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DESIGN AND ANALYSIS OF AI BASED CONTROLLER FOR NONISOLATED HIGH STEP UP DC–DC CONVERTER

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Abstract
DC-DC converter topologies are gaining popularity for their use as an interface between photovoltaic (PV) source and load. In this work, a coupled inductor (CI) based novel soft switched DC-DC converter topology has been proposed for PV application. A passive clamp circuit consisting of a capacitor and a diode has been chosen as an active clamp circuit to lower the voltage stress on the switch, hence improving the converter's voltage gain. To improve the dynamic response of the converter, AI based controllers namely Fuzzy Logic controller (FLC) has been incorporated. Thus, the proposed converter's performance with FLC is validated using MATLAB simulation. From the results, it is revealed that the proposed converter allows improved conversion ratio by increasing the turns ratio of the coupled inductor and by adding more networks and VMCs. This topology presents a reduced electromagnetic interference (EMI) levels when compared existing with boost type converters. Hence, it is a viable alternative to PV applications.
Keywords: PV, Non isolated converter, FLC, High Voltage Gain.

Introduction

In recent decades, the development of pollution-free energy sources such as wind, PV and fuel cells has played a significant role in energy generation. However, the maximum output voltage of a solar panel is normally in the range of 15–40V. As a result, high voltage gain converters are required to generate a high output voltage from a low input voltage [1]. Boost converters are typically utilized in such cases. By varying the duty cycle, high output voltages can be achieved in boost converter. But the higher duty cycle result in conduction losses, which in reduces converter efficiency by increasing the voltage drop. Numerous strategies have been developed to overcome the limits of standard converters (Boost and Buck–Boost) [2].

Isolated and non-isolated high step-up converters are later utilized to achieve higher voltage from PV. In Isolated converters, transformer is used to achieve high voltage gain. But leakage inductances, voltage spikes across the switch and substantial switching losses degrades the efficiency of this converter [3].

When compared to the isolated converter, the non-isolated converter has a simpler structure and cheaper cost. But it also suffers from same drawbacks as that of isolated converters. Many strategies such as VM cells [4], switched capacitors[5], switched inductors [6], and connected inductor (CI) [7] have been incorporated with traditional converters to boost its voltage gain.

High conversion ratios are possible using Switched-Capacitor (SC) converters. However, the converter has a low efficiency and providing a capacitor charging channel is difficult. When the semiconductor switch is activated, a large pulsed current passes through the main switch and numerous diodes, increasing current stress and conduction losses. To eliminate the diode recovery issue and limit the peak current, a resonant inductor is coupled in the switched-capacitor converter [8].

High output voltage gain can be achieved by using converters with a switched-inductor topology. The switched-inductor-based converters make use of two inductors that are charged in parallel and discharged in series. The switched-inductor converter, on the other hand, suffers from extreme voltage stress across the semiconductor switch [9]. By simply increasing the turns ratio of the converter's connected inductors, a high DC gain can be produced.

A coupled inductor with a high turn's ratio can cause leakage inductances. This results in substantial power dissipation and low efficiency [10].

The leakage inductance energy can be recovered to solve this problem. By using a voltage clamp circuit in CI based converters, good results can be achieved [11]. Furthermore, the active clamp circuit may effectively solve the problem of leakage inductance; nevertheless, it is quite expensive because it necessitates high-power switch drive circuits. As a result, the converter with a passive clamp circuit for improved performance was demonstrated [12].

The implementation of clamp circuits in converter offers low voltage stress, energy recovery etc., Nevertheless, the converter has a large input ripple current, which leads to have problems with PV MPPT. To override this, researchers proposed CI-based interleaved converters [13]. Due to minimal input current ripple, converters having a CI with multiple cores are best suited for solar applications. Furthermore, the usage of numerous magnetic cores will increase the topology's complexity and cost, compared to other common CI-based converters [14] .

