https://communications.science.ankara.edu.tr

Commun.Fac.Sci.Univ.Ank.Series A2-A3
Volume 63, Number 1, Pages 1-16 (2021)
DOI: 10.33769/aupse.757924
ISSN 1303-6009 E-ISSN 2618-6462

Received by the Editors: June 25, 2020; Accepted: October 01, 2020

ENHANCED BOOST CONVERTER WITH GaN BASED POWER SWITCHES AND SWITCHED-CAPACITOR

Korhan CENGİZ

Department of Electrical-Electronics Engineering, Faculty of Engineering, Trakya University, Edirne, TURKEY

ABSTRACT. To increase the voltage gain of power electronic circuits, several voltage converters have been designed by researchers. Especially, the boost based converters are used by designers for numerous devices and systems because of their reliability. Generally, in these studies, researchers propose to use high frequency transformers, silicon based diodes and inductance based sub-circuits. However, the improvement on new generation power transistors should be considered as an alternative way to provide these goals because of their lower inner resistances, lower switching losses and adoptability for new generation devices. Therefore, in this paper, usage of these kinds of semiconductors to improve the voltage gain performance of traditional boost converter is proposed. With this enhanced design and usage of new semiconductor switches, we obtain approximately 70% more output voltage gain than traditional boost converter. The proposed converter provides significant gain, high scalability in duty cycle vs output voltage usage and portability for weight restricted systems. The enhanced boost based converter is modelled in Simulink to verify the analytical voltage gain equations. Finally, the proposed model is compared with traditional boost converter in term of gain performance.

1. INTRODUCTION

Gain is a very significant concept in all electronic devices, circuits and systems. Some systems such as power amplifiers are designed to increase the power gain. To obtain higher current gains, the current mirrors are used frequently in various electronic circuits. Voltage gain of the circuit is the most important performance metric of the Boost type DC/DC Converters [1]. Generally, the traditional boost converters work efficiently between 0.6-0.8 duty ratios. In traditional applications,

Keyword and phrases. Boost converters, GaN based switches, power electronics

korhancengiz@trakya.edu.tr
0000-0001-6594-8861

© 2021 Ankara University

to obtain higher gains, a high-frequency transformer is added to the circuit, such as in flyback converters [3-4]. Transformer usage in those converters causes a dramatic increase in the weight of the circuit. This issue restricts the portability of the circuit and also increases its magnetic loss [5-6]. Moreover, recent years, authors in numerous studies try to improve the performance of boost based converters to obtain higher voltage gains. The studies in [1-2] give us comprehensive surveys for boost based converters which are designed to obtain higher gains. However, when these studies are examined in details, all of them use diodes or transformers in their topologies but usage of those elements cause higher switching and magnetic losses. Inner resistances and switching losses are lower than the silicon based semiconductors (diodes) in the previous studies of [1-2], hence, using new generation switching elements can provide higher voltage gains.

