Two-Switch High Gain Non-Isolated Cuk Converter

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Abstract−**This paper introduces a two-switch high gain non-isolated Cuk converter which can be used as a high gain DC-DC converter in renewable energy, such as photovoltaic and fuel cell, applications because their output is low. As the conventional, the proposed Cuk converter provides negative output voltage but with a higher voltage in magnitude. The main advantage of the proposed converter is having lower voltage stress with the ability to maintain a higher voltage gain. By combining a switched-inductor and a switched-capacitor into the conventional Cuk converter, the proposed Cuk converter has the ability to reach 13 times the input voltage for a duty cycle D of 0.75. Also, by attaching more switched-inductors to the proposed Cuk converter, more voltage gain can be achieved. A complete theoretical analysis of the Continuous Conduction Mode (CCM) of the proposed Cuk converter is presented and the key aspects of the circuit design have been derived. Also, a comparison in terms of voltage gain and voltage stress between the proposed Cuk converter and Cuk converters using other techniques is presented. The proposed Cuk converter has been designed for 100W rated power, -152V output voltage, 50kHz switching frequency, and 75% duty cycle. The presented converter is simulated in Matlab/Simulink and the results are discussed.**

Keywords-Cuk converter; DC-DC converters; photovoltaic; switched-inductor; switched-capacitor

I. INTRODUCTION

Due to the expected depletion of the traditional energy sources, the world pays growing attention to alternative ones [1]. Nowadays, most attention goes to the photovoltaic (PV) energy source because it is a pollution free, stable system, and has continuous reduction in cost [2]. The price of a PV panel went from $4.90/WPK in 1998 down to $1.28/WPK in 2011 which means 74% reduction. PV systems are used today in many applications, such as water pumping, battery charging, home power supply, etc. [3-5]. Figure 1 shows a block diagram of a typical sustainable energy system, which is composed of renewable energy sources, a high step-up DC-DC converter, a DC grid, and an inverter for AC applications. Usually, the rated voltage of renewable energy sources, such as PV and fuel cell, is at low level, and thus, a high gain DC-DC converter is required. Generally, the most commonly used topology to supply high output voltage is the conventional boost converter. However, when the conventional boost converter is operated at a high output voltage, the duty cycle will become unity. This will lead to induce high current ripple, low efficiency, and result in severe reverse-recovery as well as high Electro

Magnetic Interference (EMI) problems [6-8]. Many high step-up DC-DC converters have been proposed and are utilized in renewable energy applications [9-16].
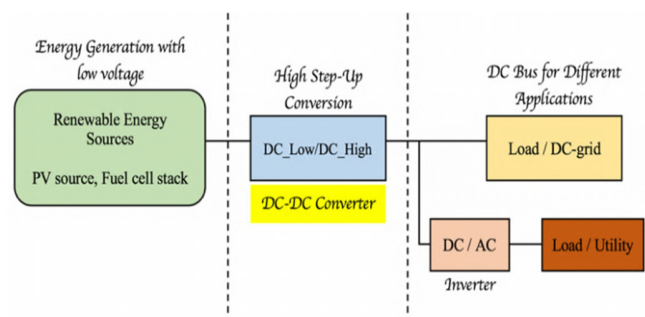

Fig. 1.   A typical renewable energy source system.

In this paper, the main aim was to design a DC-DC converter with high voltage gain and low voltage stress on the main semiconductor switch. This was done by integrating both the switched-inductor and the switched-capacitor techniques into the conventional Cuk converter. The Cuk converter has many advantages over other non-isolated converters, such as having non-pulsating input and output currents, low output voltage ripple, and good steady-state performance [17-19].

