

A High Efficiency Quadratic Gain DC–DC Converter for Low Voltage Renewable Sources

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Abstract

High gain DC–DC converters have become increasingly important in several applications including renewable energy systems, electric vehicles, and DC microgrids because of the necessity of converting low input voltages to high output voltages efficiently. This study focuses on the design and performance analysis of a high gain DC–DC converter that operates in the Continuous Conduction Mode (CCM). The use of CCM guarantees low current ripples, efficient energy transfer processes, and stable operations. The proposed converter utilizes combinations of inductors, capacitors, diodes, and controlled switches in order to ensure the conversion of low input voltages to higher outputs at a significantly high voltage gain without employing extremely high duty cycles. The converter topology has been designed to optimize the energy transfer and storage process by taking advantage of the various operating modes. The proposed converter design has been able to reduce the voltage stresses applied on the switching components hence improved reliability and better performances. Due to its high voltage gain capability, the suggested converter can be employed in applications such as photovoltaic systems and battery operated systems, which require step-up conversions. Simulations demonstrate the performance of the proposed converter in terms of efficiency and continuous currents.

Keywords: ON/OFF Operation, Forward & Reverse Bias, Sync with Switching, Enables Energy Transfer, Blocks Reverse Current.

1. Introduction

Over the last few decades, there have been tremendous advancements in renewable energy sources, electric vehicles, and DC micro-grids, which have created a high demand for highly efficient power conversion techniques [1]. In many practical cases, the input voltage is usually low, and it needs to be increased for effective usage of these systems, especially in PV systems and fuel cell systems [2].

The conventional DC-DC converters such as the traditional boost converter can be used in increasing the voltage level of electrical energy; however, they face a number of shortcomings, such as high switching loss, increased voltage rating on semiconductor devices, and low efficiency when operated at high duty cycles [3]. High-gain DC–DC converters have been developed using advanced converter topologies that involve the use of switched inductors, switched capacitors, voltage multiplier cells, and coupled energy transfer [4].

From various modes, Continuous Conduction Mode (CCM) stands out because it provides a smaller current ripple, increased efficiency, and increased stability [5]. The reason why CCM operation is recommended is that the inductor current never goes to zero during this mode, thus providing for smooth energy conversion, less electromagnetic interference, and optimal operation of the converter. With such benefits, it is possible to claim that the developed high-gain DC–DC converter includes many passive and active elements, such as inductors, capacitors, diodes, and control switches, thus increasing its gain ratio.

2. Literature Review

In recent years, several novel high gain DC-to-DC converter structures have been proposed in the literature, which can overcome the weaknesses of the traditional boost converters. Boost converters offer a simple topology with reduced number of components; nevertheless, very high gains can be achieved through high duty ratios that result in increased conduction losses and voltage stresses, which leads to reduced efficiency. In order to tackle such disadvantages, more sophisticated structures of high gain converters based on switched inductor, switched capacitor, voltage lifting, and quadratic gain techniques have been proposed in the literature.

The study [1] has suggested a novel high gain single switch quadratic modified SEPIC converter, where the use of quadratic gain technique provides an efficient method for

increasing voltage gain. The proposed converter allows wide-range operating conditions with low voltage stresses in semiconductor devices, and thus making it ideal for DC microgrid application systems. An asymmetric switch-inductor boost converter without isolation was presented in [2] that provides improved voltage gain along with constant input/output current flow. Symmetrical voltage-lift circuit configuration enhances the energy transfer process while mitigating the stresses on active elements. The converter topology is ideal for renewable energy systems that require reliable high step-up voltage conversion.

The high step-up transformerless DC-to-DC converter using switched-inductor and quasi-Z-source networks was introduced in [3]. The proposed DC-to-DC converter increases voltage gain and decreases voltage stress without using coupled inductors and transformers. In addition, the quasi-Z-source network improves the input current continuity, making it a suitable candidate for photovoltaic and distributed generation applications. A transformerless ultra-high-gain DC-to-DC converter topology utilizing switch-inductor, switch-capacitor, and voltage multiplier configurations was presented in [4] for DC microgrids. The proposed multi-gain technique can significantly boost the output voltage by incorporating multiple gain techniques.

The same applies to another converter which uses a non-coupled inductor and is known as a single-active-switch high-voltage-gain DC–DC converter that was described in [5]. This DC-to-DC converter is characterized by an increased voltage gain but at the same time uses a simple topology to reduce stresses within its components while ensuring conversion efficiency. Nowadays, more attention is being paid to converters with quadratic gain. For instance, a novel DC–DC converter with ultra-high voltage gain, quadratic gain characteristic, and enhanced efficiency for renewable energy applications was designed in [6].

A quadratic boost converter with minimized voltage stress was discussed in [7], which also demonstrated quadratic gain characteristics but minimized stress. Further advancements in quadratic converters can be seen in [8] and [9]. Specifically, some innovative designs of high-voltage converters with quadratic gain characteristics were created with an aim to improve voltage gain, efficiency, and decrease current ripples. Besides quadratic gains, researches have also developed other higher order gain structures. As an example, in [10], a unique non-isolated cubic DC-DC converter was presented in order to extend the voltage conversion ratio in renewable power supply schemes. In another study, [11], a highly efficient quadratic high gain

step-up converter was presented which had better boosting characteristics with greater applicability in low voltage renewable power supplies.

Despite all the benefits demonstrated by the discussed converters in terms of higher voltage gain, efficiency and decreased voltage stress, there are still some shortcomings such as high number of components, complex circuitry, input current ripple and lack of flexibility in operation. Another challenge that arises from these converters is the achievement of higher gain together with continuous current operation and decreased stress on the switching devices. This motivates the need for improved high efficiency quadratic gain DC-DC converter topologies operating in CCM (Continuous Conduction Mode).

