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High Gain of Single-switch Voltage Multiplier Converters for DC Power Supply Applications

***Abstract**. DC converters with high ratio of output-input voltage are commonly used in various applications, such as high voltage dc impulse generator, or harnessing energy from weak power sources including piezo electric, thermoelectric etc. This paper presents a single active switch of boost converter combined with cascade voltage multiplier to generate a high gain output voltage. The voltage multiplier module employs two diodes and two capacitor sets. Each capacitor is alternately charged through the diode, and then discharges in series with the source voltage. Every module steps up twice of the input voltage, thus, connecting modules in series provides high output ratio compared to the source voltage. Simulation of the proposed system with three modules of voltage multiplier, and a flyback converter was conducted for comparison. The voltage multiplication using diode shows superb performances compared to the one, which uses mutual inductance. The results indicate that the proposed system has a linear voltage gain for various input voltages, and a constant output voltage under various load resistances.*

*Streszczenie. Przetwornice prądu stałego o wysokim stosunku napięcia wyjściowego do wejściowego są powszechnie stosowane w różnych zastosowaniach, takich jak generator impulsów prądu stałego wysokiego napięcia lub wykorzystanie energii ze słabych źródeł zasilania, w tym piezoelektrycznych, termoelektrycznych itp. W artykule przedstawiono pojedynczy aktywny przełącznik przetwornicy doładowania. z mnożnikiem napięcia kaskadowego do generowania wysokiego napięcia wyjściowego wzmocnienia. Moduł powielacza napięcia wykorzystuje dwie diody i dwa zestawy kondensatorów. Każdy kondensator jest ładowany naprzemiennie przez diodę, a następnie rozładowuje się szeregowo z napięciem źródła. Każdy moduł zwiększa dwukrotnie napięcie wejściowe, dzięki czemu szeregowe łączenie modułów zapewnia wysoki współczynnik wyjściowy w porównaniu z napięciem źródłowym. Dla porównania przeprowadzono symulację proponowanego układu z trzema modułami powielacza napięcia i przetwornicą typu flyback. Mnożenie napięcia za pomocą diody wykazuje znakomite osiągi w porównaniu z tym, który wykorzystuje indukcyjność wzajemną. Wyniki wskazują, że proponowany układ charakteryzuje się liniowym wzmocnieniem napięciowym dla różnych napięć wejściowych oraz stałym napięciem wyjściowym przy różnych rezystancjach obciążenia. (**Przekształtnik o dużym wzmocnieniu z mnożnikiem napięcia z jednym przełącznikiem do zastosowań w zasilaniu prądem stałym***

Keywords: single switch, boost converter, dc voltage multiplier, diode-capacitor cascade, flyback converter
Słowa kluczowe: przekształtnik typu boost, mnożnik, duże wzmocnienie

1.Introduction

Conventional dc-to-dc dc converter is widely used for power supply systems. The circuit, device, and applications of converter types, including boost for stepping up the voltage was comprehensively discussed in [1]. Applications of the converters for uninterruptible power supply (UPS), dc motor drive, maximum power point tracker were discussed by other researchers [2]-[4]. For low power supply applications such as wearable equipment, IoT sensors, the demand of high voltage gain is needed. The power commonly comes from abundant sources including human body heat, exhaust thermal of incinerator, vibration etc. The generator may use thermoelectric, piezo electric, photovoltaic that generates small amount of power per cell. Modification of boost converter performing wide input voltage range and wide load range was proposed [5]. Employing boost converter for such applications to achieve high voltage gain was introduced in [6]-[7]. Another effort uses several boost converters that are connected in cascade also introduced in [8]. It requires several switches and time control system to operate. A topology to modify of boost with isolated and mutual inductance is provided by a flyback converter [9]. High gain of voltage ratio can be obtained, but it suffers from saturated condition of the core [10]. Other methods to achieve a high gain use voltage multiplier. It consists of capacitor-diode circuit, but it mostly to be used for ac system [11]. A dc-to-dc converter combined with voltage multiplier was proposed in [12]. It attaches a quadratic boost converter and diode-capacitor circuits. The system requires two active switches (transistors), instead of single switch, which may be simpler.