II. POWER CIRCUIT

A MOSFET, a diode, a capacitor, and an inductor have been added to the conventional Cuk converter to maintain high voltage gain and low voltage stress in order to form the proposed Cuk converter as shown in Figure 2. A MOSFET and an inductor are added to form the switched-inductor in which the two inductors are charged in parallel when the two MOSFETs are on, and they get discharged in series when the two MOSFETs are off. Moreover, the diode and the capacitor are added to perform the switched-capacitor in which the two capacitors are discharged in series when the two MOSFETs are on, and they get charged in parallel when the two MOSFETs are off.

III. MODES OF OPERATION

The proposed Cuk converter is analyzed in Continuous Conduction Mode (CCM). The operation of the proposed converter is that either both the MOSFETs are simultaneously on or off. Thus, two modes of operation exist.
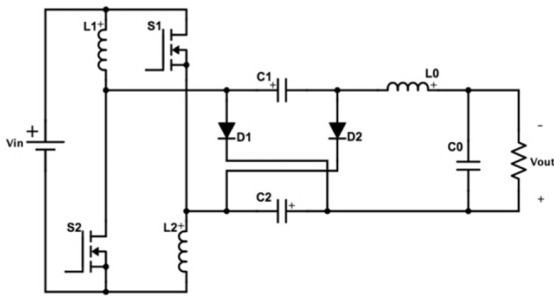
Fig. 2.   The proposed Cuk converter.

A. On-Mode

When the two MOSFETs S_1 and S_2 are simultaneously conducting, the two inductors L_1 and L_2 of the switched-inductor are charged in parallel by the input supply voltage Vin. The current direction is shown in Figure 3. Also, the two diodes D_1 and D_2 are reversed-biased, and therefore the two capacitors C_1 and C_2 get discharged in series. The load is supplied by the input voltage V_{in} and the discharged energy from the two capacitors C_1 and C_2.
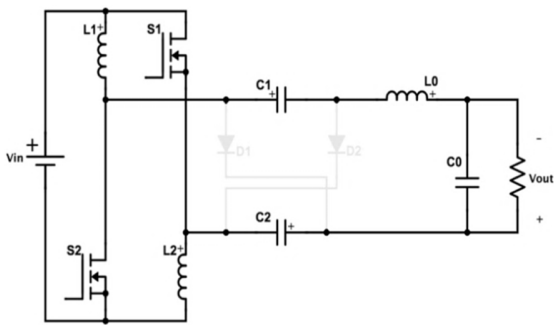

Fig. 3.   The proposed Cuk converter in on-mode.

B. Off-Mode

When the two MOSFETs are simultaneously not conducting, the two inductors of the switched-inductor are discharged in series. The current direction is shown in Figure 4.
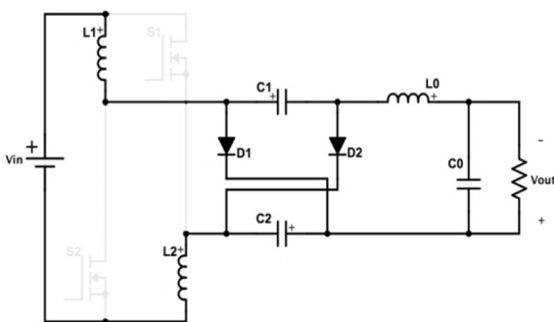

Fig. 4.   Proposed Cuk converter in on-mode in off-mode.

Also, the two diodes are forward-biased, and therefore the two capacitors are charged in parallel. The load is supplied by the input voltage V_{in} and the discharged energy from the two