2. Related Works

A single-switch boost topology with a new voltage multiplier (VM) is presented in this paper [8]. When it is compared with existing boost converters, not only the higher voltage conversion ratios are obtained, but also voltage stresses across semiconductors are reduced. Further, the voltage conversion ratios and voltage stresses of the switches of the proposed topology are arranged by the number of the VM cells. The control and drive circuits for the proposed converter are as simple as boost converters and they do not include additional switches. The authors of [9] propose a non-linear output voltage tracking controller for a boost converter. Non-linearities, parameter uncertainties and load variations are taken into consideration in details. The design of an auto-tuner, that automatically adjusts the control gain according to the output voltage error to improve transient performances is presented. Moreover, the closed-loop system which provides the performance recovery without any steady-state errors in the presence of parameter and load variations is investigated. In [10], a novel isolated high gain boost converter with switched capacitor which employs two symmetrical switched boost networks along with an enhanced control scheme based on the combination of the PWM and phase-shift modulation is presented. Using symmetrical switched boost network increases the voltage gain of the proposed topology. In addition, usage of a switching algorithm on the proposed converter provides several benefits. Moreover, the steady-state analyzes, design procedure of the components, and voltage and current stresses of the semiconductors are presented in details. [11] proposes a dual input converter with dual boost and integrated voltage multiplier cell to obtain high voltage gains for renewable energy systems. Output voltage regulations during load variations and input disturbances is provided by the utilization of suitable control actions. The small-signal model based on state space averaging followed by small-signal linearisation is demonstrated with MATLAB and powersim (PSIM). Voltage regulations and active current sharings are obtained from the simulations and experimental results. The circumstantial analyzes and design of a soft switching boost converter is proposed in this article [12]. The proposed converter includes a resonant LC tank connected between the drain terminals of the switches. This structure povides zero voltage and zero current commutations of all devices and makes the converter applicable for high frequency applications. Differ from existing studies on current-fed resonant converters, the theoretical analyzes of this paper contains the effect of the input filter inductors. In this study, a novel non-isolated interleaved boost converter with high voltage ratio based on coupled inductor and switched capacitor is presented [13]. Further, voltage lift capacitors are utilized to ease the voltage spikes across the power switches but also provides high voltage gains. The voltage stresses on the power switches are detectably lower than the output voltage, especially at higher output voltages. Thus, the low voltage rated switches can be admitted. A two-phase interleaved coupled inductor based boost converter in the single-phase operation is presented in [14]. The operation modes of the proposed converter in switching cycles and half line cycles are analyzed. Also, a prototype is built to demonstrate the analyzes. Implementation and design of a single-switch coupled-inductor based boost converter are proposed in [15]. With the usage of the coupled inductor, the proposed converter obtains high voltage gains without extreme duty cycles. In addition, low switch voltage stress is attained, therefore low voltage rating MOSFET is allowed to obtain low conduction losses. Finally, the proposed converter operates with continuous input current, that is useful for the batteries, fuel cells, and photovoltaic applications. In [16], a boost converter for low voltage thermal energy harvesting applications is proposed. The main purpose of this study is to provide self start-up and efficient conversions at low input voltages. The start-up is obtained by utilization of a cold starter based on a low voltage oscillator and a charge pump. The proposed converter has two low-side switches to optimize the low voltage start-up and efficient steady-state conversions. Boost converter design with switched-capacitor is proposed in [17]. In here, The switched-capacitor provides unique solutions to the existing methods. The proposed converter ensures energy efficiency and low cost. The proposed converter is applied to hybrid electric vehicles. The interesting study in [18] proposes a novel application of thermoreflectance based temperature measurements performed on a gallium nitride high electron mobility transistor. This transistor is applied to aboost converter to collect measurements of dynamic temperature distributions across the semiconductors. [19] proposes an interleaved soft switching boost converter for high voltage applications. The soft switching is achieved by using the auxiliary semiconductors. The novel operation idea of the proposed converter provides high voltage gains. In [20], LCL resonant boost converter is presented. The proposed converter consists of a full-bridge inverter module, a transformer, a flyback transformer, a resonant circuit and a rectifier part. To obtain various output values, the proposed circuit operates in low voltage gain mode or high voltage gain mode. Especially, in higher voltage gain modes, the converter operates in PWM with boost and LCL resonance. High step-up and low voltage stress are proposed in [21]. The voltage doubling capacitors are added to the traditional boost converter to decrease the input current ripples and voltage stresses on switches. To provide a voltage multiplier part at the output of the converter, the