The VM cell circuit, which has been proposed by several researchers, also improves the converter voltage gain. VM circuits can be used in DC–DC boost converters in a variety of ways. The diode-capacitor voltage multiplier usually boosts the converter output voltage. The VM converter delivers significant voltage gain, but drawbacks such as voltage balancing, lowering efficiency and complexity also exists [15]. Many innovative converter topologies with high conversion efficiency and voltage gain have been also developed[16]. To obtain high voltage gain, the converters can also employ well-known techniques such as switched inductor, switched capacitor and voltage lift capacitors.

The voltage lift capacitors are used at the converter's output to raise the output voltage by employing inductors and capacitors. The output shunt capacitors are used to reduce ripple on the output. The capacitors can also inject voltage lift in voltage lift-based converters. Inductors can able to reduce the current stress on the switch and diodes. This makes it more suitable for photovoltaic applications [17].

Many studies have proposed switching strategies such as zero-voltage switching (ZVS) [18] and zero-current switching (ZCS) [19] and switching techniques to minimize power loss. However, the switching power loss can be mitigated using soft and hard switching on the converter. Soft switching is used for switching frequencies above 20 kHz and hard switching is used for switching frequencies below 20 kHz [20].

Ref.[21] proposes an n-cell design for switched-capacitor-based converters that delivers high output voltage gain and minimal voltage stress across the switch. However, each cell has two inductors, which increases the size, cost, and efficiency.

Cascading 'n' conventional step-up converters with 'n' number of controllable switches or employing a single controlled switch is another method for obtaining large voltage gain. This topology, however, is not suited for high-voltage applications because high voltage stress across the switch reduces system efficiency while also increasing system size and cost [22].

The step-up voltage gain can also be achieved by tailoring a coupled inductor, VM cells, switched capacitor, switched inductor, and so on. However, these boosting strategies may result in high voltage/current stress over the switching devices.

Furthermore, due to a significant conduction loss, it affects the efficiency of the converter. Therefore high switching frequency should be chosen to improve efficiency. However, switching losses and EMI concerns will increase and again results in reduced efficiency. In order to increase the voltage gain of the converter, a non-isolated boost converter with coupled inductor and VM cell circuit has been proposed. Even though this design has increased gain, it causes phase lag. As a result, a feedback controller capable of ensuring the converter's static and dynamic performance is required. PID, fuzzy logic (FL) and sliding mode are examples of analogue and digital methods. SMC is used to regulate the output of converter. The commonly used closed loop control mechanism in many industrial control systems is PI controller.

However, in order to design controller parameters, these controllers require a precise mathematical model of the system. As a result, they are more sensitive to parameter changes. So implementation of these analogue controllers is unsuitable for reliable performance. As a result, an artificial intelligence (AI) technique-based controller has played a significant role in industrial drive control. Several AI-based heuristic controls have since been developed.

Because of its automatic tuning capability, a fuzzy logic controller is becoming more popular among these. Its parameters can also be tuned for a wide range, so it can be adjusted / tuned for a wide range of changes in its operating condition. Hence, this work formulated a fuzzy to enhance the performance of the proposed converter.

Operation of the proposed converter topology

The proposed converter's circuit diagram is depicted in Fig. 1. A coupled inductor, a single switch, VM cells, and a passive clamp circuit are utilized in the proposed converter.