inductors. The switching diagram of the steady-state waveforms with enlarged variations in CCM of the proposed Cuk converter is shown in Figure 5.
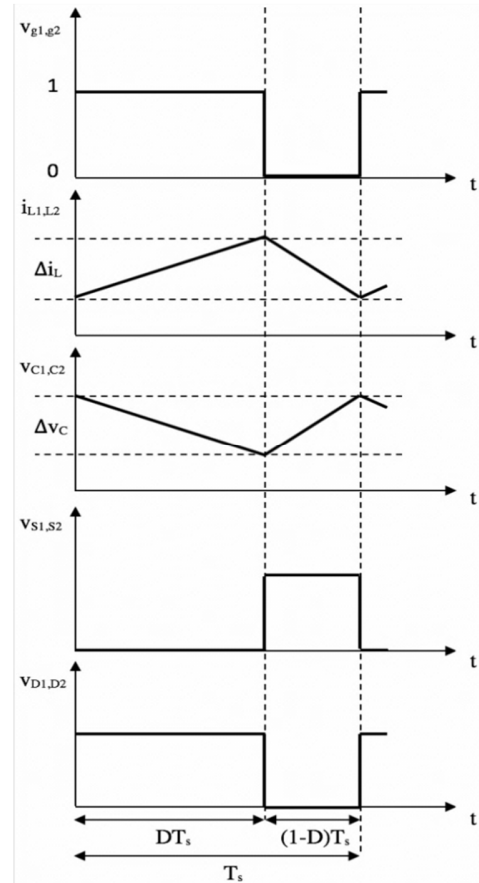

Fig. 5.   Main steady-state waveforms of proposed Cuk converter.

IV.   CIRCUIT ANALYSIS

To simplify the analysis, it is assumed that the proposed Cuk converter is operating in steady-state. Likewise, the following assumptions are made: all components are ideal (100% efficiency), the input voltage V_{in} is pure DC, and all capacitors C_1, C_2, and C_{out} are sized to have a relatively small voltage ripple at a switching frequency (f). When the two MOSFETs S_1 and S_2 are on, the voltage across the inductors L_1, L_2, and L_{out} are expressed in (1) and (2) ($C_1=C_2=C$):

$$V_{L_1} = V_{L_2} = V_{in} \quad (1)$$

$$V_{L_{out}} = V_{in} + 2V_C - V_{out} \quad (2)$$

where V_C stands for the voltage across capacitors C_1 and C_2.

When the two MOSFETs S_1 and S_2 are off, the voltages across the inductors L_1, L_2, and L_{out} are expressed in (3) and (4):

$$V_{L_1} = V_{L_2} = \frac{V_{in} - V_C}{2} \quad (3)$$

$$V_{L_{out}} = V_C - V_{out} \quad (4)$$

The expressions in (5) and (6) can be obtained by applying the volt-second method to the inductors L_1, L_2, and L_{out}:

$$V_{in}D + \left(\frac{V_{in} - V_C}{2}\right)(1 - D) = 0 \quad (5)$$

$$(V_{in} + 2V_C - V_{out})D + (V_C - V_{out})(1 - D) = 0 \quad (6)$$

From (5), the voltage across C_1 and C_2 is expressed in (7):

$$V_C = \frac{(1+D)}{(1-D)}V_{in} \quad (7)$$

By substituting (7) into (6), the ideal voltage gain in CCM for the proposed Cuk converter is expressed in (8):

$$M_{CCM} = \frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}} = \frac{(1+3D)}{(1-D)} \quad (8)$$

The output inductor average current $I_{L_{out}}$ can be considered equal to the output average current I_{out}. Therefore, (9) is obtained from (8).

$$I_{L_{out}} = I_{out} = \frac{(1-D)}{(1+3D)}I_{in} \quad (9)$$

Also, the input inductor currents can be obtained in (11) by using (10).

$$I_{in} = \left(2I_{in} + I_{L_{out}}\right)D + I_L(1 - D) \quad (10)$$

$$I_L = I_{L_1} = I_{L_2} = \frac{(1+D)}{(1+3D)}I_{in} = \frac{(1+D)P_{out}}{(1+3D)V_{in}} \quad (11)$$