3. Methodology

The proposed high gain DC–DC converter consists of an input voltage source V_{in} , two inductors $L1$ and $L2$, two capacitors $C1$ and $C2$, two diodes $D1$ and $D2$, two controlled switches $Q1$ and $Q2$, and a resistive load R . The circuit is designed to achieve a high voltage gain while operating in Continuous Conduction Mode (CCM), ensuring that the inductor currents remain continuous and do not fall to zero.

At the input stage, the source V_{in} supplies power to the converter. Inductor $L1$, placed near the input side, acts as the primary energy storage element, storing energy when the switches are turned ON. Capacitor $C1$ is connected in parallel with the input and functions as an intermediate energy storage element, assisting in voltage boosting and stabilizing the input side. Diode $D1$ is connected between the inductors and ensures proper current flow during different switching intervals by allowing current in only one direction.

The second stage of the converter includes inductor $L2$, which plays a key role in transferring the stored energy to the output. When the switches are turned OFF, the energy stored in both inductors $L1$ and $L2$ is released through the diodes. Diode $D2$ conducts during this interval and directs the energy towards the output side. Capacitor $C2$ acts as the output filter capacitor, smoothing the output voltage and supplying continuous power to the load R .

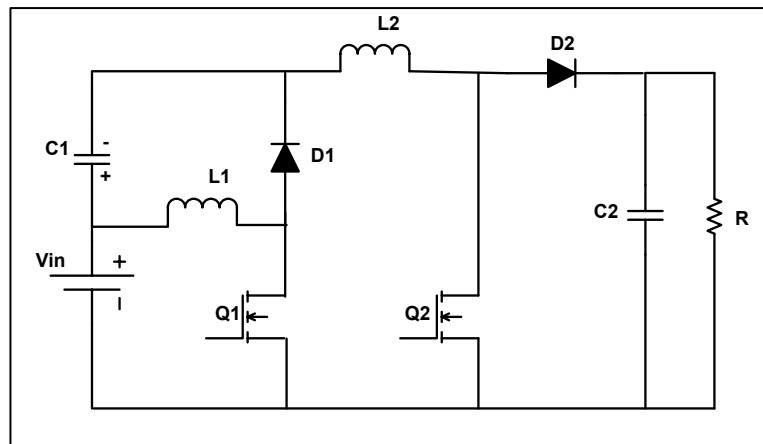


Figure 1. Proposed Converter Circuit Diagram

The Figure 1 illustrate the switches $Q1$ and $Q2$ are controlled using a PWM signal to regulate the operation of the converter. In the ON mode, both inductors hold energy, and in the OFF mode, this energy is discharged through the output capacitor, which causes an increase in the output voltage level. The use of inductors and capacitors allows achieving high voltage gain levels for the given converter configuration without resorting to high duty cycles. Also, in this topology, voltage stresses across the switch are reduced. Therefore, this topology efficiently uses the energy storing and transfer capabilities to provide high voltage gain levels.

Mode:1

During Mode 1, both switches $Q1$ and $Q2$ are turned ON. In this condition, diodes $D1$ and $D2$ become reverse biased, preventing current flow toward the output side. The input voltage source V_{in} directly supplies energy to the inductors $L1$ and $L2$, causing them to store energy in the form of magnetic fields.

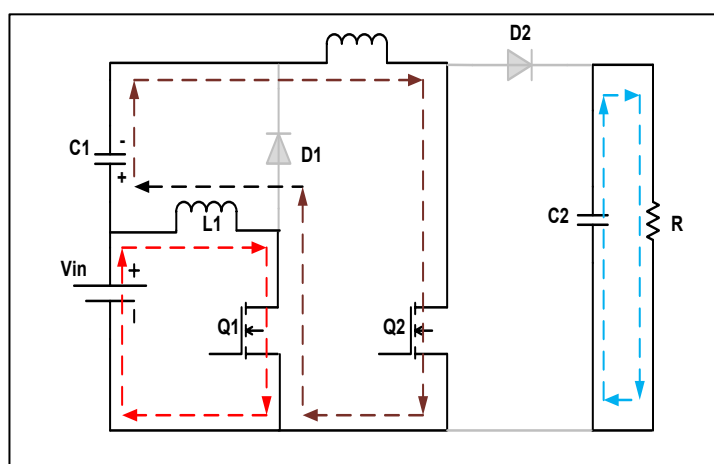


Figure 2. Proposed Converter Circuit Diagram Mode1

$$V_{in} = V_{L1} \tag{1}$$

$$V_{L2} = -V_{C1} - V_{in} \tag{2}$$

$$V_{C2} = V_{C0} \tag{3}$$

The inductor currents increase linearly during this interval.

The Figure 2 illustrate meanwhile, the output capacitor $C2$ provides the required energy to the load, maintaining a continuous output voltage. Since the inductors are charging and no energy is transferred to the output, this mode is referred to as the energy storage interval. As the converter operates in continuous conduction mode, the inductor currents do not fall to zero at any point.

Mode:2

During Mode 2, both switches $Q1$ and $Q2$ are turned OFF. As a result, diodes $D1$ and $D2$ become forward biased, allowing current to flow toward the output. The inductors $L1$ and $L2$, which stored energy during Mode 1, now release this energy. Inductor $L1$ discharges through diode $D1$, while inductor $L2$ discharges through diode $D2$ and transfers energy to the output capacitor $C2$ and the load.

