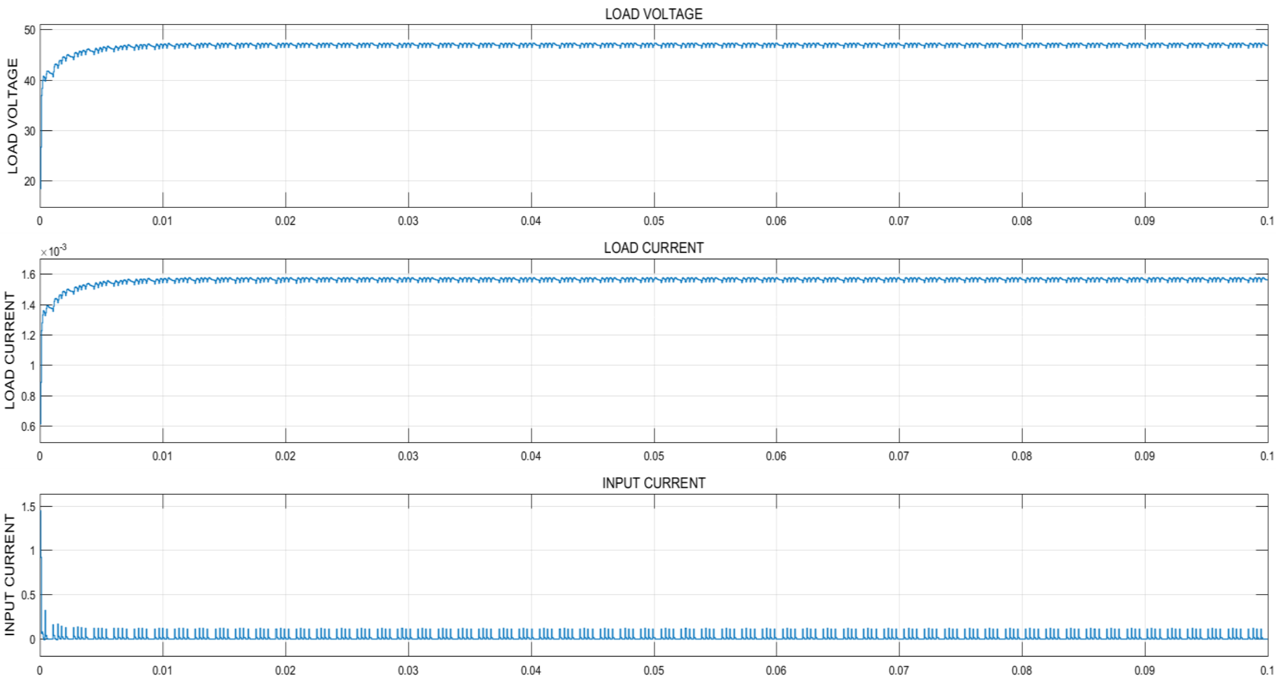

Fig. 8: Simulation of Optimized PI Controlled Main Series-Elementary Converter k = 33