This paper presents a single switch boost converter combined with diode-capacitor voltage multiplier. The voltage gain depends on the duty cycle and the number of cascades multiplier circuits.

2.Single-switch Step-up DC Converter

Boost Converter

Basic step-up of dc voltage can be met by converters such as boost, buck boost, or cuk converters. This employs single controllable switch combined with inductor and capacitor circuits. Boost converter has widely been used in many applications, such as for maximum power point tracker of solar PV, or low consumption of wearable device, Internet of Things sensors, etc. The diagram of a boost converter is shown in Fig. 1.

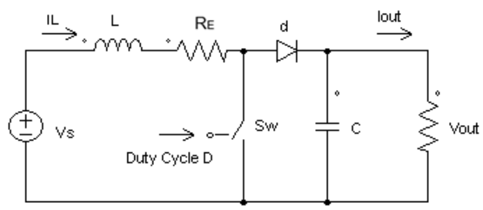


Fig. 1. Conventional boost converter

The output voltage of a Boost converter is managed from the duty cycle (D), which terms of the duration ratio between the on-state and the period time (T) of the semiconductor switch Sw. The voltage gain, or the ratio of the output (V_{out}) to the input voltage (V_s) is defined as follows

$$(1)\quad \frac{V_{out}}{V_s} = \frac{1}{1-D}$$

When the switching frequency (f) of the switch is set as 10 kHz, then the period time (T) is 1 x 10^{-4} seconds. The duty cycle D is 0.75 meaning that the switch turns on (t_{on}) for 75% x 10^{-4} seconds, while turns off (t_{off}) time is 0.25 x 10^{-4} seconds as shown in Fig. 2. According to (1), when the duty cycle D = 0.75 results in 400% stepping up of the source voltage.

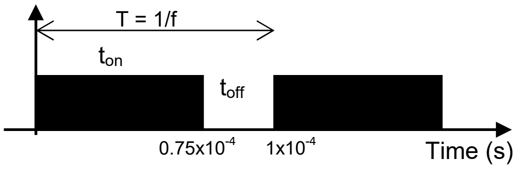


Fig. 2 Timing diagram of the switch at f=10 kHz, D=0.75

Due to the non-ideal characteristics of the switch, the duty cycle D is commonly limited up 0.75. Upper than the value, losses caused by the switching process may be higher. When the converter works on continuous conduction mode, the ripple of inductor current (Δi_L) and the critical value of the inductor (L) can be calculated as follows:

(2) $\Delta i_L = V_S\, t_{on} / L$
(3) $\Delta i_L = V_s\, D / (f\, L)$

Flyback Converter

Another single switch converter which has higher voltage gain is flyback topology. It has similar principles to the boost converter, but the flyback employs a mutual inductance, or transformer, as shown in Fig 3.

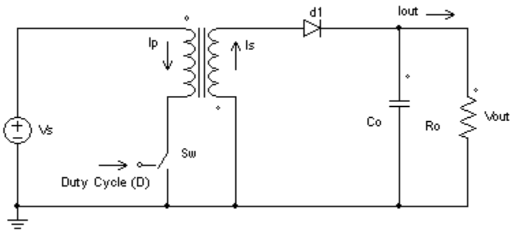


Fig. 3. Flyback Converter

It steps up the voltage by adjusting the duty cycle D for charging and discharging the inductor. Then, the discharge voltage is isolated and multiplied through the mutual inductor. The voltage multiplication depends on the turn ratio of the primary (N_p) and secondary (N_s) of the inductor. For an ideal transformer the output voltage of flyback converter is as follows:

(4) $$\frac{V_{out}}{V_s} = \frac{N_S/N_P}{1-D}$$

The inductance of the primary and secondary sides is calculated as follows:

(5) $L_p = L_s\,(N_p/N_s)^2$

As can be seen in (4), the flyback output voltage depends on the turn ratio of the transformer, and the duty cycle. A transformer has a restriction its performances by limitation of magnetic flux of the core. When the transformer is in saturated condition, the induced voltage from the linked inductance may not follow the turn ratio, thus the output voltage varies from the designed. Transformer saturation may occur when it is overloaded from excessive voltage, current, or frequency in the windings. This is one of the disadvantages of flyback converter.