The voltage stress across the two diodes D_1 and D_2 are expressed in (12):

$$V_{D_1} = V_{D_2} = \frac{2}{(1-D)}V_{in} \quad (12)$$

The voltage stresses across the two MOSFETs are expressed in (13):

$$V_{S_1} = V_{S_2} = \frac{1}{(1-D)}V_{in} \quad (13)$$

The peak-to-peak variation in input inductor's currents $(\Delta i_{L_{in}} = \Delta i_{L_1} = \Delta i_{L_2})$ is expressed in (14):

$$\Delta i_{L_{in}} = \Delta i_{L_1} = \Delta i_{L_2} = \frac{DTV_{in}}{L_{in}} = \frac{DV_{in}}{fL_{in}} \quad (14)$$

The peak-to-peak variation in output inductor's current $\Delta i_{L_{out}}$ is expressed in (15)

$$\Delta i_{L_{out}} = \frac{DT(V_{in} + 2V_C - V_{out})}{L_{out}} = \frac{D(V_{in} + 2V_C - V_{out})}{fL_{out}} \quad (15)$$

The peak-to-peak variation in capacitor's voltage Δv_C is expressed in (16).

$$\Delta v_C = \frac{DTI_{out}}{C} = \frac{DP_{out}}{M_{CCM}V_{in}fC} \quad (16)$$

V. CIRCUIT EXTENSIONS

More switched-inductors can be attached to the proposed Cuk converter instead of the single inductors at the input side. This will lead to increase the voltage gain ratio even more. Also, to reduce the size of magnetic components, the inductors can be integrated into one magnetic core.

A. Attaching More Switched-Inductors

In order to increase the voltage gain even more, the single inductors at the input side of the proposed Cuk converter can be replaced with a switched-inductor. In this case, the voltage gain reaches above 23 when D=0.75. The power circuit is shown in Figure 6. The voltage gain can be expressed as:

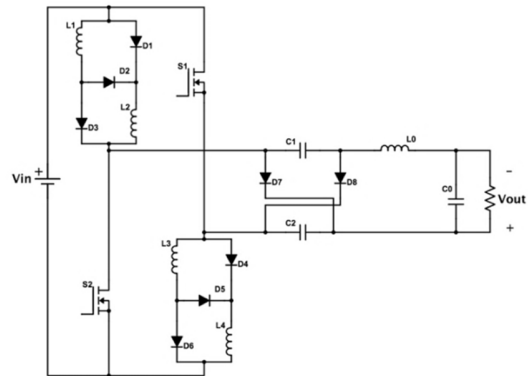$$M_{CCM} = \frac{V_{out}}{V_{in}} = D + (1 + D)\frac{(1+3D)}{(1-D)} \quad (17)$$

Fig. 6.   More switched-inductors attached.

B. Coupled Inductors

Actually, all the inductors presented in the last section share the same value of inductance and have the same operation condition. Therefore, to reduce the size of magnetic components, the inductors can be integrated into one magnetic core as shown in Figure 7.
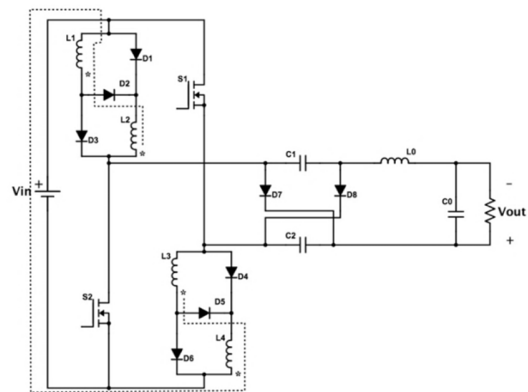

Fig. 7.   Magnetic components integration.

VI. COMPARISON ANALYSIS

In Table I, a comparison can be seen between the proposed Cuk converter, the single-switch Cuk converter [20], the hybrid switched-capacitor Cuk converter [21], the three-switch Cuk converter [22], and the conventional Cuk converter in terms of voltage gain, voltage stress, and number of components. The voltage gain and the voltage stress are graphically represented in Figures 8 and 9 respectively. As can be seen in Figure 8, the highest voltage gain can be accomplished by the proposed Cuk

converter. However, the converter having the lowest voltage gain is the conventional Cuk converter. As can be seen in Figure 9, the converter having the highest voltage stress is the conventional Cuk converter. On the other hand, the lowest voltage stress can be maintained using the proposed Cuk converter. Therefore, the proposed Cuk converter is suitable for applications requiring higher voltage gain with lower voltage stress.

