# Fuzzy Controlled High Gain Nonisolated DC to DC Hybrid Boost Converter

**M. V. Sudarsan, Ch. Sai Babu, and S. Satyanarayana**

**Abstract** DC to DC conversion at high voltage gain is an imperative feature for many applications particularly for photovoltaic grid-connected system. The voltage conversions at large gain in boost converter are restricted due to the diode reverse-recovery problem and the stress on the switch. In this paper, a hybrid boost converter (HBC) that operates at high voltage gain is analyzed. This converter topology has better features like large voltage conversion for the smaller duty cycles, reduced voltage and current stress on the active switches. Also, the dynamic performance of the HBC is analyzed in the closed-loop operation with fuzzy logic controller for the variations of supply voltages and load resistances. The simulation model of 400 V, 10 KW HBC is designed and implemented in MATLAB/Simulink, and the obtained results verify the better performance of HBC over boost converter.

**Keywords** Boost converter · Hybrid boost converter · Large voltage conversion ratio · Fuzzy logic controller

## 1 Introduction

Renewable energy resources can be a legitimate option for the fossil fuels due to their clean and cost-effective features. To use these renewable energy sources like wind,

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solar, fuel cell as inputs for generation of electrical power, there is a necessity to step-up low-level voltage to the required voltage level to meet the AC utility. This high voltage conversion is possible with boost converter at large duty cycles. The operation at large duty cycles leads higher conduction losses, lower conversion efficiency and diode reverse-recovery problems; also, it uses large inductor to mitigate the current ripple produced due to the very short period of switch turn OFF time and requires a very fast, expensive comparator in the duty-cycle generation circuit. To overcome the above-mentioned drawbacks, there is a necessity of designing a high voltage gain converter [1].

In this paper, an HBC which operates in combination of active and passive switching elements boosts up the voltage at higher gain over a wide range and also mitigates the above-mentioned drawbacks. HBC is formed with two similar inductors connected with two power semiconductor switches on input side, diode and capacitor on load side. The large voltage conversion ratio in this HBC is possible with the inductors charging in parallel when the switches are in ON state and discharges their energy to the load by connecting in series when the switches turn OFF and the voltage stress and current stress of the switches are reduced. For achieving a controlled output voltage in the converter against line and load-side disturbances, there is a necessity of controlling the switches on time using the controllers. Here, to have a better performance of the controlling action, fuzzy logic controller is used which has advantages of simplicity, heuristic nature and adaptability for all linear and nonlinear systems. Also, the designing of fuzzy controller does not require the complete information of the system.

## 2 Boost Converter

Figure 1a explains the topological diagram of the boost converter, and its operation is analyzed in continuous mode of operation.

**Stage-I** ($t_0$–$t_1$): In this stage, the inductor charges linearly and stores energy for a period of $DT_s$. The turn ON of the switch isolates the load from the supply. The inductor voltage in this stage is

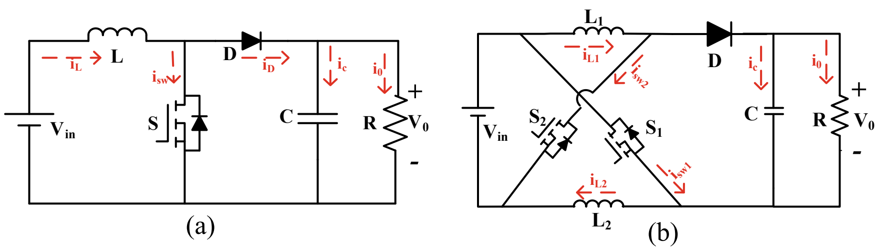



**Fig. 1** **a** Boost topology and **b** HBC topology

$$v_{\mathrm{L}}(t) = L\frac{\mathrm{d}i_L(t)}{\mathrm{d}t} = V_{\mathrm{in}} \tag{1}$$

**Stage-II** ($t_1$–$t_2$): In this stage, the turn OFF of the switch makes a path for charged inductor to discharge its stored energy and transfers its energy from supply to the load. The inductor voltage during OFF period (1–$D$) $T_{\mathrm{s}}$ is

$$v_{\mathrm{L}}(t) = L\frac{\mathrm{d}i_{\mathrm{L}}(t)}{\mathrm{d}t} = V_{\mathrm{in}} - V_0 \tag{2}$$