3.The Proposed Single-switch Voltage Multiplier

The proposed system combines a boost converter and diode-capacitor voltage multiplier as shown in Fig. 4.

The system consists of module 1 and connected in series with module 2, 3, etc. The Module 1 comprises a conventional boost converter. It steps up the input voltage V_s by adjusting the duty cycle. The output is in terminal V_{o_1}. The Module 2 has 2 diodes and 2 capacitors. The Module 2 is charged by the Module 1 and is released in series connection at the terminal V_{o_2}. The Module 3 and others can be attached in series connection as required.

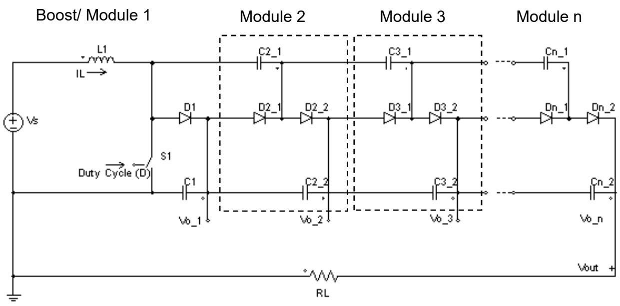
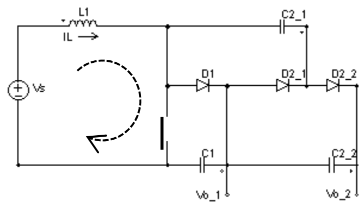
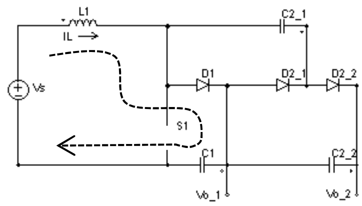


Fig. 4. Boost with voltage multiplier

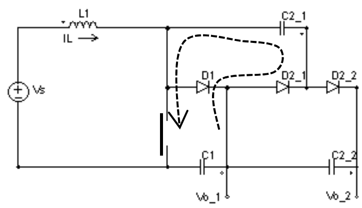
The principles are described in the following as shown in Fig. 5. The first stage of the system starts with the Module 1 that the switch is in conduction mode, as depicted in Fig. 5 a). Charging mode of the inductor L begins when the switch is "on" for a certain time depending on the switching frequency and the duty cycle. This mode stores magnetic energy inside the inductor as temporary electric current.



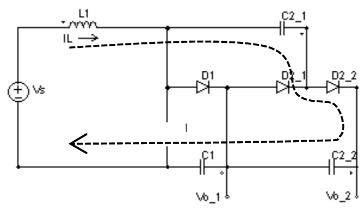
a) Switch 'on' – cycle 1, charging inductor L



b) Switch 'off' – cycle 2, charging C_1



c) Switch 'on' – cycle 3, charging C_{2_1} by C_1



d) Switch "off" – cycle 4, charging C_{2_2}

Fig. 5. The operation principles of the proposed system

The second cycle occurs when the switch S is in disconnected condition, as shown in Fig. 5 b). This mode releases energy stored in the inductor L together with the voltage source V_s to charge the capacitor C_1 through the diode D_1. Thus, the output voltage at the terminal V_{o_1} is always higher than the input voltage V_s. When the duty cycle is set as 0.5, the output voltage will be twice compared to V_s, according to Equation (1).