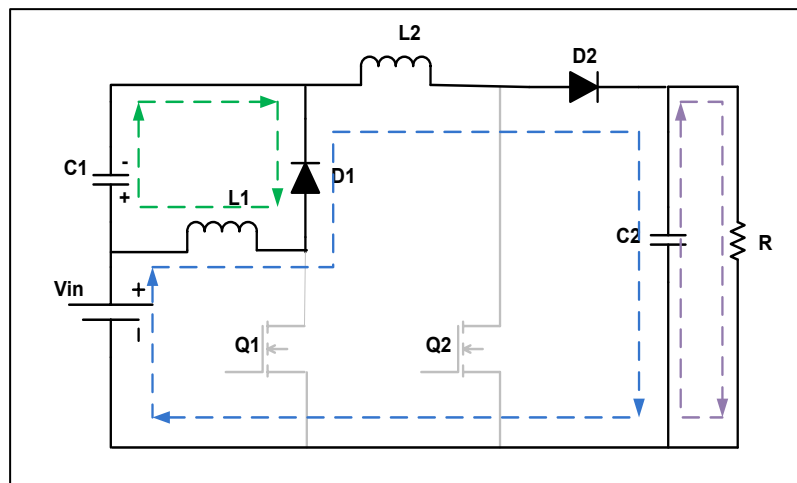


Figure 3. Proposed Converter Circuit Diagram Mode2

$$V_{L1} = -V_{C1} \tag{4}$$

$$V_{L2} = V_{C2} - V_{in} - V_{C2} \tag{5}$$

$$V_{C2} = V_0 \tag{6}$$

The Figure 3 illustrate the combined effect of the input source and the energy released by the inductors results in a boosted output voltage, achieving high voltage gain. During this interval, the inductor currents decrease but remain above zero, ensuring continuous conduction mode operation. This mode is known as the energy transfer interval, as power is delivered to the load

The given Figure 4 shows the key waveforms of a DC–DC converter during switching operation, including gating signals, inductor currents, and diode/switch voltages. The top waveform represents the gating pulse, which controls the switching device by turning it ON and OFF periodically. The triangular waveforms (red and green) represent the inductor currents, which increase linearly during the ON state (energy storage) and decrease during the OFF state (energy transfer), indicating operation in continuous conduction mode (CCM). The square waveforms (blue and brown) represent the voltages across switches or diodes, alternating between high and low levels depending on whether the device is conducting or blocking. When the switch is ON, the corresponding diode is reverse biased (negative voltage), and when the switch is OFF, the diode becomes forward biased, allowing current to flow to the output. The synchronized behavior of these waveforms clearly illustrates the energy storage and transfer process, confirming proper switching action and efficient operation of the high-gain DC–DC converter.

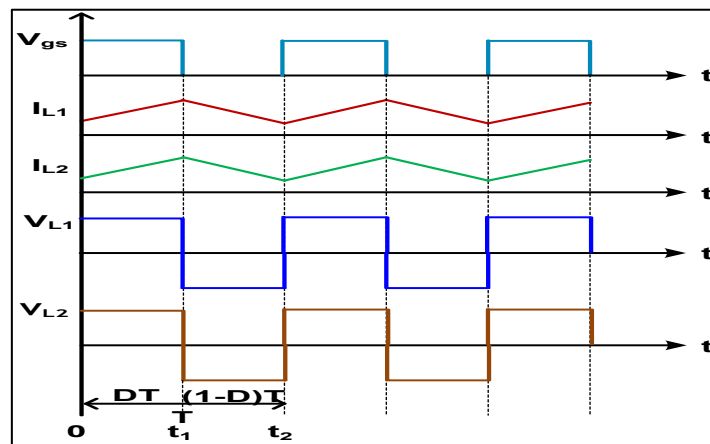


Figure 4. Model Graph of Inductor Voltage and Current

The given Figure 5 represents the voltage waveforms across different diodes in the DC–DC converter. Each waveform shows a square-type signal, indicating the switching behavior of the diodes during operation. When the diode voltage is near zero or slightly positive, the

diode is forward biased and conducting current, allowing energy to flow toward the output. When the voltage becomes negative, the diode is reverse biased, blocking current flow.

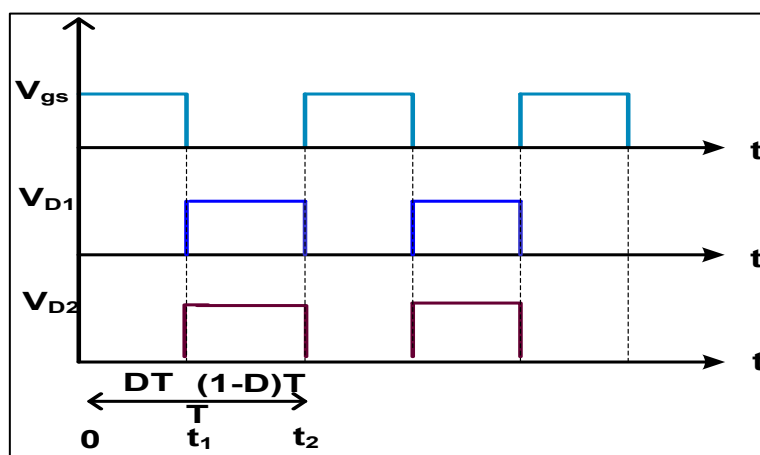


Figure 5. Model Graph of Diode

The represents the waveforms are time-shifted, which means the diodes conduct at different intervals depending on the switching state of the MOSFETs. This sequential conduction ensures proper energy transfer between different stages of the converter. The alternating ON and OFF states of the diodes confirm that they are working in coordination with the switching pulses, enabling efficient voltage boosting. Overall, these waveforms demonstrate correct diode operation, ensuring controlled current flow and proper functioning of the high-gain DC–DC converter.