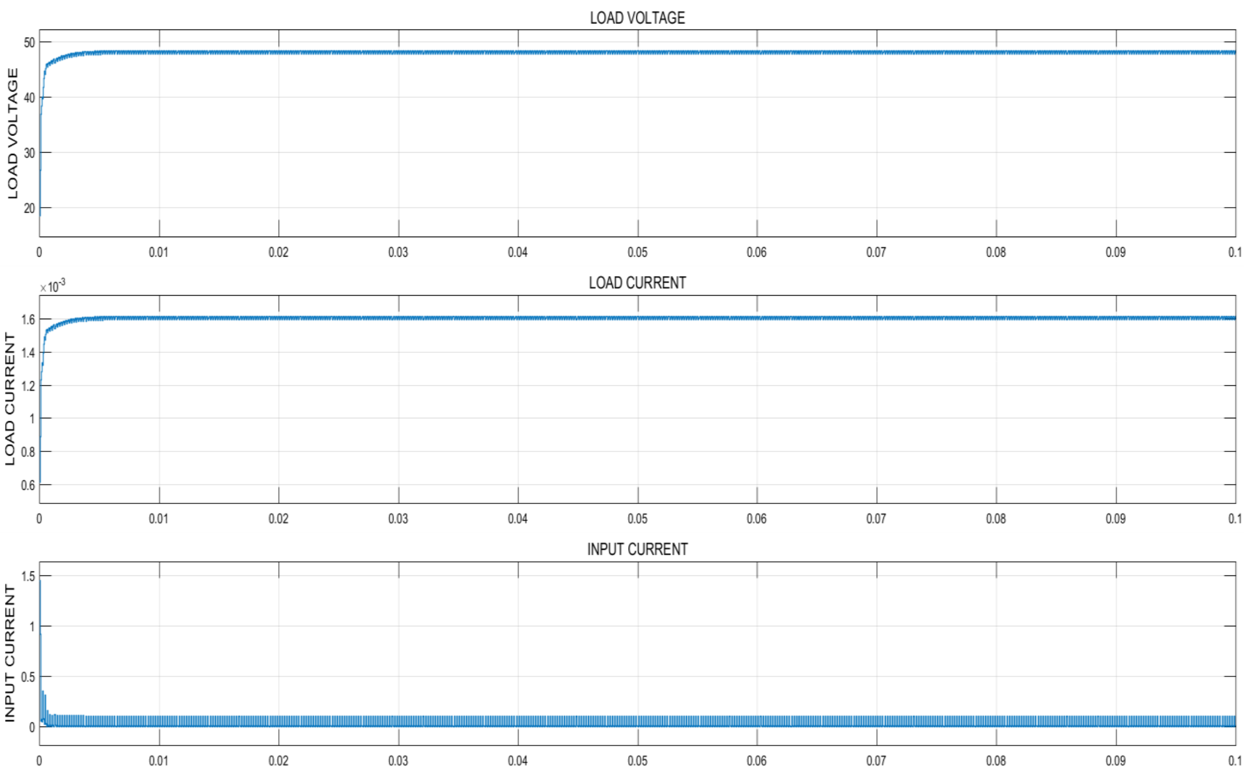

Fig. 9: Simulation of Optimized PI Controlled Main Series-Elementary Converter k = 4