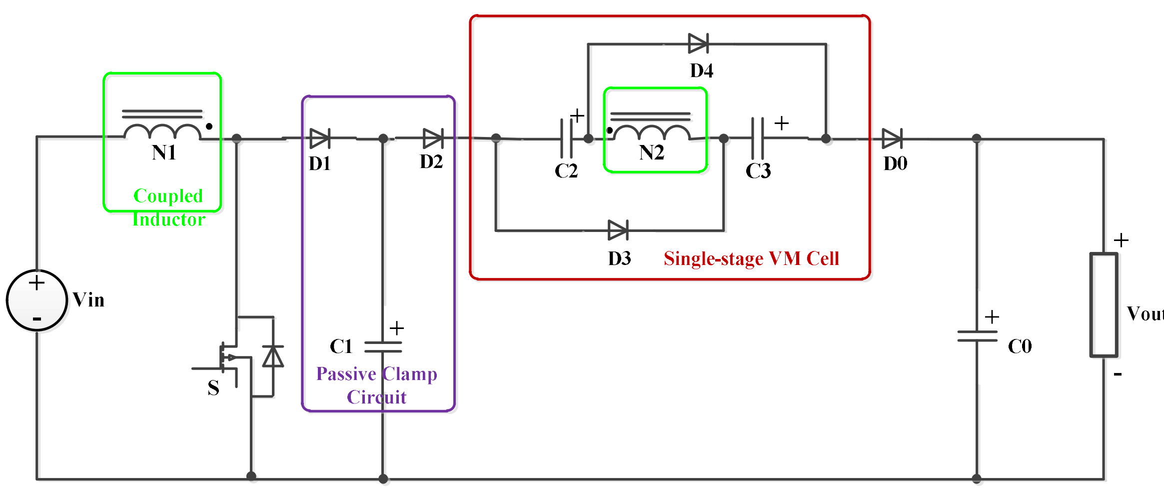

Figure 1.Circuit diagram of the proposed converter

The leakage energy generated by the inductor's leakage inductance is recovered by the clamp capacitor (C1). The coupled inductor aids in charging the VM cell capacitors, increasing the converter's voltage gain.

The proposed converter has four modes of operation.

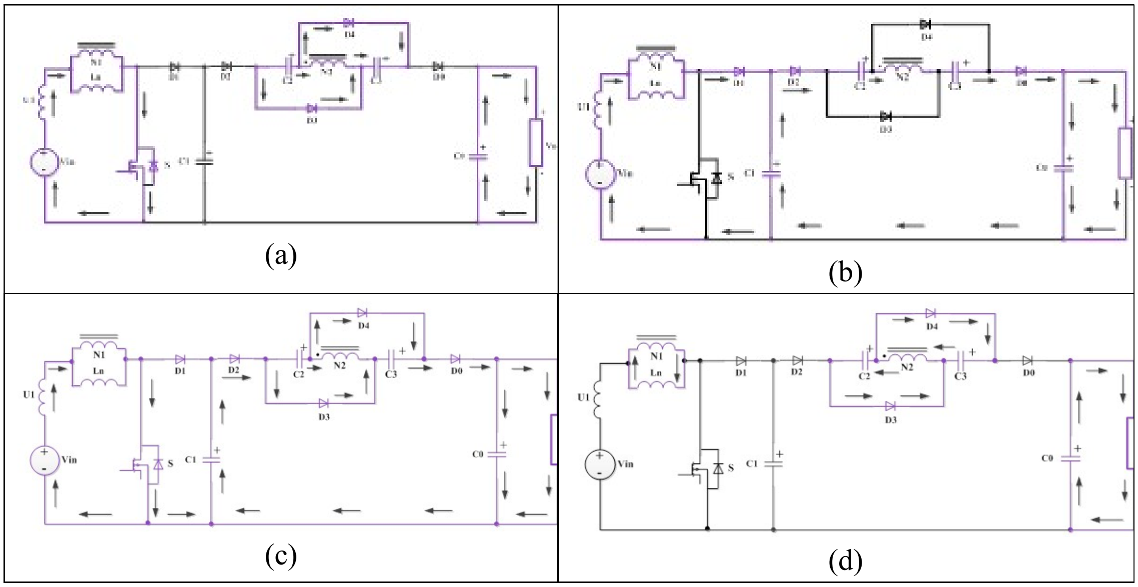

Figure 2. Modes of operation

Mode I

Fig. 2a shows mode I operation, and during this mode, the switch S is turned on, and the diodes D3 and D4 are forward biased. The energy from the input source is transferred to Lm and the switch S. The capacitors C_2 and C_3 are charged by the energy transferred from magnetizing inductor (Lm) to the secondary winding of the coupled inductor. The load is supplied through the energy stored in the output capacitor (C_0).

Mode II

Fig. 2b shows mode II operation, and during this mode of operation, the switch S remains in on-state. Along with the diodes D3 and D4, the diodes D0 and D2 are forward biased, and D1 is reverse biased. During this mode, the voltage across the capacitors C_2 and C_3 acts as a source. The energy is transferred to load, and the output capacitor (C_0) starts to charge through the diodes.