3.1 Gain Equation

The voltage gain of the proposed high gain DC–DC converter operating in Continuous Conduction Mode (CCM) is given by

$$\frac{V_0}{V_{in}} = \frac{1}{(1-D)^2} \quad (7)$$

This expression indicates that the output voltage V_0 is boosted significantly compared to the input voltage V_{in} as a function of the duty cycle D . Unlike a conventional boost converter, which has a gain of $\frac{1}{1-D}$, the proposed converter achieves a quadratic gain relationship, resulting in a much higher voltage step-up capability. As the duty cycle increases, the denominator $(1-D)^2$ decreases rapidly, thereby increasing the output voltage. This increased gain is made possible because of the combination of the inductors and capacitors that are able to store and

deliver energy efficiently during switching. The second feature of this gain is its quadratic nature, meaning that a high output voltage can be obtained even at moderate duty cycles, and therefore, switching losses will be minimized along with reduced voltage stress on semiconductors. The presented circuit design is therefore more efficient and can be implemented in renewable energy conversion, electric cars, or DC microgrids.

3.2 Parameter Design

3.2.1 Inductor Design

In the proposed high gain DC – DC converter operating in Continuous Conduction Mode (CCM), the inductors L_1 and L_2 are designed separately since their current ripples are not equal, i.e., $\Delta I_{L1} \neq \Delta I_{L2}$. This is due to the different roles and positions of the inductors within the converter topology. Inductor L_1 is directly connected to the input side and primarily stores energy during the ON state, while inductor L_2 is involved in transferring energy to the output during the OFF state. The inductance values are determined based on allowable current ripple, switching frequency, and duty cycle. The design equations for the inductors are given by

For L_1 ,

$$L_1 = \frac{v_{in} D^2}{\Delta I_{L1} (1-D) f_s} \quad (8)$$

For L_2 ,

$$L_2 = \frac{V_{in} D^2}{\Delta I_{L2} (1-D)^2 f_s} \quad (9)$$

3.2.2 Capacitor Selection

The design of capacitors in the proposed high gain DC-DC converter is primarily determined by the switching frequency f_s and the allowable ripple voltage ΔV_C . Capacitors play a crucial role in maintaining voltage stability, reducing ripple, and ensuring continuous power supply to the load. The fundamental capacitor relation $I_C = C \frac{dV}{dt}$ is used to derive the required capacitance values based on the ripple constraints.

For the output capacitor C_1 , which is responsible for supplying the load and smoothing the output voltage, the capacitance is given by

$$C_1 = \frac{DI_0}{\Delta V_{C_0} f_s} \quad (10)$$

where I_0 is the output current and D is the duty cycle. This equation shows that the capacitance is directly proportional to the output current and duty cycle, and inversely proportional to the switching frequency and allowable voltage ripple.

For capacitor C_2 , which acts as an energy transfer and filtering element, the capacitance is expressed as

$$C_2 = \frac{2DI_0(1+D)}{\Delta V_{C_1} f_s (1-D)} \quad (11)$$

The capacitor is useful in stabilizing the output and facilitates energy transfer in switching modes. Generally, the value of the capacitor depends on the permissible voltage ripple, switching frequency, duty cycle, and load current. The appropriate choice of capacitors guarantees minimized voltage ripples, efficient operations, and the stable running of the converter in CCM.

3.2.3 Voltage Stress Across Diode and Switch

During mode 1, the switch is turned on. In this mode diode D_1 and D_2 are reverse biased. Thus, voltage equation for diode D_1 and D_2 is written as,

Voltage stress equation across diode (D_1)

$$\frac{V_{D1}}{V_0} = -\frac{(1-D)}{2} \quad (12)$$

Similarly, the voltage stress across diode D_2 is equal to the negative of the output capacitor voltage,

$$\frac{V_{D2}}{V_0} = -1 \quad (13)$$

showing that diode D_2 is subjected to full output voltage in reverse bias during Mode 1.

For the switches, since both Q_1 and Q_2 are in the ON state, the voltage across them ideally becomes zero. The voltage stress across switch Q_1 is given by

$$V_{Q1} = 0 \quad (14)$$

The voltage stress across switch Q_1 is given by

$$V_{Q2} = 0 \quad (15)$$

3.2.4 Effect of Non-Ideality on Output Voltage

Non-ideal characteristics of the proposed converter will be discussed in this section based on considering the internal resistances of the switch, inductors, capacitors, and diodes, which make up the system. Forward voltage drop of diodes will also be accounted for here. Each voltage drop has an influence, to a certain degree, on the efficiency of the converter. The voltage drop impact on output voltage in each of these components is determined separately in this section.

For Switches:

$$V_0 = \frac{V_{in} - r_{sw} I_{sw} D^2}{(1-D)^2} \quad (16)$$

For Inductors:

$$V_0 = \frac{V_{in} - r_{L1} I_{L1} + r_{L2} I_{L2} (1-D)}{(1-D)^2} \quad (17)$$

For Diodes:

$$V_0 = \frac{V_{in} D - r_{d1} I_{d1} (1-D) + r_{d2} I_{d2} (1-D)^2}{(1-D)^2} \quad (18)$$

For Capacitors:

$$V_0 = \frac{r_{C1} I_{C1} D^2 + V_{in} - r_{C1} I_{C1} + r_{C2} I_{C2} (1-D)^2}{(1-D)^2} \quad (19)$$

Overall, the inclusion of such non-ideal components results in poor voltage gain performance, higher losses, inefficiencies, and greater thermal stresses in the circuit. Thus, proper selection of components and design are crucial in ensuring optimal performance of the DC-DC converter with high gain.