coupled inductors are connected in series and combined with capacitor diode structure. The authors of [22] propose a boost converter which includes a startup circuit for using as a thermoelectric energy harvester. Also, a novel low-leakage logic gates are utilized to reduce the startup voltage. A novel boost converter with coupled inductor and voltage lift circuit technique is presented in [23]. Higher voltage conversion ratios are obtained by utilizing a low turn ratios of the coupled inductor. Usage of low turn ratios provide to reduce the peak voltage values on semiconductors. Further, the voltage lift circuit is considered to increase the voltage gain. The mathematical analyzes and comparisons demonstrate the efficiency of the proposed circuit. The authors of [24] aim to present an accurate analyzes of sliding mode boost converter dynamics based on the locus of a perturbed relay system (LPRS) scheme. They develop a non-linear model for LPRS representation of boost converter. The LPRS method is also utilized to analyze the effect of the propagation of an external disturbance. In [25], the authors propose a new quadratic boost converter. In the proposed circuit, the inductor currents are low. The mathematical derivations for CCM and the analyzes for power losses are presented for the proposed converter. In addition to them, by utilizing state space averaging method, the small-signal model of the converter is obtained. A maximum efficiency tracking scheme for an inductive power-transfer (IPT) system based on a boost converter is presented in [26]. Impedance matching (IM) is accomplished by providing the equivalent load impedance to be stable against load variations. The optimal equivalent load impedance derivations are made. Moreover, the impedance transfer characteristics of the boost converter in both continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are derived. Evaluation results show that the proposed IM scheme provides the maximum power transfer efficiency for several load variations. In [27], a small signal model of valley V2 controlled boost converter is proposed by the authors. Average method and sampled-datamethod that provides precision in switching frequency are combined. In addition, the compensator is analyzed for V2 boost converters. The designed small signal model is demonstrated with experiments. According to the experimental results, by utilizing the simple proportional integral compensator, the proposed converter is compensated well and it provides fast transient performance. In this study, the authors present an optimized high power multi-phase interleaved bidirectional boost converter [28]. To obtain fast and accurate analyzes and design, a generalized scheme is utilized in calculations of required phase inductance and output capacitance. Also, genetic algorithm (GA) optimization scheme is applied to the inductor design. An interleaved multilevel boost converter (interleaved-MBC) based on minimal voltage multiplier (VM) cells for high voltage applications is proposed in [29]. In this proposed converter, decreased number of capacitors and diodes are utilized when it is compared with existing converters. The mathematical derivations are performed by considering the nonidealities for this converter. The operation of the proposed converter is presented for continuous and discontinuous conduction modes with boundary situations. In [30], a step up quadratic boost converter with coupled-inductor is designed. The voltage gains of the proposed circuit are improved by increasing the duty cycles due to the quadratic boost structure. To decrease voltage stress on the components, a coupled-inductor based voltage doubler is used. In addition, the leakage inductor current is applied to obtain zero-current switching on output diode. A non-isolated quadratic boost converter (QBC) which provides a low-output-voltage ripples when compared with traditional QBCs is proposed in [31]. The proposed converter is a good candidate for applications which need high voltage gains in renewable energy systems. The analyzes and evaluations of the proposed converter are demonstrated via simulations and mathematical derivations. Isolated boost DC–DC converter is investigated in [32]. Comparative evaluations about DC-DC converters are performed. Principles of operation, derivations of static voltage gains, current and voltage stresses on the components, component stress factor, the effect of number of components, power loss, power density and cost are compared and analyzed. The analyzes and evaluations are also conducted with simulations. An improved energy balance control (IEBC) scheme is proposed with integration of simplified energy balance controller (SEBC) in [33]. The designed IEBC decreases the output voltage errors without the need of estimation of circuit energy losses. The IEBC operates in continous and discontinous current modes, therefore, exact static dynamic performances are obtained. In [34], the authors aim to design a costeffective clamping capacitor boost (CCB) converter with high voltage gains. According to the simulation results, the voltage gain of the proposed CCB converter is increased when it is compared with traditional boost converter. The proposed CCB converter is a cost-effective option for high voltage gain applications in the renewable energy generation systems. A three-port DC–DC converter is designed to provide the flow of power from input source to load and battery in [35]. The converter includes a bidirectional path that uses two redundant switches and two diodes. The proposed converter provides single-stage power flow from input to the battery and load to ensure higher efficiency. To obtain maximum input power and output voltage the duty cycles are adjusted. Three operation modes are considered to the control the designed converter. In addition, separated closed-loop controllers are implemented by using a decoupling network.