Thus, the voltage and current gains of the converter are obtained by averaging the inductor voltage to zero and are given as

$$\frac{V_0}{V_{\mathrm{in}}} = \frac{1}{1-D} \quad \text{and} \quad \frac{I_{\mathrm{in}}}{I_0} = \frac{1}{1-D} \tag{3}$$

The values of boosting inductor and the filtering capacitor are designed for an input ripple current $\Delta I$ and for an output ripple voltage $\Delta V_0$ as

$$L = \frac{V_{\mathrm{in}} D}{\Delta I f_{\mathrm{s}}} \quad \text{and} \quad C = \frac{V_{\mathrm{o}} D}{R\Delta\, V_0 f_{\mathrm{s}}} \tag{4}$$

## 3 Hybrid Boost Converter

The topology of HBC consists of two similar weighted inductors cross-connected with a pair switches $S_1$ and $S_2$ from the input supply to the load through the diode and capacitor and is shown in Fig. 1b. $S_1$ and $S_2$ operate for same duty cycles in general less when compared to the ratio of the boost converter. HBC operation is based on the switched inductor concept, where the two inductors of same inductance will charge in parallel during ON period of switches and will discharge during OFF period of switches by connecting the inductors in series [2]. This process of charging and discharging the inductors achieves the high voltage gain for increasing the voltage level with smaller duty cycles.

### *3.1 Continuous Mode of Operation*

**Stage-I** ($t_0$–$t_1$): During this stage, the turn ON of the power switches $S_1$, $S_2$ connects the inductors $L_1, L_2$ in parallel to the supply voltage $V_{\mathrm{in}}$ and gets charged by increasing currents linearly from a minimum value to $i_{\mathrm{Lpeak}}$ at time $t_1$. The rectifying diode gets turned OFF and makes the load disconnecting from the input supply, whereas the current to the load is supplied by the charged capacitor. Thus, the inductor voltages and the blocking voltage of the diode during this interval are

$$v_{\mathrm{D}} = V_0 + V_{\mathrm{in}} \tag{5}$$

The input ripple current during this period of conduction is

$$I_{\mathrm{in\ ripple}} = \frac{2V_{\mathrm{in}}D}{f_{\mathrm{s}}L} \tag{6}$$

**Stage-II** ($t_1$–$t_2$): In this stage, the turn OFF of the power switches $S_1$, $S_2$ connects the inductors $L_1$, $L_2$ in series and discharges their energy to load and filtering capacitor through the turned ON diode. The current thus decreases linearly from $i_{\mathrm{Lpeak}}$ to minimum value at time $t_2$. Thus, the inductor voltages during the discharging period are

$$v_{\mathrm{L1}} = v_{\mathrm{L2}} = \frac{V_{\mathrm{in}} - V_{\mathrm{o}}}{2} \tag{7}$$

As per the volt-second balance principle, making the voltage across inductor over one cycle of time period to zero, the voltage conversion gain of HBC [3] is

$$\frac{V_{\mathrm{o}}}{V_{\mathrm{in}}} = \frac{1+D}{1-D} \tag{8}$$

The blocking voltage of the power switches in stage-II during OFF period is given by

$$v_{S_1} = v_{S_2} = \frac{V_{\mathrm{in}} + V_{\mathrm{o}}}{2} \tag{9}$$

## 3.2 Discontinuous Mode of Operation

**Stage-I** ($t_0$–$t_1$): The operation in this stage is similar as in continuous mode of operation, and the inductors $L_1$, $L_2$ get charged in parallel from zero current to the peak value $i_{\mathrm{Lpeak}}$ within $DT_{\mathrm{s}}$. The capacitor current in this interval is equal to the load current in opposite direction (Fig. 2).