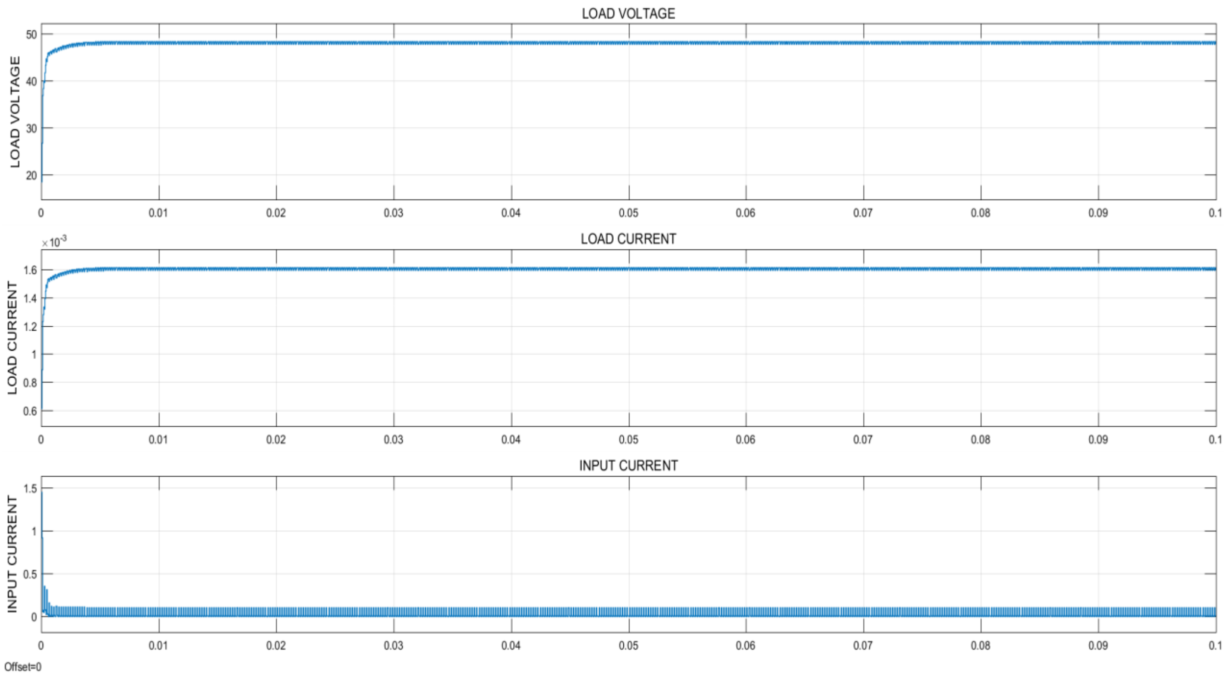

Fig. 10: Simulation of Optimized PI Controlled Main Series-Elementary Converter k = 5

Table 2: Comparison of PI Controlled Main Series-Elementary

Duty Ratio	Vin	Gain	Vout(calculated)	Vout (V)	Ts
0.33	20	2.4925	49.8 V	46.85 V	7.239 ms
0.4	20	2.66	53.2 V	48.48 V	5.8 ms
0.5	20	3	60 V	57.7 V	3.074 ms

To overcome this, a fuzzy controller was used that requires only knowledge, but not the detailed model, to frame rules.

In this work, a fuzzy controller is applied to a positive output super lift converter. The controller commences three stages: fuzzification, fuzzy rule base, and defuzzification. It is fed by two inputs, mainly the error and the change of error. The error is obtained by comparing the output voltage of the converter with the reference voltage and is further fed to the optimized PI controllers, followed by the fuzzy controller. The duty cycle of the switching device is controlled by the output of the intelligent controller. Triangular belongingness functions of 7 nos with a range of -1 to 1are used to characterize the input and output. A Mamdani architecture is used for fuzzy control, and there are 49 rules formed interpreted through max-min alignment, and a crisp value of output is obtained through the centre of gravity technique.

It has been observed that the ripple content is reduced, and the rise time and settling time are reduced for the fuzzy control super lift converter when the duty ratio is 40 % and its membership functions are given in Figure 11 (a-c), and the surface viewer in Figure 12. The waveforms obtained are shown in Figure 13 (a-b).

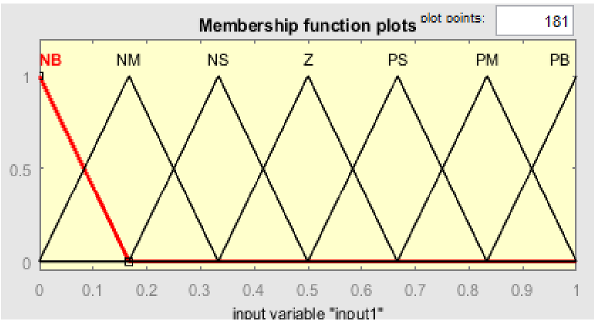

Fig. 11(a): Membership function for input error

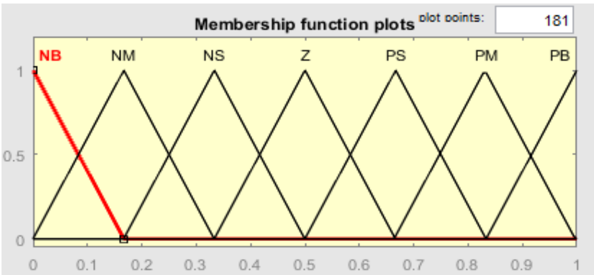

Fig. 11(b): Membership function for input Change in error

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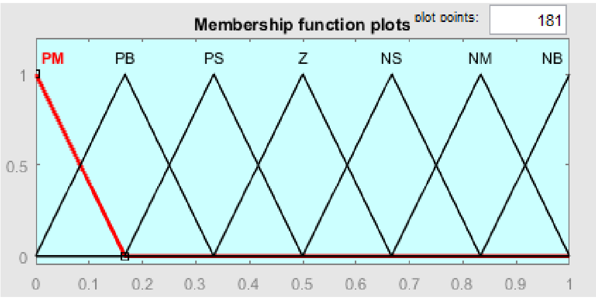


Fig. 11(c): Membership function for output –duty cycle

Artificial Neural Network Control

A prior knowledge of the system is required for the fuzzy controller. So, for a higher series converter, framing of rules becomes tedious. To add simplicity to the controllers, artificial neural control is commonly employed in the power converters. The artificial neural network has a resemblance to the human brain, in which there are various nodes connected via limbs.