Mode III

Fig. 2c shows mode III operation, and during this mode, the switch S is turned off. The diodes D1, D2 and D0 are forward biased, and the diodes D3 and D4 are reverse biased. The input voltage (Vin) is supplied directly to the load through the diodes D1, D2 and D0 along with the coupled inductor. The residual energy stored in the clamp capacitor (C_1) is transferred to the load. This mode ends when the primary leakage inductance current reaches zero. and this mode is concise time mode. In this way, the voltage stress on the MOSFET switch S is reduced by the clamp capacitor and clamp diode (D1).

Mode IV

Fig. 2d shows mode IV operation, and during this mode, the switch S remains turn off state, and the diodes D1, D2, D3, D4 and D0 are reverse biased. During this mode, the energy due to the magnetizing inductor is discharged into the capacitors C_2 and C_3. The magnetizing inductor current is reduced due to the energy discharge through D3- and D4. Since the output capacitor C_0 is charged during modes II and III, the output capacitor C_0 solely supplies energy to the load. This mode ends at t=t5, and the switch S is turned on for the next switching cycle. During this mode, the currents are falling, and at t=t5, the currents reach zero.

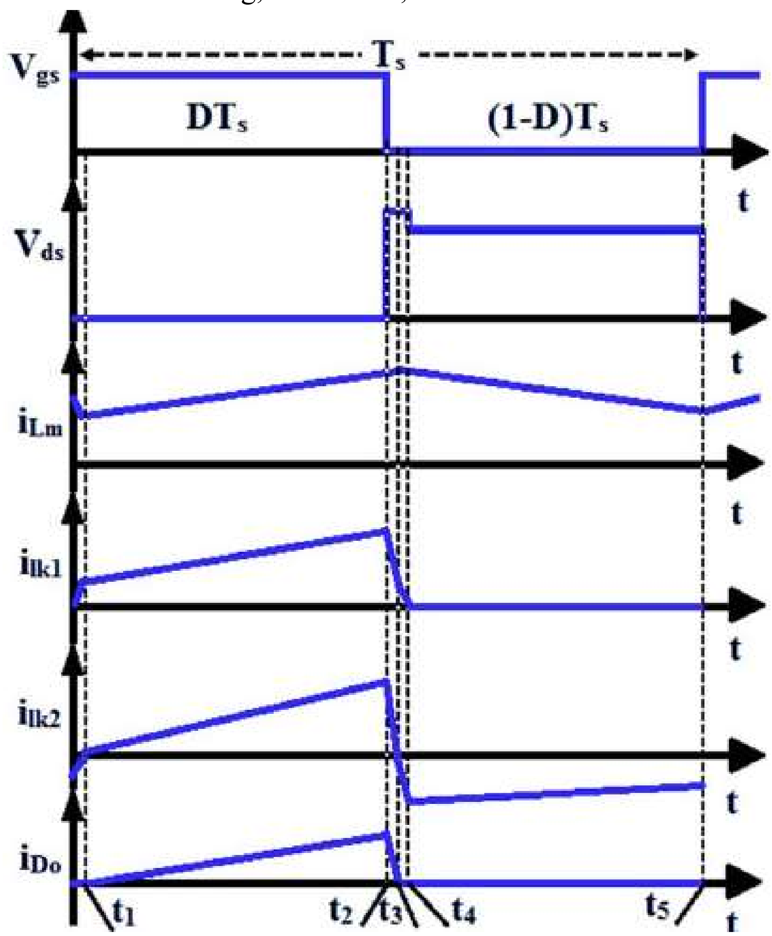

Figure 2e. Waveform during one switching period

Thus, the voltage gain of the proposed converter can be expressed about

$$Gain = \frac{1 + D + nDk(1 + D)}{2(1 - D)}$$

The voltage gain of the converter for various duty ratios in CCM is shown in Fig. 3. For the steady state analysis, the coupling coefficient (k) is considered as 1, and the turns ratio (n) is selected as 1.