The above mentioned studies and solutions in the literature have some advantages especially in voltage gains. However, all the latest related works have complex converter structures with additional circuit components. Therefore, to overcome these problems, an enhanced boost converter topology to obtain higher voltage gains by using Gallium Nitride (GaN) based High Electron Mobility Transistor (HEMT) [7] with simple circuit structure and less number of switches is proposed in this paper. The enhanced circuit topology will provide higher voltage gains, flexible usage in practical systems, and significant weight saving for new generation systems such as drones and electrical vehicles.

3. Improved Boost Converter Topology

Proposed circuit is a modified version of traditional DC/DC Boost Converter, with implementation of an input capacitance which is illustrated in Fig. 1.

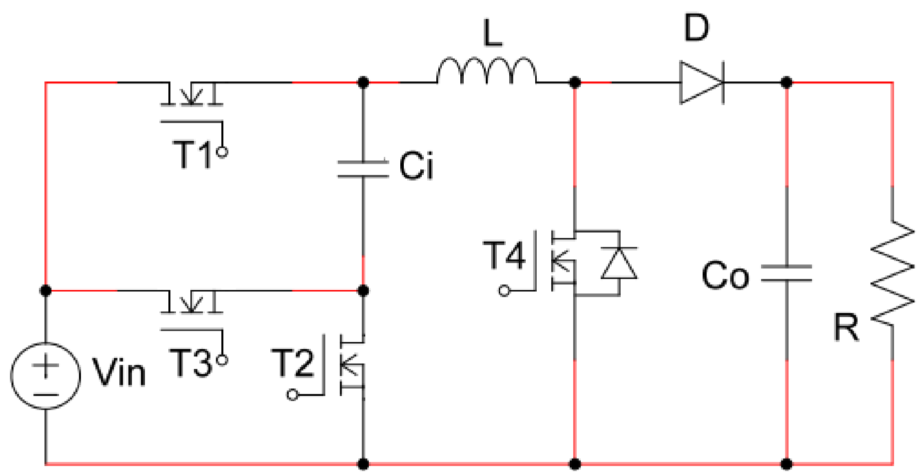

Figure 1. The modified Boost converter circuit

The main idea behind this enhanced circuit is to charge additional capacitor with using the switches T_1 and T_2 as shown in Fig. 2 and then connect it in series with the voltage source using the switches T_3 and T_4 to provide higher voltages than traditional boost converter on the output side as shown in Fig. 3. In here, R_1, R_2, R_3 and R_4 correspond to on-state resistances of T_1, T_2, T_3 and T_4 respectively. Also, R_{Ci} and R_{Co} are series resistances of capacitors C_i and C_o respectively.

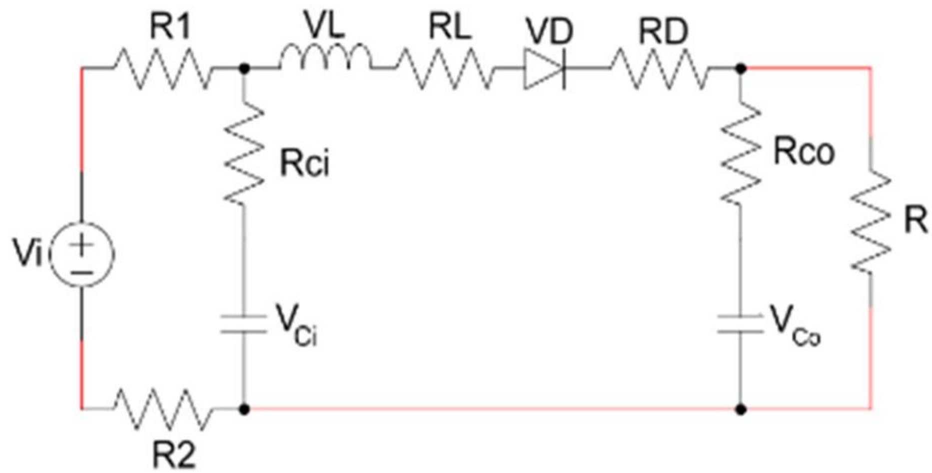

FIGURE 2. T_1 & T_2 on, T_3 & T_4 off, C_i is being charged from the voltage source