TABLE I.   PROPOSED AND OTHER CUK CONVERTERS COMPARISON

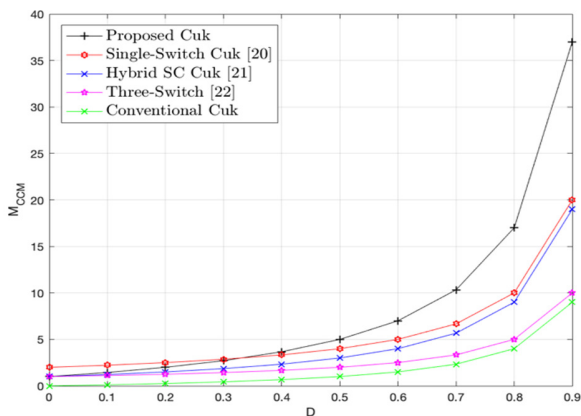| Cuk Converters	Gain (M_{CCM})	Switches count	Diodes count	Capacitors count	Inductors count
Proposed	$\dfrac{(1+3D)}{(1-D)}$	2	2	3	2
Single-switch [20]	$\dfrac{2}{(1-D)}$	1	3	3	1
Hybrid SC [21]	$\dfrac{(1+D)}{(1-D)}$	1	2	3	2
Three-switch [22]	$\dfrac{1}{(1-D)}$	1	2	2	1
Conventional	$\dfrac{D}{(1-D)}$	1	1	2	2

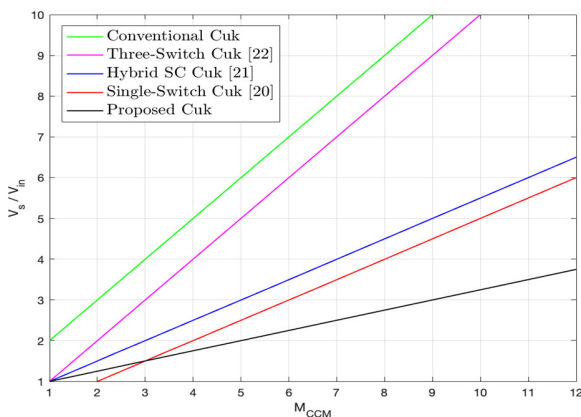Fig. 8.   Voltage gain comparison.

Fig. 9.   Normalized voltage stress comparison on active switches.

VII.   SIMULATION VERIFICATION AND DISCUSSION

A prototype 12/-152V design is developed in Matlab/Simulink to verify the performance of the proposed Cuk converter. A Simulink prototype has been designed in Matlab as shown in Figure 10. The simulation specifications of the proposed Cuk converter are 12V input voltage, -152V output voltage, 100W rated power, 50kHz switching frequency, and 75% duty cycle. Detailed parameter values are shown in Table II. The voltage stress and current stress across the two MOSFETs S_1 and S_2 are 47V and 5A respectively. The voltage stress and current stress waveforms are shown in Figure 11. Figure 12 shows the voltage waveforms of diodes D_1 and D_2 which each one has a voltage stress of -90V. Diodes D_1 and D_2 are reversed biased when the two MOSFETs S_1 and S_2 are on, and they are forward-biased when the two MOSFETs S_1 and S_2 are off. The voltage waveform of the two capacitors C_1 and C_2 is shown in Figure 13. The current waveforms of the three inductors L_1, L_2, and L_{out} are shown in Figure 14.
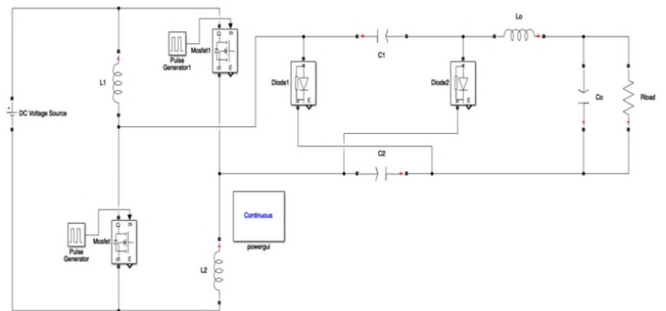