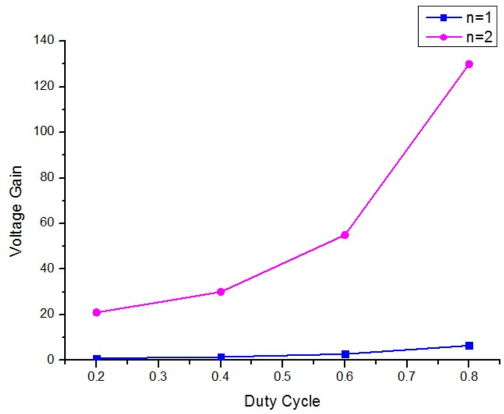

Figure 3. Duty cycle versus voltage gain at k=1

From Fig. 3, it is observed that the output voltage is increased by varying the duty cycle and changing the turns ratio. However, the coupling coefficient does not have much impact on the output voltage of the converter. The dynamic performance of the proposed converter can be enhanced by implementing controllers.

Design of FLC

The proposed FLC uses fuzzy sets (NGB, NGM, NGS, ZE, PSS, PSM, PSB) to translate crisp variables into linguistic variables. As a result, the suggested FLC has the following characteristics:

• Fuzzification is achieved through the employment of the Continuous Universe of Discourse and seven fuzzy sets of triangular Membership Functions (MF) for input and output.

• Mamdani's 'min' operator is used for Implications.

• For defuzzification, the 'centroid' method is utilized.

Figures 4a, 4b, and 4c demonstrate the triangular MFs for input/output variables. When building an FLC, understanding the behaviour of the system is critical. Inference rules are used to express this knowledge.

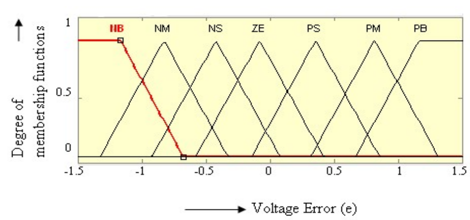

Figure 4a. MFs for *e*

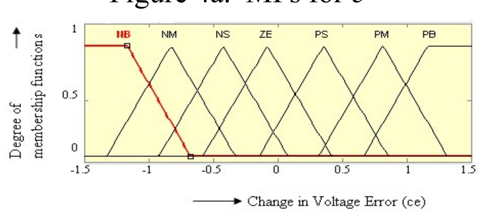

Figure 4b. MFs for Δ*e*

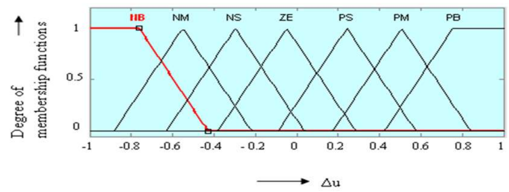

Figure 4c. MFs for Δu

Figure 4d depicts a 3D surface image of the FLC rule base..

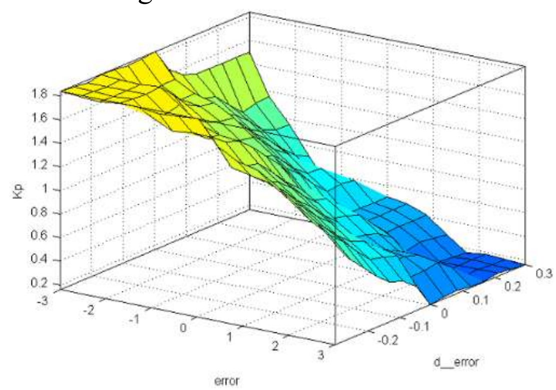

Figure 4d. 3D surface view of proposed FLC

Simulation results and discussions

The suggested converter is simulated using the MATLAB simulation software tool to ensure its validity. Table 1 lists the parameters that are necessary for simulation. Both open-loop and closed-loop simulations are performed on the converter.

Table 1 .Parameters for the proposed converter simulation

Parameters	Values
Switching frequency	15kHz
Voltage gain	10
Duty cycle	0.62
n	2
Lm	66 µH
Llk	3.3 µH
C1, C2 and C3	20 µF
C0	440 µF

Performance analysis under Open loop condition

The converter is evaluated in open-loop and closed-loop modes. Under closed loop condition, FLC is implanted to increase dynamic performance of the converter. Figure 5. depicts the converter's waveforms under open loop condition.