**Stage-II** ($t_1$–$t_2$): The turn OFF of power switches $S_1$, $S_2$ in this stage connects the inductors $L_1$, $L_2$ to connect in series and discharges their energies to the capacitor and the load through the turned ON diode. The current in these inductors decreases from its peak value to zero at time instant $t_2$. The expression of peak currents with reference to the current profile in discharging period is

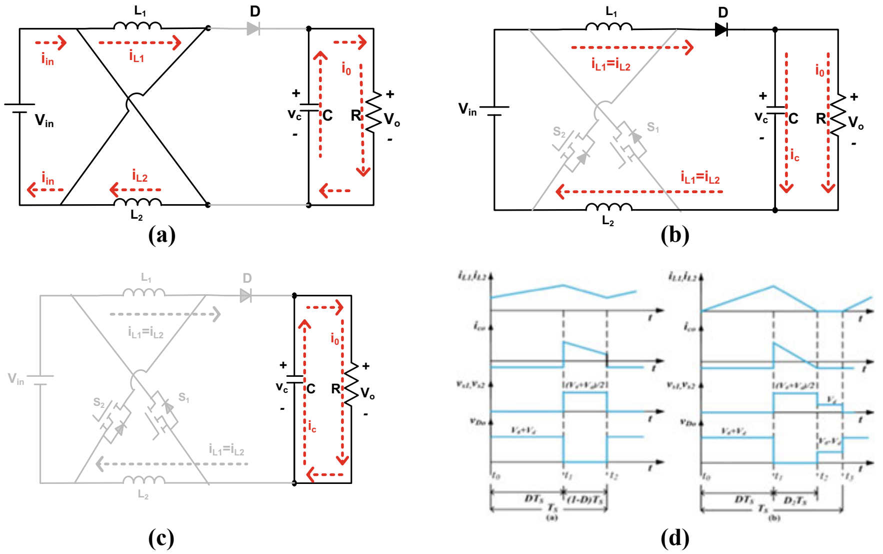



**Fig. 2** Hybrid boost converter with switches in **a** ON state, **b** OFF state, **c** OFF state in DCM and **d** waveforms in CCM and DCM

$$i_{\mathrm{Lp1}} = i_{\mathrm{Lp2}} = \frac{V_0 - V_{\mathrm{in}}}{2Lf_{\mathrm{s}}} D_2 \tag{10}$$

On equating the peak currents from stage-I and stage-II, the duty cycle $D_2$ is

$$D_2 = \frac{2DV_{\mathrm{in}}}{V_0 - V_{\mathrm{in}}} \tag{11}$$

**Stage-III** ($t_2$–$t_3$): The switches $S_1$, $S_2$ and diode $D$ get turned OFF. The capacitor supplies the current to the load until the next cycle of operation. The zero current in these inductors makes the discontinuous operation. The steady-state analysis of the converter is done based on the capacitor current over a cycle of time period. The average current of the capacitor over a cycle of operation is [4].

$$I_{\mathrm{co}} = -\frac{V_0}{R} + \left(\frac{DV_{\mathrm{in}}}{V_0 - V_{\mathrm{in}}}\right)\left(\frac{V_{\mathrm{in}}D}{Lf_{\mathrm{s}}}\right) = \frac{D^2V_{\mathrm{in}}^2}{(V_0 - V_{\mathrm{in}})Lf_{\mathrm{s}}} - \frac{V_0}{R} \tag{12}$$

Defining the normalized time constant of inductor as $\tau_{\mathrm{L}}$ equals to ratio of *L/R* to switching cycle period ($T_{\mathrm{s}}$), and on substituting this in the above equation, the voltage gain in the discontinuous mode is $M_{\mathrm{DCM}} = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{D^2}{\tau_L}}$.

**Fig. 3** Specifications of boost and HBC converters

| Parameters | Boost | HBC |
|---|---|---|
| Input voltage $V_{\text{in}}$ | 100 V | 100 V |
| Output voltage $V_0$ | 400 V | 400 V |
| Output power $P_0$ | 10 KW | 10 KW |
| Switch frequency $f_s$ | 20 kHz | 20 kHz |
| Capacitor $C_0$ | 120 μF | 96 μF |
| Inductors $L_1$ and $L_2$ | 0.75 mH | 0.6 mH |

The analysis of HBC at boundary conduction mode is

$$\tau_{\text{LB}} = \frac{(1-D)^2 D}{2(1+D)} \tag{13}$$

If time constant $\tau_{\text{L}}$ of the converter is smaller than the $\tau_{\text{LB},}$ then the converter operates in DCM operation [5].