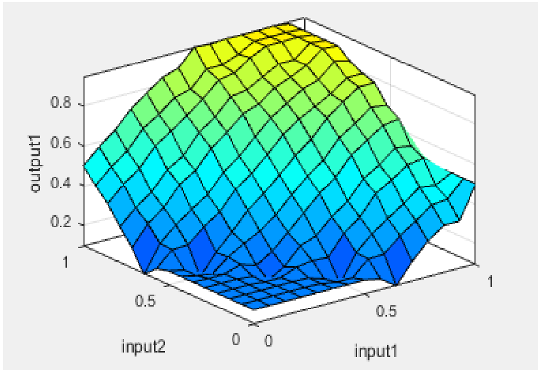
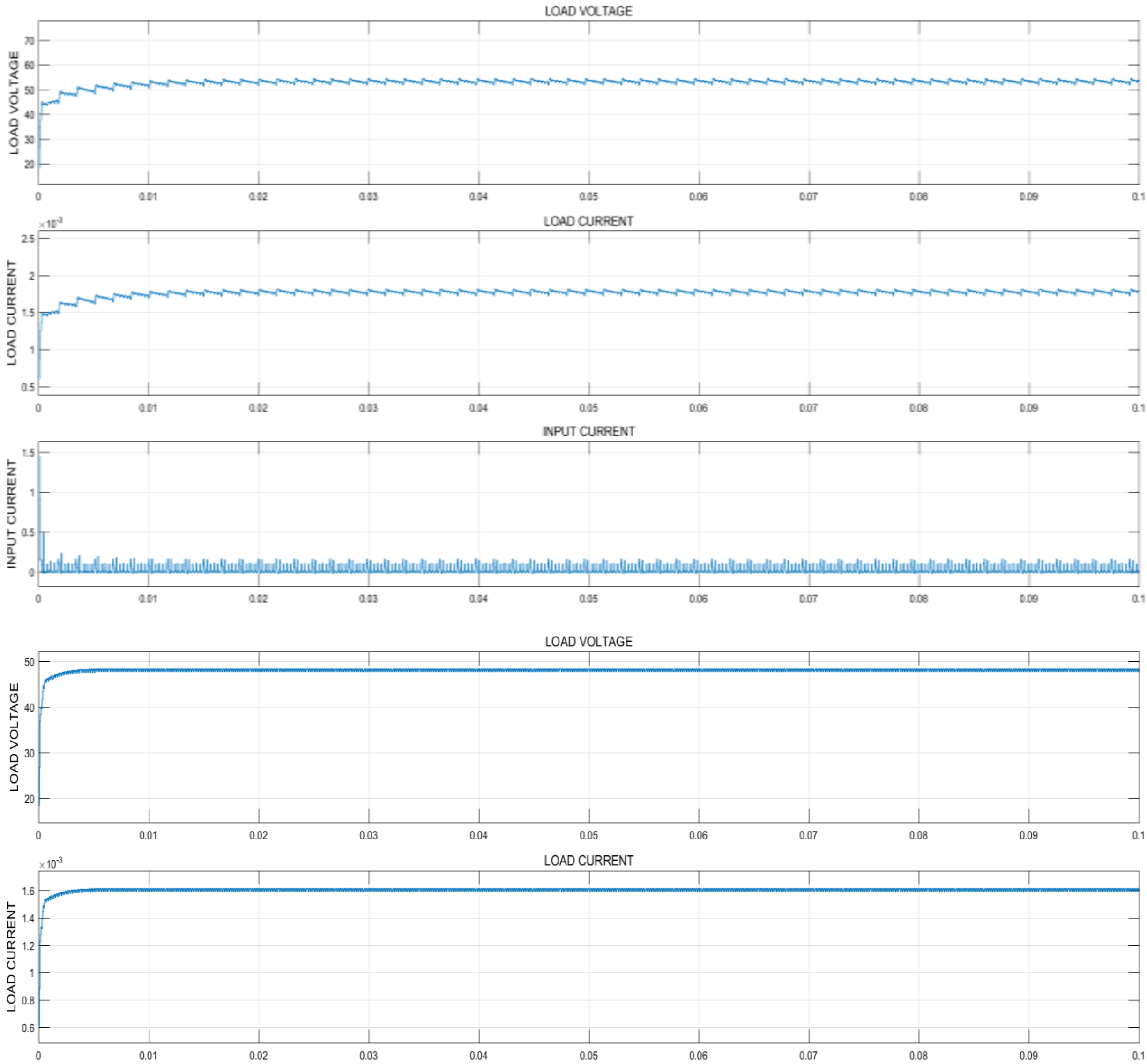