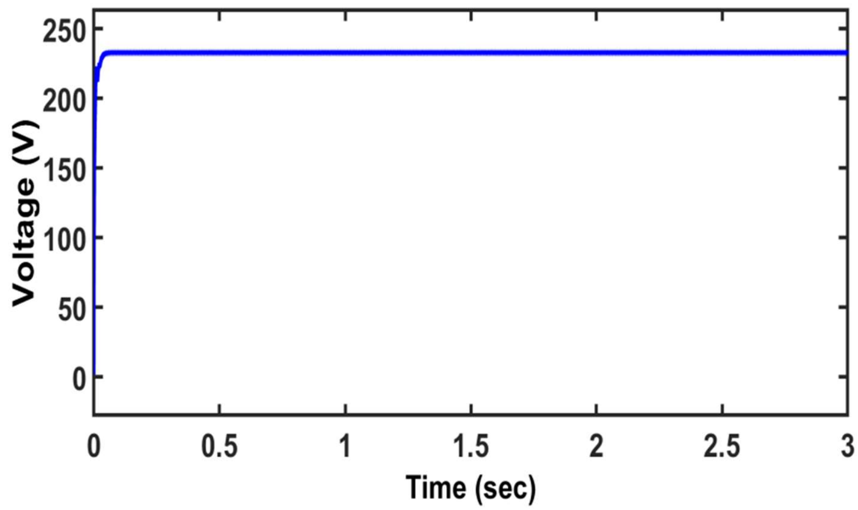

Figure 5. Converter's Output voltage.

The voltage stress on the switch and diodes is shown in Figure 6.

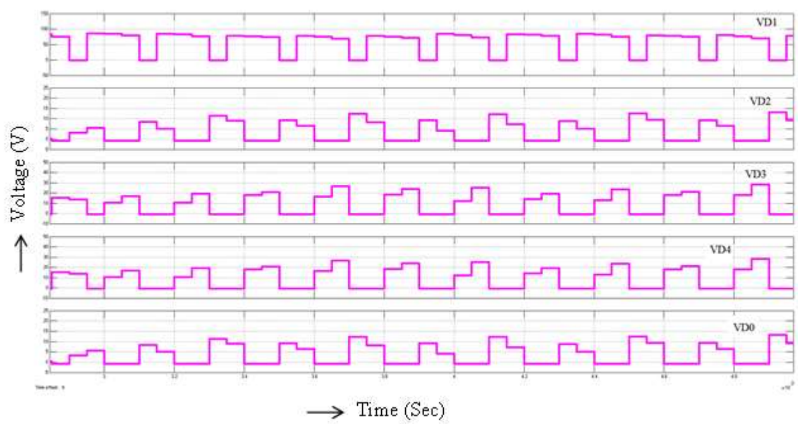

Figure 6a. Voltage stress on the Diodes

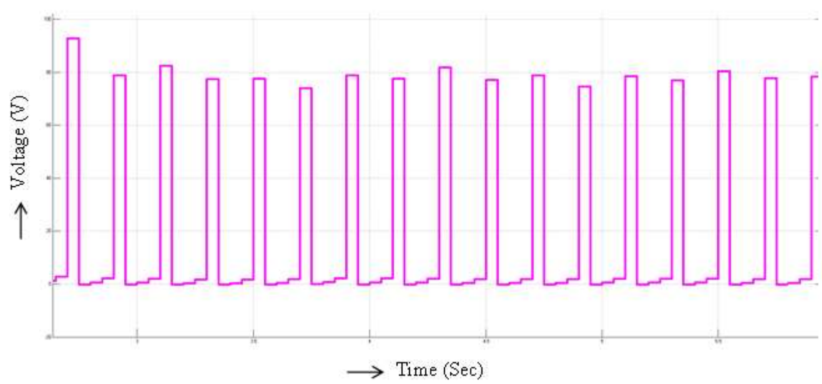

Figure 6b. Voltage stress on the switch

The voltage stress on the MOSFET switch is an average of 70 V, which is less than that of the output voltage. Similarly, the clamp diodes (D1& D2) are subjected to a voltage stress of

60 V and 21.9 V, respectively.

Because D1 is the primary clamp diode, it is subjected to the high voltage stress than that of D2. The average voltage stress on VM cell diodes such as D3, D4 is 40 V. Finally, because it blocks the reverse current, the output diode D0 does not experience maximum stress, and its average stress is 26.65V.