# 4 Closed-Loop Control of Active Network Converter

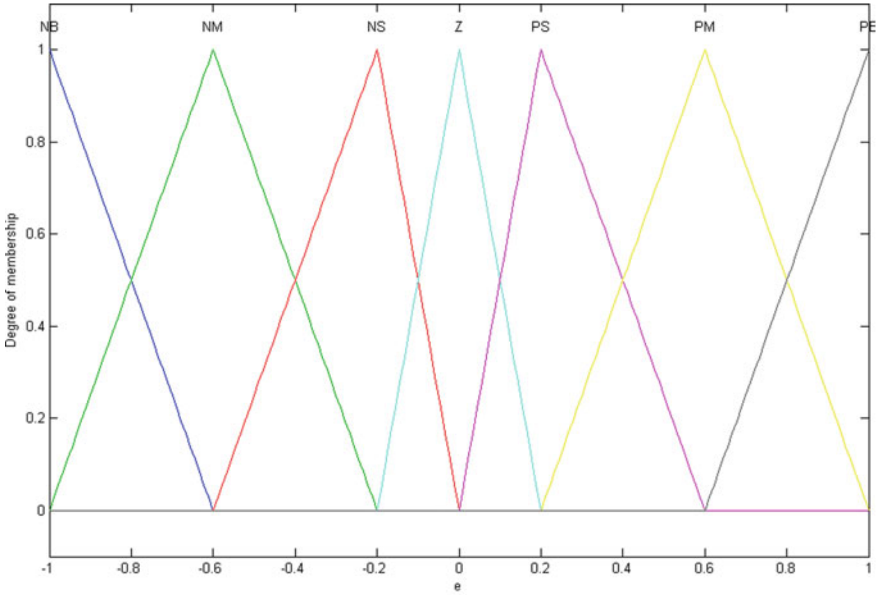
## 4.1 *Fuzzy Controller*

The Mamdani-type fuzzy logic controller in this work consists of three stages, namely fuzzification, fuzzy inference engine and defuzzification. In the first stage, the inputs error, change in error (e($t$) and ce($t$)) and output u($t$) of the controller are fuzzified with triangular membership functions. Each input variable is defined with seven linguistic terms and output variable with eleven linguistic terms as shown in Fig. 4a, b. In the second stage, 49 if-then rules are formed with antecedent as e($t$), ce($t$) and consequent as u($t$). An *and—or* operation is performed, and a fuzzy output is generated from the inference engine through the defined rule. In the third stage, the output in fuzzy terms is defuzzified to the control signal using centroid method.

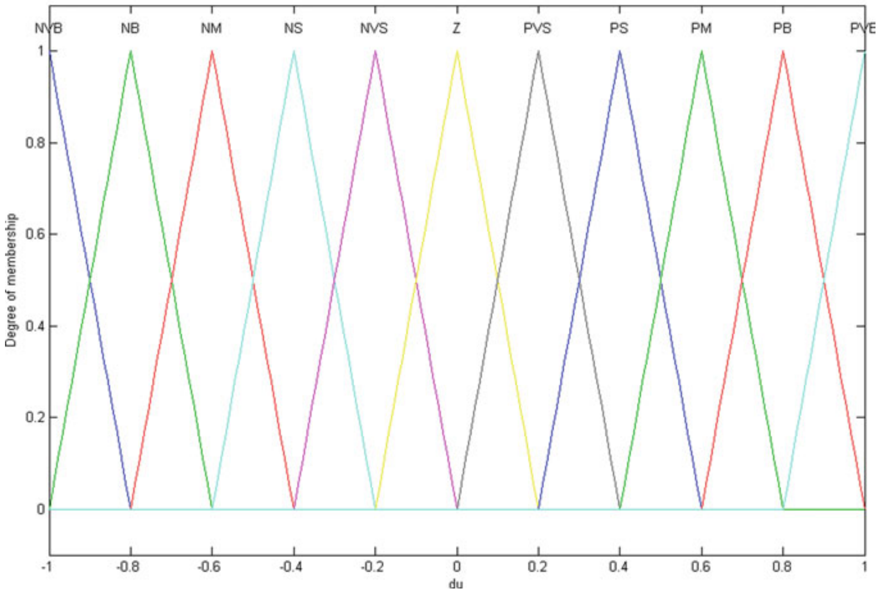
# 5 Simulation Results

The MATLAB/Simulink results of converters during steady-state and their dynamic performance are analyzed in both open and closed-loop operations.

Figure 5a, b shows the output voltage and current responses of 10 KW boost converter boosting the voltage to 400 V with a duty ratio of 75% and delivers a load current of 25 A. The output voltage ripple and current ripple of boost converter are observed to be 8 V and 0.4 A, respectively.