4. Simulink and Results

Figure 6 shows a DC-DC converter circuit designed for high gains in MATLAB/Simulink. The circuit begins with a DC supply voltage source, which can be

replaced by sources of renewable energy such as solar panels and batteries. The supply voltage is then fed to inductors, modeled through a series RLC circuit, where the inductors store energy whenever the switches are on. The two switching devices are MOSFET switches that operate at a high frequency; they are actuated through pulse generators. Energy is stored in the inductors when the switches are ON and is discharged to the output when they are OFF.

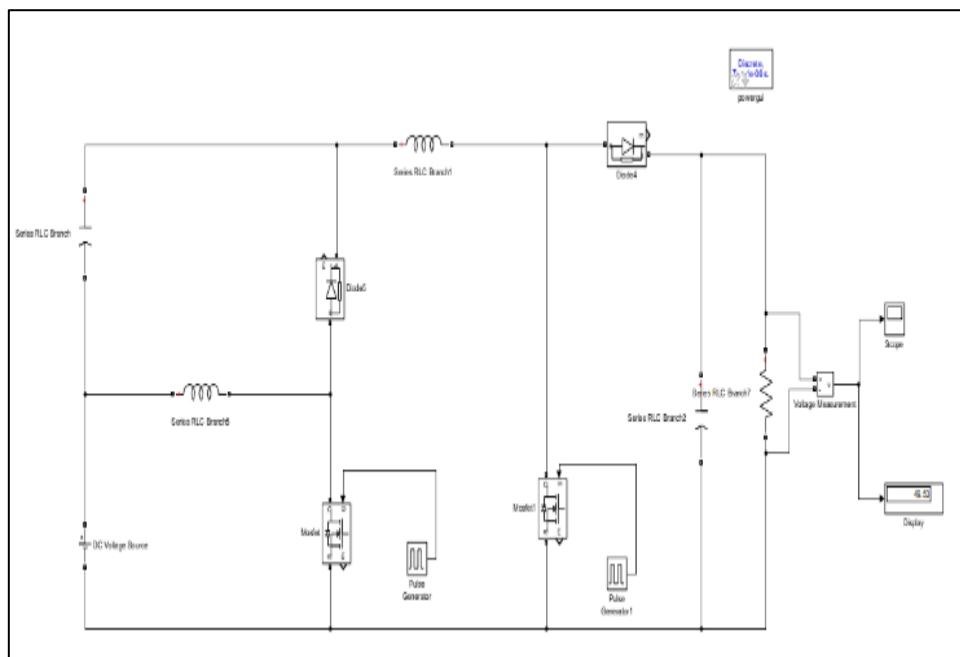


Figure 6. Simulink Model of High-Gain DC–DC Converter

From the Figure 6 above, the fact that there are many inductors, diodes, and switching devices present shows that it is a high gain or quadratic type of converter. This means that a high voltage can be obtained compared to the normal boost converter. The output voltage is filtered using the capacitor to reduce any possible ripples. Also, there is a resistive load representing the actual load that will be connected to the circuit. The voltage measurement, scope, and the display blocks show the actual output voltage of about 49.5 V.

Figure 7 is the output waveform that is used to control the operation of a switching device (MOSFET). The waveform is shown above and consists of alternating voltages between 0 and 1, indicating when the switching device is operating in the OFF mode and when it is on. For example, a signal of value 1 indicates that the MOSFET is on. This will enable the current to flow in the circuit and enable the inductor to store energy.

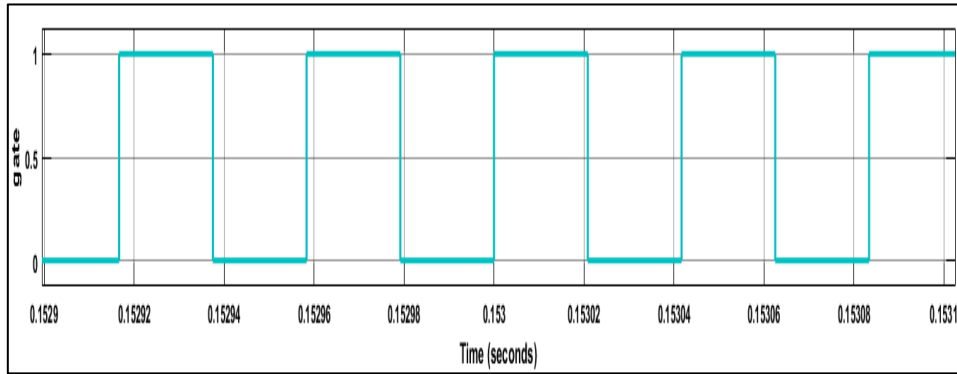


Figure 7. Gating Pulse Waveform for MOSFET Switching

Figure 7 shows that the time the signal is ON for each switching cycle is known as the duty cycle, which governs the value of the output voltage of the converter. The pulses shown in the waveform are equally spaced, which means that there is a constant switching frequency in the system, while the time taken by the ON process defines the energy transfer. Therefore, the gating signal becomes important in controlling the operations of the DC-DC converter.

Figure 8 below illustrates the input voltage (V_{in}) of the converter. This signal shows a constant straight line, which means that the input is a constant DC supply voltage, roughly at 12V. Contrary to the waveforms of the switch signals or inductor currents, the input signal is constant over time; therefore, it implies that the DC-DC converter is supplied by a constant power source.