The third stage is shown in Fig. 5 c) that the switch S is "on" again. It charges the inductor L again. At the same time, this cycle puts C_1 and C_{2_1} in the position of parallel connection. Therefore, capacitor C_{2_1} is charged by C_1 through D_{2_1}. It results in the same terminal voltage of both capacitors.

The next cycle charges the capacitor C_{2_2}, when the switch S is disconnected mode, as illustrated in Fig. 5 d). The charging energy comes from the source voltage V_s, stored energy in the inductor L, and in capacitor C_{2_1}, through diode D_{2_1}. Thus, the voltage at the terminal V_{o_2} will be 300% of the input voltage V_s. More Modules can be embedded in series until the required voltage is obtained.

Noted that $V_{o\_n} = V_{out}$, then the voltage gain is modified using Equation (1). When the system employs n modules, the expression is as follows:

(6) $V_{out} = \frac{nV_s}{1-D}$

(7) $\frac{V_{out}}{V_s} = \frac{n}{1-D}$

Equation (7) calculates the voltage gain under an ideal condition, where the internal resistance of the inductor (R_E) is assumed zero, and the diode drop voltage is ignored.

When the system is for harnessing power from weak sources such as piezo electric, thermal electric, etc., then the drop voltage of the diodes shall be considered. The drop voltage on a transistor or diode circuit is varies depending on the operating voltage and current. In this application, it is assumed equal to V_d. The number of the module is n = 3. Referring to the steps in Fig. 5, the drop voltage V_d can be calculated as follows:

- Fig. 5b, at the end of the cycle, the terminal output voltage V_{o_1} equals to the capacitor voltage, V_{c1}. Thus, $V_{o\_1} = V_{c1}$
- Fig. 5c, the current flows from V_{c1} to V_{c2_1} through the diode D_2 and the switch, the drop voltage becomes 2 V_d. The capacitor voltage is $V_{c2\_1} = V_{c1} - 2V_d$
- Fig. 5d, the cycle of charging from the source and V_{c2_1} results in $V_{o\_2} = 2V_{c1} - 4V_d$
  - Further steps result in $V_{o\_3} = 3V_{o\_1} - 6V_d$

In general, the terminal of output voltage at the module n is as follows

(8) $V_{o\_n} = n\,V_{o\_1} - (n-1)\,n\,V_{o\_1}$

.Results and Discussion

Two systems, flyback and boost with voltage multiplier converters were analysed and simulated. Both converters were designed with V_s = 100V. The flyback converter that the design was determined in [9], is resumed in Table 1. The proposed boost with voltage multiplier converter is designed to supply resistive load 600 Ω at the duty cycle D = 0.5 with the switching frequency 20 kHz.

Tabel 1. Component for flyback converter

Component	Value
N_p	6 turns
N_s	30 turns
L_p	8.6 μH
L_s	249 μH

The following is the results of the proposed system under several conditions such as the change of load resistances, duty cycles, source voltages. The performances were compared to the flyback converter.

Fig. 6 shows the output voltage of boost-voltage multiplier consisting of 3 stages, when it was applied a constant duty cycle, and constant load resistance. At the first stage, the output terminal is V_{o_1}, which is the output of boost converter. A boost converter with D = 0.5, results in an output voltage as 200% or 200 V. The second stage shows twice of the first curve. Thus, V_{o_2} has 400 V, while the third stage is slightly below 600 V.

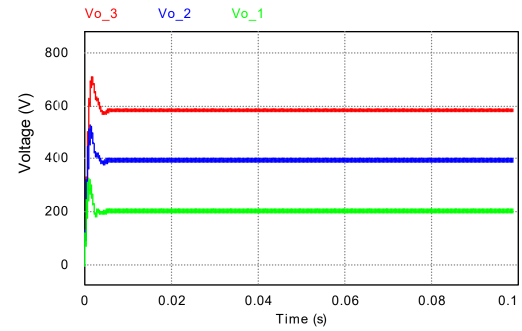


Fig. 6. Terminal voltage of each stage of the proposed system

When the output of terminal V_{o_3} is compared to the feedback voltage V_f, both curves seem closed to 600% of the source voltage as shown in Fig. 7. The response shows an underdamped curve for the proposed system, but an overdamped for the flyback converter.