Fig. 10.   Simulink model of the proposed Cuk converter.

TABLE II.   DESIGN SPECIFICATIONS OF THE PROPOSED CUK CONVERTER

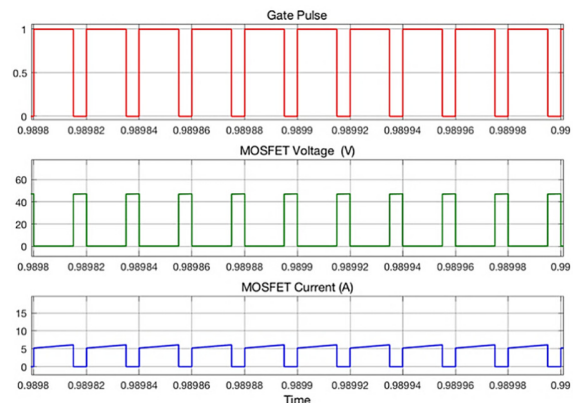| Parameter	Value
Input voltage (V_{in})	12V
Output voltage (V_{out})	-152V
Rated power (P_{out})	100W
Switching frequency (f)	50kHz
Duty cycle (D)	75%
Inductors (L_1, L_2, and L_{out})	600µH
Capacitors (C_1 and C_2)	22µF
Load (R_{Load})	230Ω

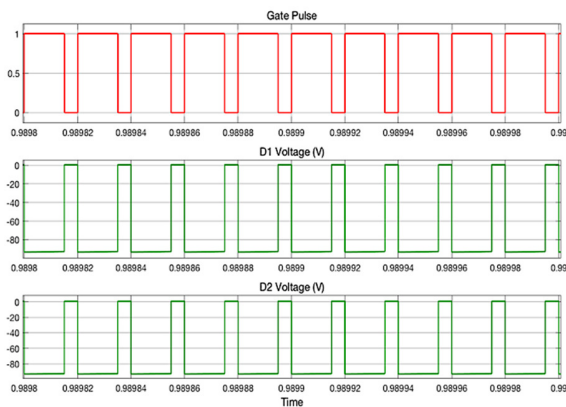Fig. 11.   Voltage and current waveforms across MOSFETs S_1 and S_2.

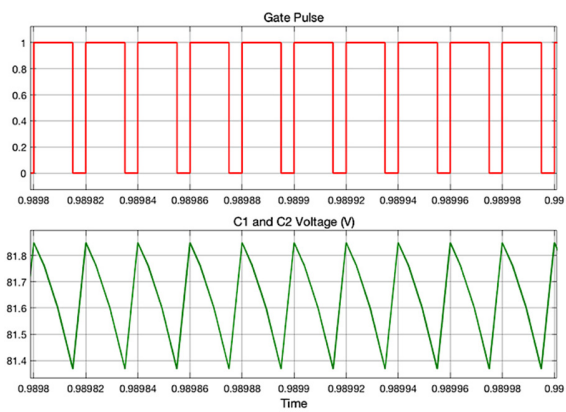Fig. 12.   Voltage waveform across diodes D_1 and D_2.