(a) Input variables e*(t)* and ce*(t)*




(b) Output Variable u*(t)*

**Fig. 4** Membership functions of **a** inputs e($t$) and ce($t$) and **b** output u($t$)

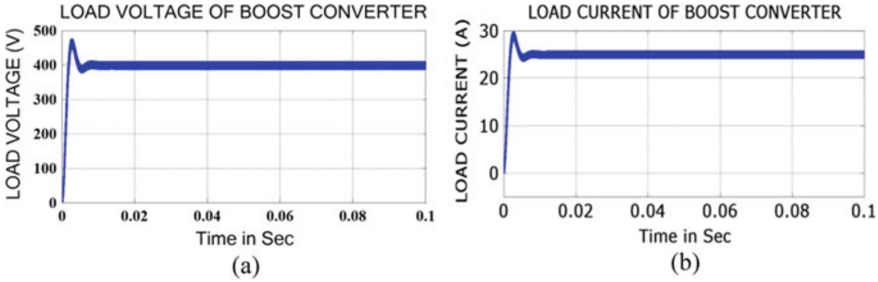



**Fig. 5** **a** Output voltage and **b** output current responses of boost converter

Figure 6a depicts the inductor current response of 100 A with a ripple content of 5%, diode voltage and current responses which blocks −400 V and carries 100 A current, switch voltage and current responses which blocks 400 V during off state and carries 100 A current during on period.

Figure 7a, b shows the output voltage and current responses of 10 KW HBC boosting the voltage from 100 to 400 V with smaller duty ratio. Because of its parallel charging of inductors during ON state of switches and series discharging of inductors during OFF stage of switches, the boosting operation with lesser duty ratio of 60% only is possible.

Hence, the issue reverse-recovery problem in the diode and conduction loss of switches are minimized. The output voltage ripple and output current ripple of HBC are 6 V and 0.4 A, respectively. Figure 6b shows the responses of all elements in HBC as current response of inductors with a less current of 65 A designed for a ripple content of 5 A, diode voltage and current responses which blocks (−500 V) and carries only 65 A current and switch voltage and current responses which has

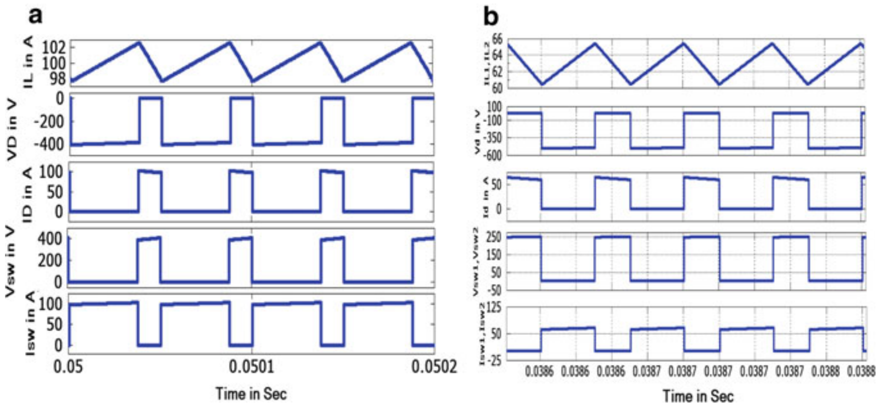



**Fig. 6** Responses of inductor currents, diode voltage, diode current, switch voltages and switch currents of **a** boost converter and **b** HBC

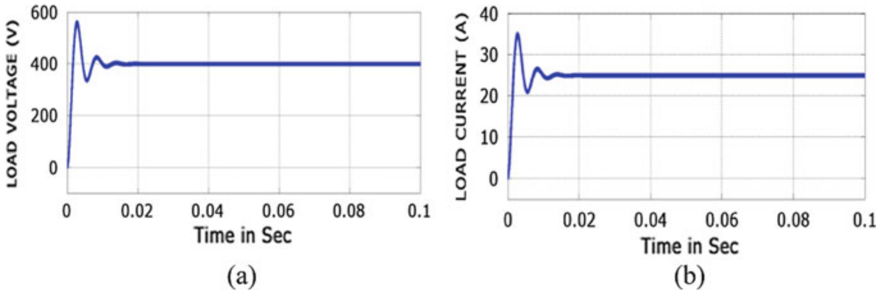



**Fig. 7** **a** Output voltage and **b** output current responses of HBC

to block only 250 V during OFF state and carries less current of only 65 A current during on period.