Performance analysis under closed loop condition

Figure 7. depicts the converter's waveforms under fuzzy controller. Under constant input voltage and load conditions, the output voltage waveforms are shown in Figure 7. At a duty cycle of 0.62, the output voltage is increased to 120V. Here fuzzy controller is implemented to establish system stability and to assist the converter in maintaining a consistent output voltage. The voltage stress on the MOSFET switch is an average of 54.25V.

D1& D2 are subjected to average voltage stresses of 45.65 V and 11.27 V, respectively. The average voltage stress on VM cell diodes such as D3, D4 is 38.45 V. Finally, because it blocks the reverse current, the output diode D0 does not experience maximum stress, and its average stress is 24.34 V.

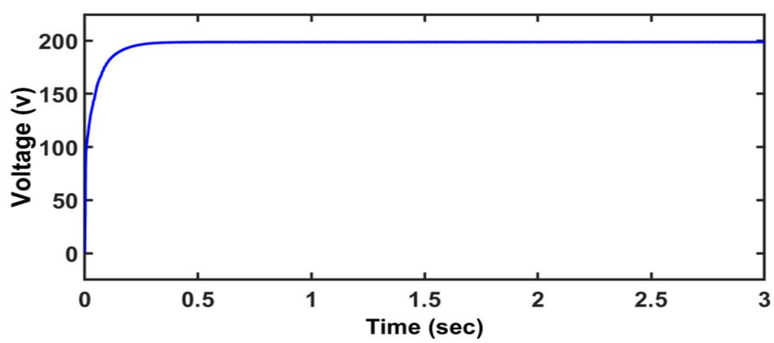

Figure 7. Converter's waveforms under fuzzy controller

Analysis of converter with change in load/ Change in input voltage

Change in load

Initially, the load resistance is about 100 Ω and the converter delivers 100V output voltage for 10V input. At t=0.5 s, the load resistance is changed to 300 Ω and the converter output voltage is equal to 97 V as depicted in figure 8.

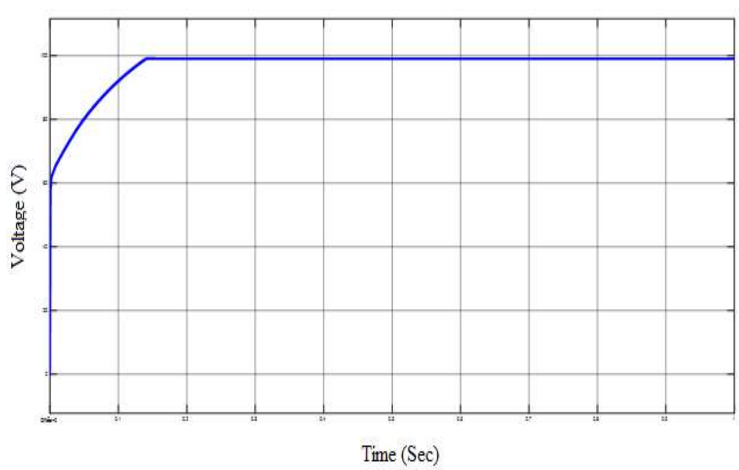

Figure 8. Output voltage when (R_L changes from 100 -300 Ω)

Change in Input voltage

Initially, the input voltage is about 20 V, which eventually raises the output voltage to 200 V and still maintains a gain of 10. At t=0.5 s, the input voltage is changed to 10 V that brings about a rise in a voltage of 100 V and the gain of 10 and is depicted in figure 9.