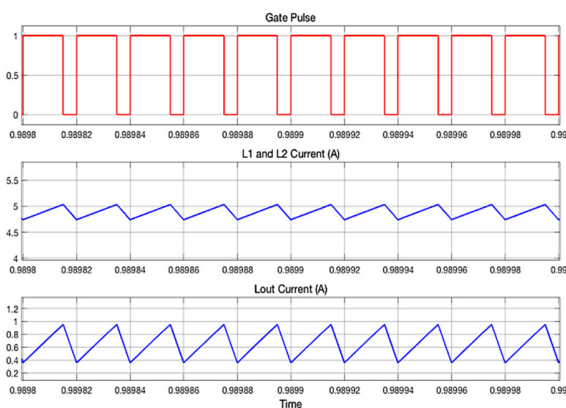Fig. 13.   Voltage waveform across capacitors C_1 and C_2.

Fig. 14.   Current waveforms across inductors L_1 and L_2.

Fig. 15.   Waveforms of V_{in}, V_{out}, and P_{out}.
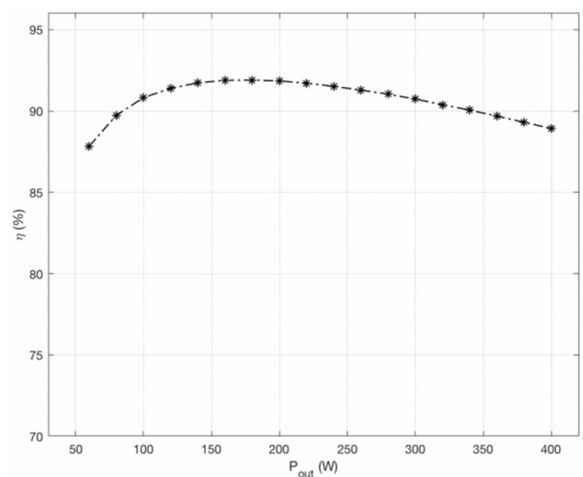
Fig. 16.   Efficiency curve as a function of the output power.

VIII.   CONCLUSION

A two-switch high gain non-isolated Cuk converter was presented in this paper. The proposed Cuk converter is useful in renewable energy applications, such as PV and fuel cell, that require high voltage gain with reduced voltage stress on semiconductor switches. The reduced voltage stress on semiconductor switches will lead to have lower R_{DS-ON}, and therefore, higher efficiency. A higher voltage gain is achieved when the single inductor and capacitor in the conventional Cuk converter are replaced with a switched-inductor and switched-capacitor respectively. Theoretically, the proposed Cuk converter is able to achieve 13 times the input voltage when the duty cycle (D) is 0.75. The steady-state analysis is verified by constricting a 12/-152V prototype Cuk converter in Matlab/Simulink.

Finally, the input voltage V_{in} (12V), the output voltage V_{out} (-152V), and the output power P_{out} (100W) waveforms are shown in Figure 15. The efficiency of the proposed Cuk converter is calculated as the output power increase as shown in Figure 16. The highest efficiency is 92% when the output power is 180W. When the input voltage is increased, the efficiency of the proposed Cuk converter is increased because the input current decreases, and therefore, the conduction losses on switches get reduced.
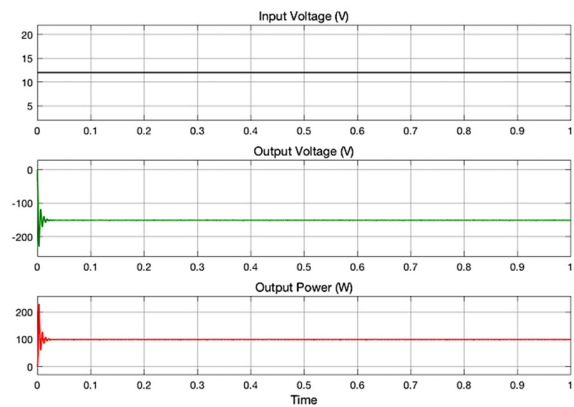
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