Thus, from responses of Figs. 5, 6 and 7, the performance of HBC is superior than boost converter, and hence, the dynamic operation of HBC is analyzed in closed loop with PI and fuzzy logic controllers to regulate the voltage at 400 V under all conditions.

Figure 8 shows the voltage responses of HBC simulated in closed loop with PI and fuzzy logic controllers. The voltage response of PI-controlled HBC gives a peak overshoot of 75% and settles for a steady-state voltage of 400 V at 0.15 s, whereas the converter with fuzzy logic controller gives the better performance in terms of zero peak overshoot, less settling time of 0.05 s, small-ripple fast-rise time and zero steady-state error. Also, the robustness of fuzzy logic controller is observed for both load and supply disturbances.

Figure 9a shows the output voltage and current of HBC for a disturbance at input supply side for a decrement of voltage from 100 to 75 V at 0.5 s with a fixed load. Even under this voltage disturbance, the fuzzy controller delivers corresponding control signal which gives the required duty cycle of switches for getting a constant voltage of 400 V and 25 A at load side. Figure 9b shows waveforms of load voltage and load current of HBC with fuzzy controller for a disturbance on load side increasing

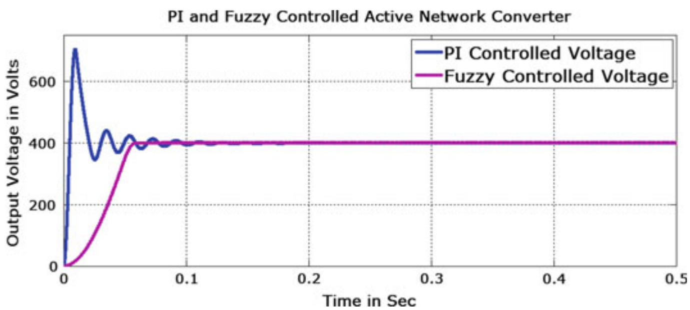



**Fig. 8** Output voltage response comparison of HBC

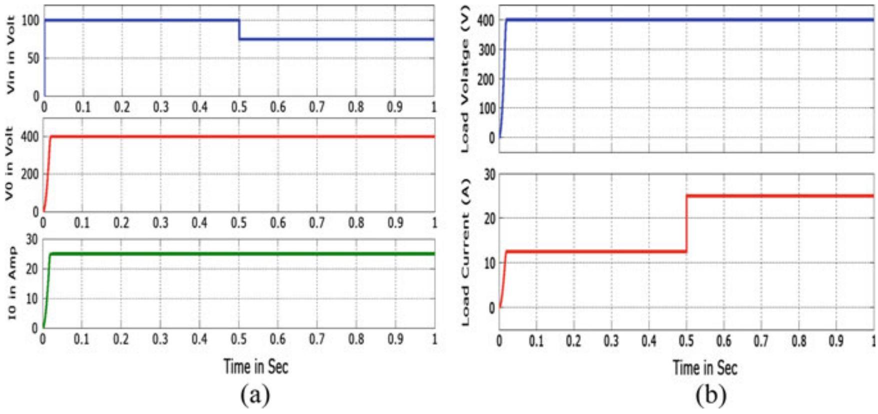



**Fig. 9** **a** Dynamic response of load voltage and load current of fuzzy-controlled HBC for decrease of supply voltage from 100 to 75 V at 0.5 s and **b** dynamic response of load voltage and load current of fuzzy-controlled HBC for increase of load by 50% at 0.5 s

the load from half to full load at 0.5 s for a fixed input voltage. Even under this disturbance also, the controller adjusts the duty cycle of the switches in such a way to generate a constant voltage of 400 V with a load current increasing from 12.5 to 25 A at 0.5 s.

## 6 Conclusion

The simulation study and analysis shows that the fuzzy-controlled HBC gives the better performance comparing with the PI-controlled in terms of its dynamic responses. Also, the HBC topology has better features like large voltage conversion for the smaller duty cycles, reduced voltage and current stress on the active switches.

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