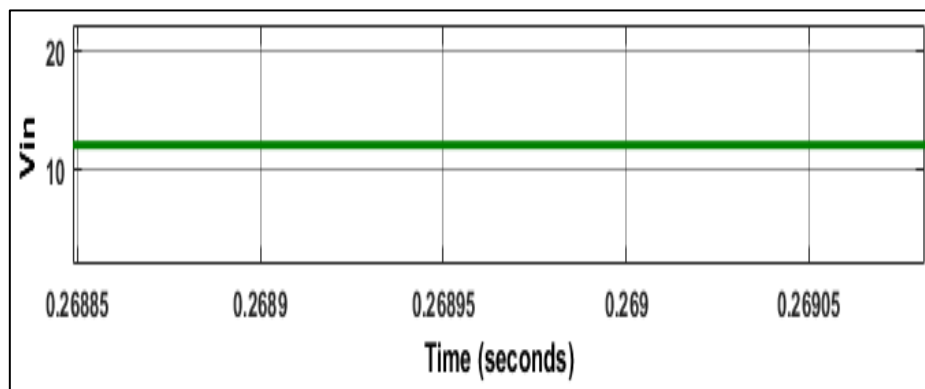


Figure 8. Input Voltage (V_{in}) Waveform of the Converter

From Figure 8, it can be seen that the constant input voltage is necessary for the analysis of the converter's performance because it has no effect on the voltage boosting or regulation. All this process takes place because of switching and other passive elements and not input variation. This proves that there is a constant input voltage in the system.

The below waveforms show the voltage levels in different switching points (V1 and V2) of the DC-DC converter. From the above graph, one realizes that both voltages have pulsating waveforms which result from the ON and OFF switching action of MOSFETs. The voltage changes between negative and positive values.

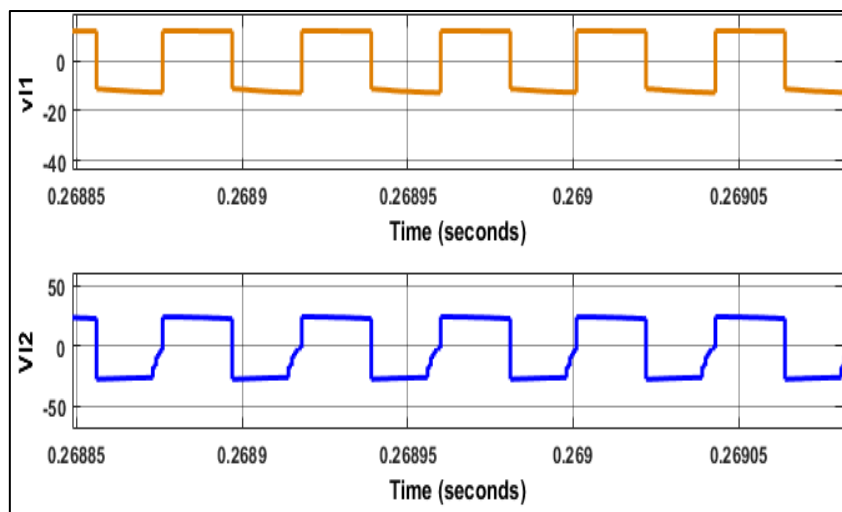


Figure 9. Inductor Voltage of V11 and V12

The Figure 9 shows the effect that, when the switch is ON, the voltage drops across the node as energy is being stored in the inductor. In addition, the graph also shows the voltage rise at the time of the switch being OFF since the energy is discharged to the output using the diode. Therefore, the step-up and the slope of the wave forms show the charging and discharging of the inductors and capacitors. The existence of two different wave forms indicates multi-stage or high gain operation where energy is being handled in several sections of the circuit. All in all, these wave forms prove that voltage boost operation takes place as intended.

The following are waveforms of currents flowing in the inductors IL1 and IL2 of the DC – DC converter. Both currents display ripple waveform. As such, this shows the nature of currents in inductors during switching converters. For example, when the switch is ON, the currents increase in the inductors as energy is being stored in the magnetic field of the inductor. Similarly, the current reduces in the OFF state since energy is being discharged to the output.

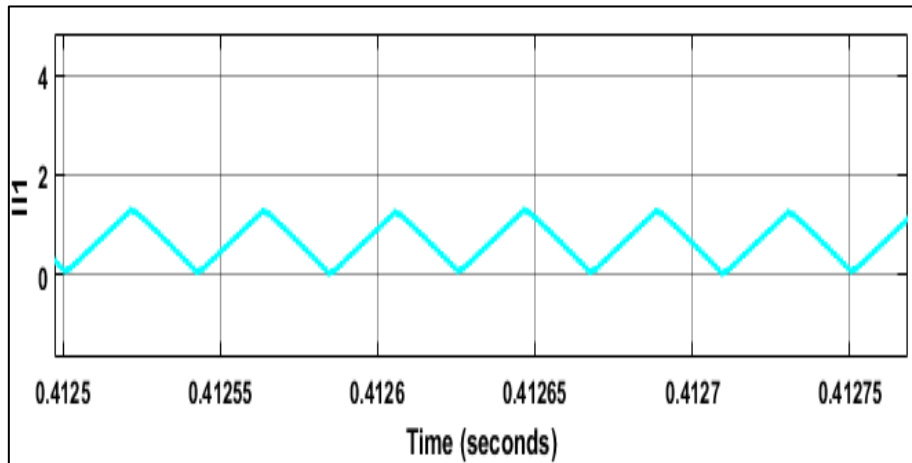


Figure 10. Inductor Current Waveforms IL1

Notably, the current in both IL1 and IL2 does not go to zero at any point in time, showing that the converter is indeed running under CCM mode. The waveform is regular and periodic in nature, hence indicating a steady-state operation.