Fig. 12: Surface Viewer of the controller



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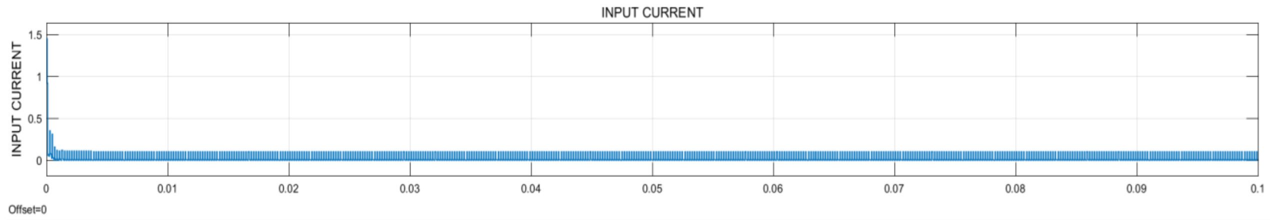


Fig. 13(a): Waveform of fuzzy controlled main series –elementary superlift converter for k =.33

Table 3: Comparison of Controllers

	K	Vin	Vo	Settling time (ts)	Rise Time (Tr)
Proportional Integral	0.4	20 V	48.48	4.43 ms	2.38 ms
Proportional Integral +Fuzzy Controller	0.4	20 V	48.48 V	4.23 ms	2.48 ms
Proportional Integral +Artificial Neural Control	0.4	20 V	48.48	3.457ms	2.093 ms
Proportional Integral	0.33	20 V	46.85 V	7.83 ms	4.13 ms
Proportional Integral +Fuzzy Controller	0.33	20 V	45.22 V	6.86 ms	3.65 ms
Proportional Integral +Artificial Neural Control	0.33	20 V	43.88	6.57 ms	3.47 ms
Proportional Integral	0.75	20 V	58.58	12.025 ms	7.157ms
Proportional Integral +Fuzzy Controller	0.75	20 V	46.23	6.767 ms	3.554 ms
Proportional Integral +Artificial Neural Control (ANC)	0.75	20 V	46.23	5.6 ms	3.067 ms

Information is passed between the neurons. Each of the neural networks concerns a non-linear function termed an activation function, which is an algebraic sum of weighted input (net input) to find the output. There is a weight assigned to each link, which is multiplied by the signal transmitted to obtain the sum of the inputs. The error is calculated and acts as input to the controller. The controller aims to minimize this error by varying the duty cycle of the switching signal.

The neural fitting toolbox of MATLAB was used to create the Artificial neural control. Sample data was taken, and the Levenberg-Marquardt algorithm was applied to train the network. MSE was calculated to estimate the performance of the controller, as shown in Figure 14 (a-c)The waveform for load voltage, current, and input current obtained is shown in Figure 15(a-b).

A comparison of different controllers applied to the main series positive output superlift converter is done as shown in Table 3. PI control, PI followed by Fuzzy, and PI with an Artificial controller were applied to the converter. It was seen that by applying the intelligent controllers, a purer DC output is obtained, and from the results, it was shown that the converter works well for the 40% duty ratio.