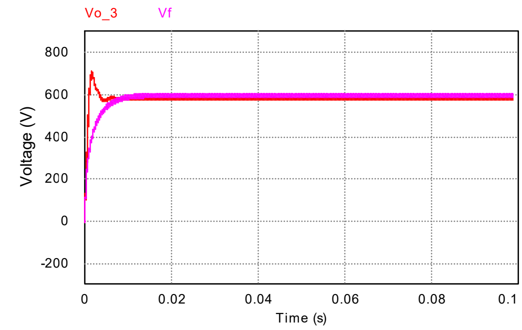


Fig. 7. Terminal voltage of the proposed system (V_{o_3}) and the flyback converter (V_f)

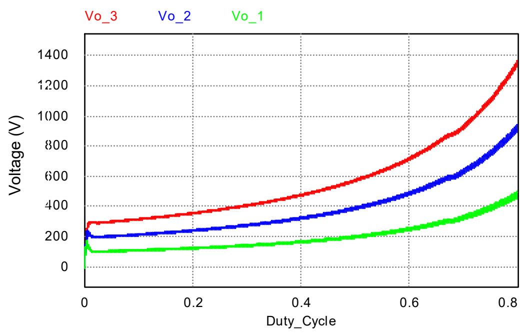


Fig. 8. Terminal voltage of the proposed system under various duty cycles

The voltage performances of boost with multiplier converter under constant 600Ω and various duty cycles is depicted in Fig. 8. It shows non-linear curves as one of boost converter characteristics. The curves present 2x, 4x, and 6x of the source voltage. At a low duty cycle, the output of V_{o_1} is still higher than the source voltage. When the duty cycle D = 0.5, the output is 200 V. At duty cycle 0.75, the output results in 400 V for V_{o_1}, 800 V for V_{o_2}, and 1200 V for V_{o_3}.

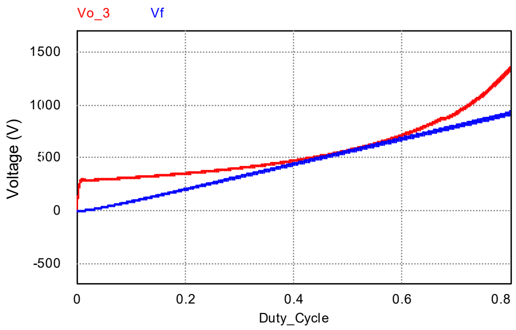


Fig. 9. The voltage performances of the proposed system and flyback converter under various duty cycles

Fig. 9 illustrates comparison of the output voltage between boost with multiplier and flyback converters. The boost is non-linear, while the flyback is linear curves. Under various duty cycles and constant load resistance, the flyback converter presents lower voltage gain compared to the proposed converter.

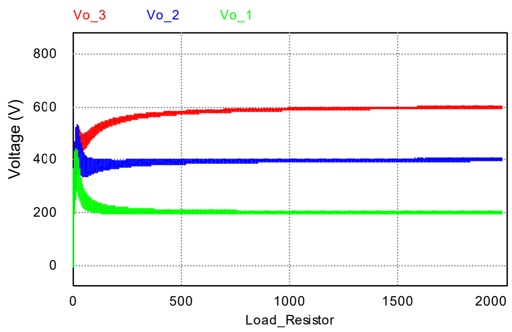


Fig. 10. Terminal voltage of the proposed system under various load resistances

Fig. 10 depicts the proposed boost with multiplier converter working under load variation. The load resistance was varied from short circuit till 2000 Ω. Since the simulation uses ideal components, the drop voltage gives a small part. Deep drop voltage and high ripples were occurred during high load or low resistance loads. This is because the energy stored in the inductor is discharged rapidly.