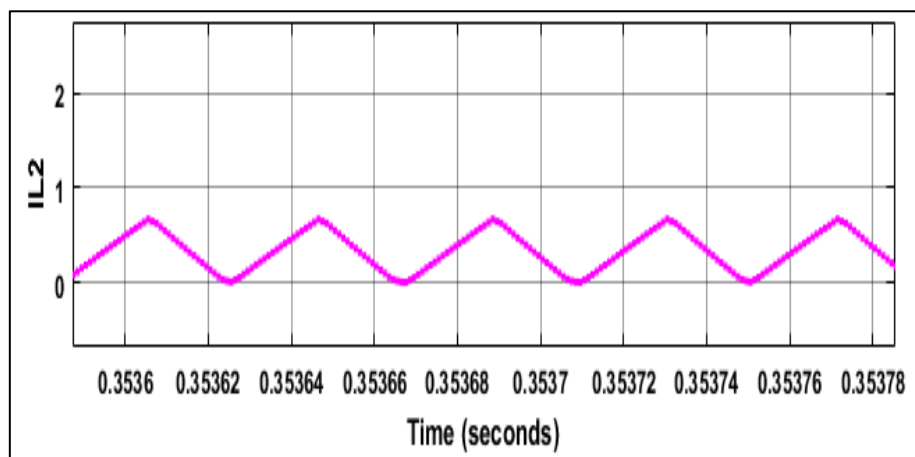


Figure 11. Inductor Current Waveforms IL2

Figure 10 and 11 clearly depict that there are two inductor currents, hence showing that it is a high-gain/multi-stage converter because energy is processed through more than one stage to produce high voltage gains.

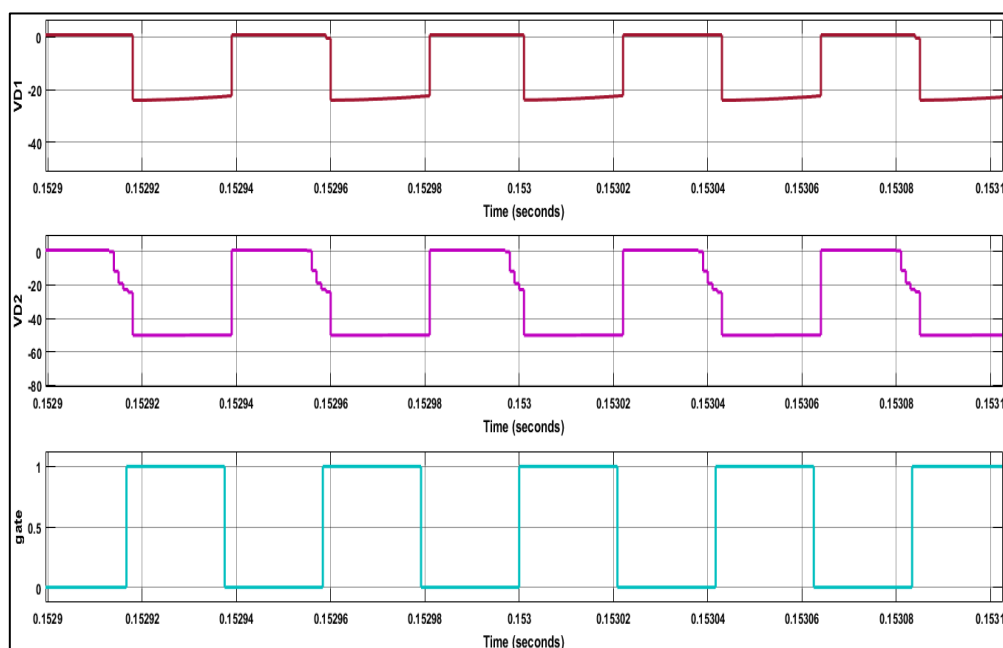


Figure 12. Diode Voltage Waveforms (VD1 and VD2)

Figure 12 illustrates the stepped characteristics of VD2 waveform, showing that there are several energy storage elements (inductors and capacitors) used in this case, thus showing that the converter works on multiple stages or with high gain. In summary, the above waveforms show the right alternate conduction of both diodes and switches, which is crucial for the converter to be able to boost the output voltage. In case when the switch is OFF, the sharp rise in voltage is experienced because of the energy stored being transferred to the output side using the diode. In fact, both the stepped and sloped sections of the waveforms show how inductors and capacitors are charged and discharged. The presence of two separate waveforms shows multi-stage or high-gain operation, which involves processing of energy in several sections of the converter.

The provided waveforms are for the voltages across the capacitors denoted as V_{c1} and V_{c2} within the DC to DC converter. Waveform V_{c1} depicts a small ripple voltage superimposed on a lower level voltage (around 10-15V). This signifies that capacitor V_{c1} is associated with intermediate storage of energy through repeated processes of charging and discharging.

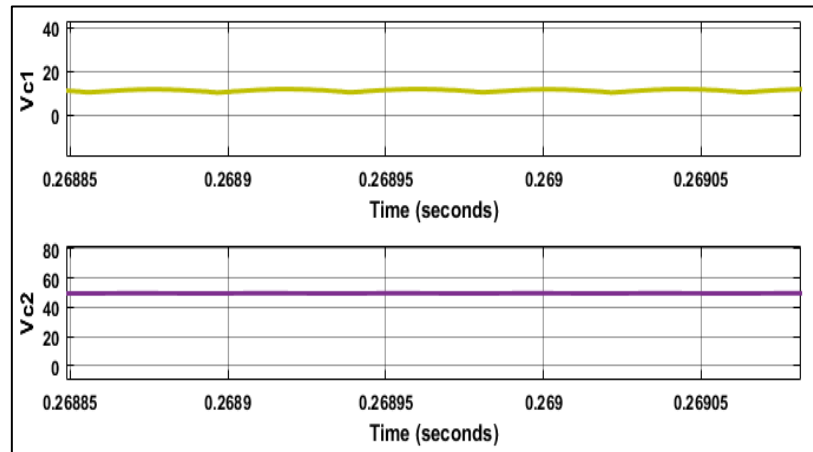


Figure 13. Capacitor Voltage Waveforms (Vc1 and Vc2)

The graph shown in Figure 13 represents the waveform of Vc2, which is nearly constant and has a higher voltage value (approximately 50 volts). This waveform is similar to the output voltage of the power supply converter. This capacitor serves as the primary filter capacitor for the output voltage and maintains its DC value by eliminating any fluctuations in the output voltage. The disparity between the voltage values and ripple reveals that the power supply converter operates through various stages where Vc1 and Vc2 play crucial roles.