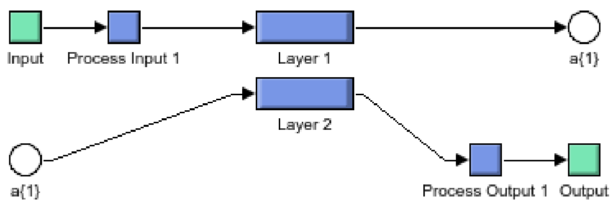


Fig. 14(a): Artificial Neural Controller (ANN) using neural Fitting tool

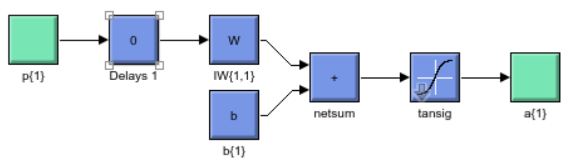


Fig. 14(b): Layer 1 of ANN

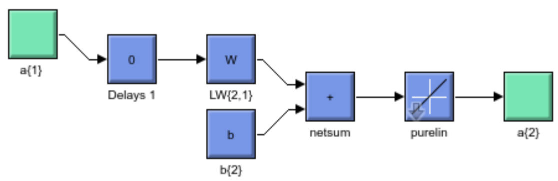
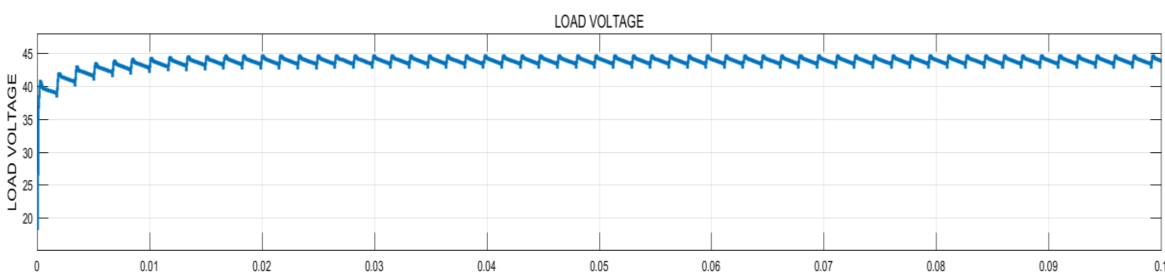


Fig. 14(c): Layer 1 of ANN



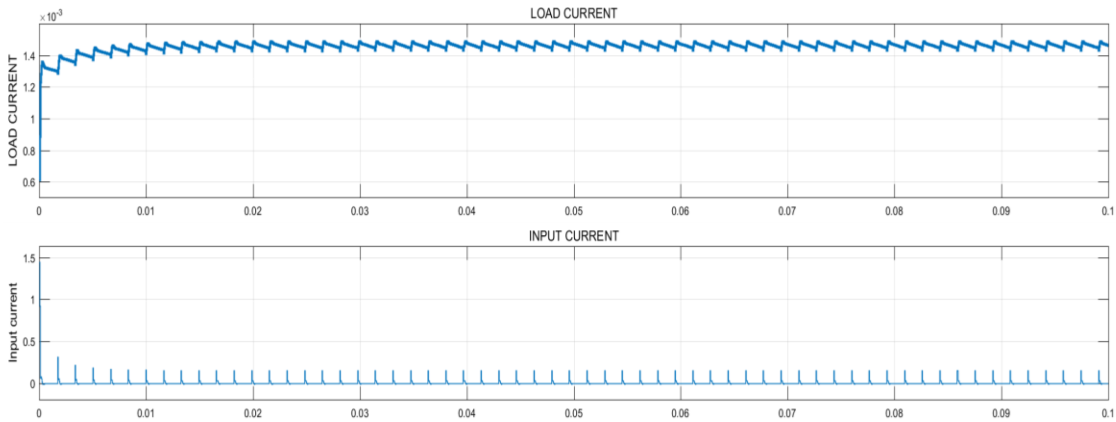


Fig. 15(a): Simulation Result of Artificial Neural Network Control for Positive Output Super lift Converter for k = .33