Fig. 11 shows the voltage variation due to load change but constant duty cycle at D=0.5 for both converters. The proposed boost converter performs almost constant output voltage at 600 V. The flyback voltage varies from 200 V till around 1000 V when in light loads. This variation may be due to the inductor core saturation.

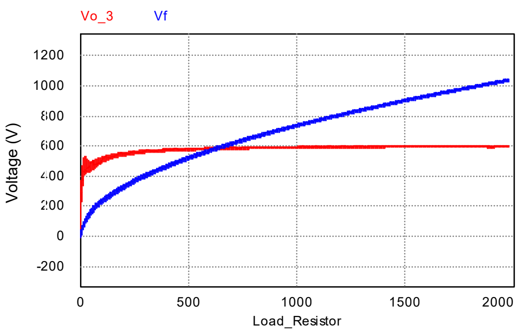


Fig. 11. The voltage performances of the proposed system and flyback converter under various load resistances

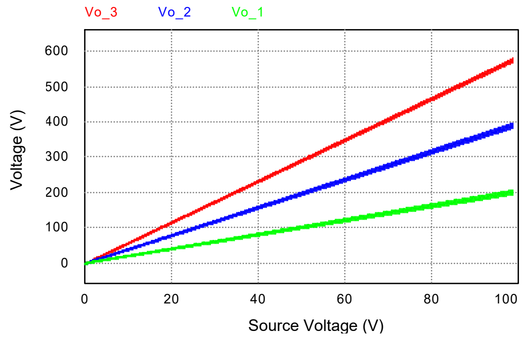


Fig. 12. The gain voltage of each stage of the proposed system

The voltage gain performances of the proposed boost were illustrated in Fig. 12. It shows a linear relationship between the change of source voltage and the output voltage under a constant duty cycle and load resistance. Similar performance is depicted in Fig. 13 compared to the flyback converter.

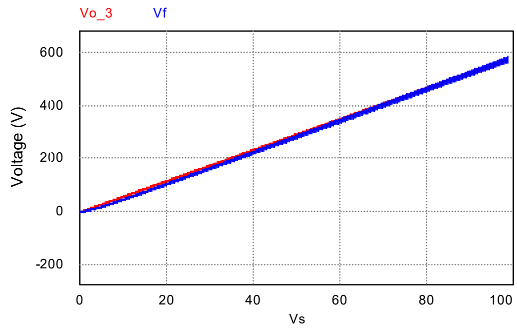


Fig. 13. The gain voltage of the proposed system and flyback converter

All the simulation results did not include the diode drop voltage. The system runs in hundreds of volts, thus the drop voltage can be ignored. On the other hand, when the operating voltage is low, then, the drop voltage of diodes is included into account. The output voltage will be slightly lower than the ideal one. Equation (8) is used to calculate the drop voltage due to the diode and switch resistances. In addition, when the system employs several cascades, the final output voltage will be lower than the ideal design.

5. Conclusion

A high multiplication voltage of dc-to-dc converter was discussed in this paper. The proposed system multiplies the source voltage depending on the duty cycle and the number of diode-capacitor cascade applied. The proposed system, a boost with voltage multiplier has better performances compared to a flyback converter. When running under various duty cycles, a high gain of the output voltage can still be achieved, even in a small duty cycle. When the load is changed, the output voltage shows almost constant, but affected by internal resistance of components and drop voltage of diodes.

For a large system application, such as dc lightning simulator, that needs a high voltage from low voltage source, the proposed system may present the best performances. The simulator needs high voltage but low current for its operations. Similar system, such as medium voltage isolation test measurement, which requires voltage of 2 kV, is favourable to use the proposed system. Applications of the system for equipment with the operation voltage as 12 volts or more, would also be suitable. However, using the proposed boost with voltage multiplier for supplying a digital logic equipment may not be recommended. Especially, when the system is sourced by a micro volt generator to feed a 3.3 volts digital equipment. This is because the drop voltage caused by diodes significantly affecting the gain performances.

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