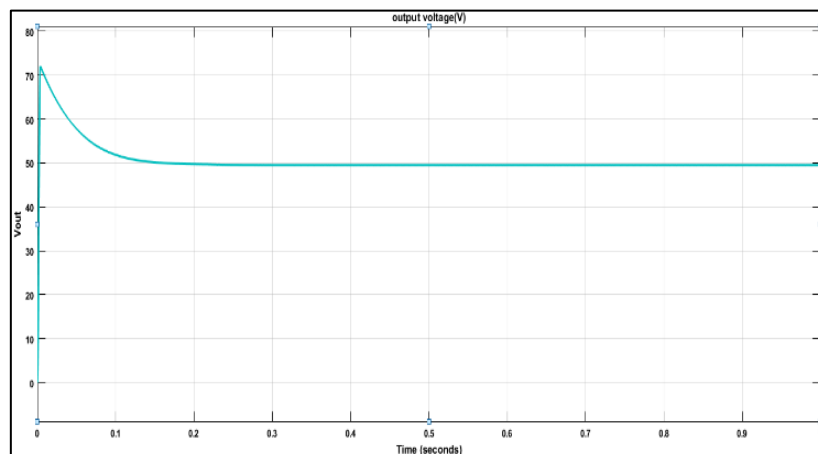


Figure 14. Transient Response of Output Voltage (Vout)

The provided wave form above denotes the time response of the output voltage (Vout) from the DC-to-DC converter. To begin with, the voltage increases quickly before attaining a maximum value of approximately 70V, where there is an overshoot. This results from the quick transition of energy, leading to the charging process of the output capacitor during its first operation. Finally, the voltage falls and stabilizes at 50V. Figure 14 provides further evidence

regarding the above analysis and represents a common phenomenon, where the voltage decreases smoothly without any oscillation. This clearly denotes good damping and stability, where the output voltage is adequately filtered by the output capacitor. The output voltage stays almost constant and without any fluctuation once steady state is achieved.

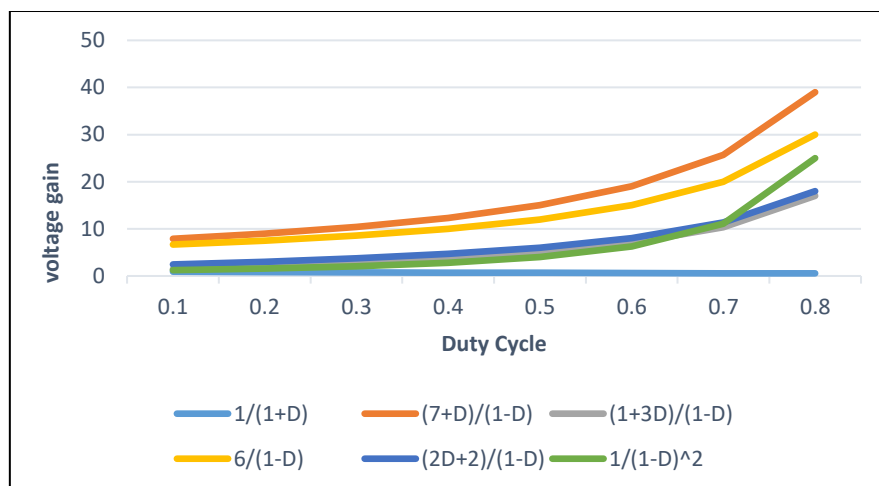


Figure 15. Gain Vs Duty Cycle

Figure 15 gives a comparison of the voltage gain features of different high-gain DC-DC converter architectures as per their duty ratio. As can be seen from Figure 15 above, the voltage gain feature increases with an increase in the duty ratio for all DC-DC converters; however, the rate of increase varies depending on the converter used. For instance, the converter architecture given by $(7 + D)/(1 - D)$ offers the maximum voltage gain owing to its effective voltage-lift switched-inductor converter architecture. Another converter architecture given by $6/(1 - D)$ also experiences significant increase in voltage gain for higher duty ratios. The converter architecture represented by $1/(1 - D)^2$ offers nonlinear increase in voltage gain since it is a quadratic converter architecture. Similarly, another quadratic converter architecture with voltage gain equal to $(2D + 2)/(1 - D)$ provides high-voltage gain. On the other hand, conventional low-gain converter architectures provide relatively poor voltage gain.

5. Conclusion

In this work, a high gain DC-DC converter running in Continuous Conduction Mode (CCM) has been presented. This paper presents a topology that takes advantage of inductor, capacitor, diode, and switch elements to get a much higher voltage gain than that of conventional boost converters without employing high duty cycle conditions. Different modes

of operations have been discussed here to get an understanding of the energy storing and energy transferring processes in order to achieve higher voltage gain by the converter. Voltage gain formula has proved that the converter works on the principle of quadrature boosting. As a result, the converter is capable of providing higher voltage gain from a low input voltage. Besides, the selection of inductor and capacitors in this work makes sure that the system operates at low ripples in current and voltage which leads to higher efficiency and stability. Moreover, this work shows lower stress in switches and diodes that make the system more reliable. However, real world components suffer from certain non-ideal characteristics leading to some energy losses.

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