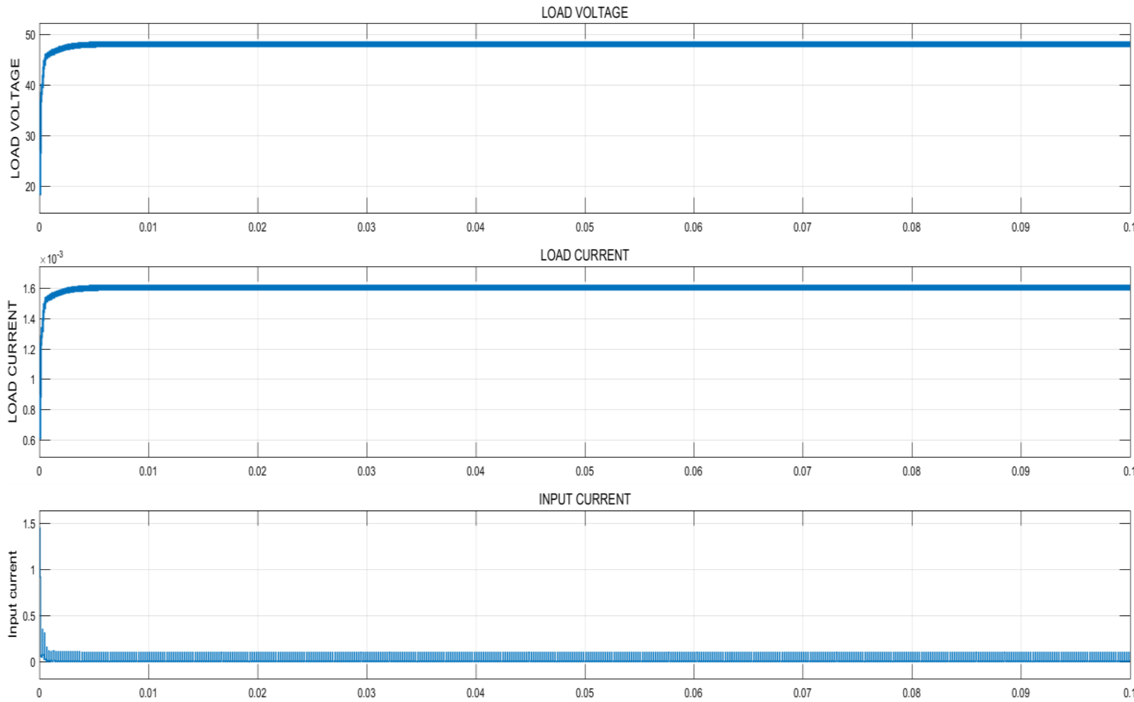


Fig. 15(b): Simulation Result of Artificial Neural Network Control for Positive Output Super lift Converter for k = .4

The comparison of the response time, which includes settling time and rise time, is made in the table. The table shows that by using intelligent controllers like fuzzy and artificial neural control, the settling time has been reduced, which is of great importance in DC-DC converters.PI and ANC settling time have been reduced by up to 50% compared with PI alone.

Conclusion

The effect of parasitic elements in existing DC-DC converters is minimised by converters using the voltage lift technique. It also improves the voltage transfer gain as compared to the boost converters. To obtain a stable response, closed-loop control is applied to the converters. Conventional and integral controllers like Proportional and Proportional are applied to converters, and intelligent controllers like Fuzzy and Artificial Neural Networks are also used. It has been seen that by using the advanced controller for the converter, rise time and settling times have been reduced. The effect of the parasitic element is also being condensed. The super lift converters provide high gain and are designed to enhance the voltage level with fewer harmonics. This will decrease the size of the filter. These types of converters can be employed in Electric Vehicle applications.

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Authors Contributions

Richa Adlakha: Contributed to the simulation and the first draft.
Ashish Grover: Contributed in creating models and verifying result.
Neha Chaudhary: Drafted paper and veryfing result.
Rashima Mahajan: Drafted the final manuscript.
Sunny Bhatia: Edited the draft and finalised the results.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication.

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