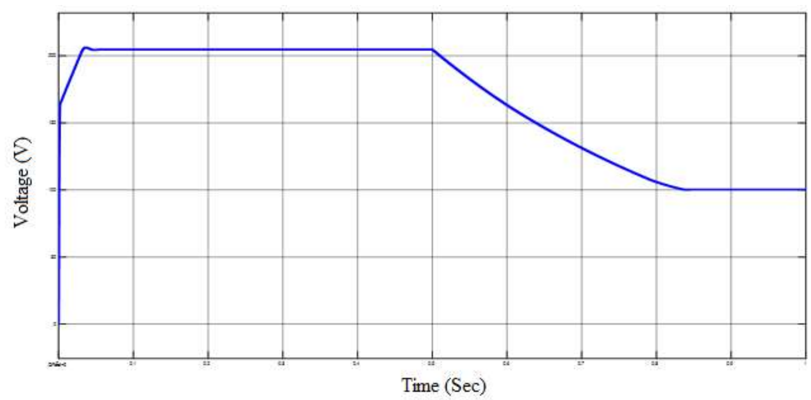

Figure 9. Output Voltage (under change in input voltage and R_L=100 Ω)

From these analysis, it is concluded that the output voltage of the converter depends on the load resistance RL and the input voltage. However, this change voltage/ load will not be reflected in the output when a controller is implemented. It remains the output voltage constant irrespective of change in input/load. The output of the converter with controllers shown in figure 10.

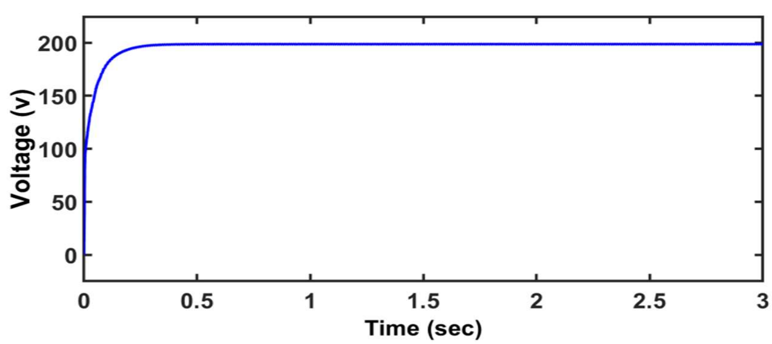

Figure 10. Converter's waveforms under fuzzy controller for change in input (Increment of voltage)

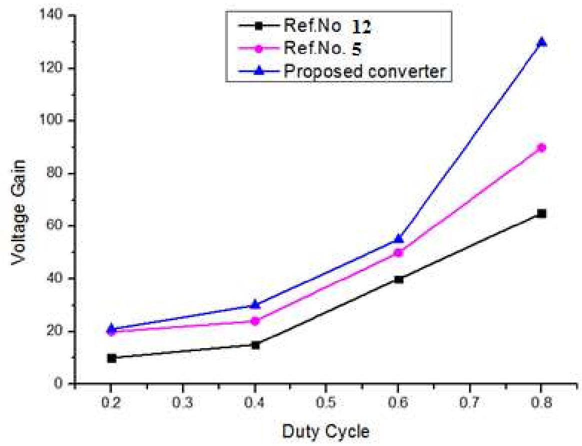

Figure 11. Comparison among various converters

From the above Figure, it is observed that the proposed converter has high voltage gain than the other converters

Conclusion

A high gain DC-DC converter suitable for a PV system is designed in this work. This study discusses a new non-isolated high step-up VM cell-based DC–DC boost converter. By using a passive clamp circuit, the switch's voltage stress is lowered to less than 50% of the output voltage. The clamp circuit may recover the leakage inductance energy, lowering losses and increasing efficiency. Aside from that, the losses are evenly distributed throughout all switching devices. Finally, it is determined that the suggested converter achieves high voltage gain with a lower duty cycle by using a coupled inductor. To increase the dynamic behavior of the converter, controllers are implemented. As the artificial intelligent techniques based controllers provide fast response times with no overshoot, Fuzzy controller is chosen to improve the dynamic behavior of the proposed system. In order to study the effectiveness of the controller, comparative study has been made with conventional PID controller. From the Simulation results, it is proven that the proposed AI based controller has the high efficiency when compared to other controllers. At the same time, the switching losses are also minimized.

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Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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