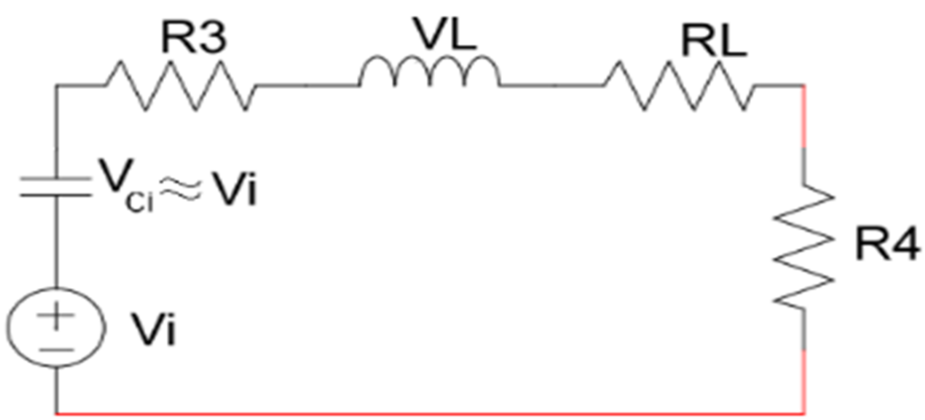

FIGURE 3. T_3 & T_4 on, T_1 & T_2 off, C_i is acting as a secondary voltage source

In proposed circuit topology, T_3 and T_4 are driven by same gating signal, while T_1 and T_2 are driven by the complement of this signal.

Here, T_s corresponds to switching period and D is duty ratio. For $(1\text{-}D)T_s$ time, both T_1 and T_2 are operating to charge input capacitance (C_i). For DT_s time, both T_3 and T_4 are operating to connect C_i and input voltage in series to provide higher voltage gain. As expected, C_i needs some time to be fully charged. Necessary charging time is a function of switching frequency, duty ratio, internal series resistance of capacitor, and on-state resistances of T_1 and T_2 which is derived and shown in (1) and (2). Here, T_{charge} shows needed minimum charging duration of C_i.

$$T_{charge} = 5(R_1 + R_2 + R_{Ci})C_i \tag{1}$$

$$(1 - D)T_s \geq T_{charge} \tag{2}$$

The key design feature of this circuit is to use an input capacitance as an input voltage multiplier which is denoted in the left side of the circuit figure. This part is integrated to the traditional boost converter to obtain $1+D$ times more voltage gain than the typical boost circuit when condition in (2) is satisfied. Considering there are no imperfections, for the situation in Fig. 2, voltage on the inductor (V_L) becomes:

$$V_L = V_i - V_o \tag{3}$$

$$V_o = V_i - L\frac{\Delta I_L}{(1-D)T_s} \tag{4}$$

$$\Delta I_L = \frac{(V_i - V_o)T_s(1-D)}{L} \tag{5}$$

For the situation in Fig. 3, assuming that (2) is satisfied, thus voltage on C_i (V_{Ci}) is equal to V_i in a very short interval of time.

$$V_L = -2V_i \tag{6}$$

$$-2V_i = L\frac{\Delta I_L}{DT_s} \tag{7}$$

$$\Delta I_L = \frac{-2V_i DT_s}{L} \tag{8}$$

Assuming that inductor is ideal, current ripple (ΔI_L) derived in (5) and (8) are equal. Therefore, from mentioned equality, the voltage gain of the proposed model becomes:

$$V_o = \frac{V_i(1+D)}{(1-D)} \tag{9}$$

From (9), it can be demonstrated that, voltage gain of proposed converter becomes *(1+D)* times of the traditional boost converter.

4. Evaluating The Performance Of The Improved Boost Converter

To evaluate the performance of the proposed circuit topology, the Matlab and Simulink are used. The proposed circuit and the traditional boost converter are modelled in Simulink for *1* second simulation time. The following circuit parameters are used in the simulations: V_i selected as *5 V* and *12 V* DC. Inductance and capacitance values are selected as *5 mH* and *440 µF* respectively. Inner resistances of all semiconductor devices selected as *7 mΩ* and finally forward voltage drop is selected as *0.7 V* [7]. The inner resistances of inductance and capacitance are determined as *0.2 Ω* and *0.1 Ω* respectively. The results of the Simulink simulations are evaluated by the help of Matlab. The modified boost converter is compared with traditional boost converter in terms of voltage gain and drive performance of the circuits. Furthermore, the proposed modified boost circuit is tested under different load conditions to investigate the behavior of the modified circuit under high and low current situations.

5. Results Of The Evaluations

In this part, the results of Simulink Model are presented. From Fig. 4, the voltage gain performance of the proposed circuit can be obtained. Mathematically, in ideal case, the expected voltage gain from this circuit is *1+D* times higher than the traditional boost converter when condition in (2) is applied to converter design. When the imperfections are considered, gain of the enhanced converter can be confirmed that approximately *1.3–1.7* times more than traditional boost converter.

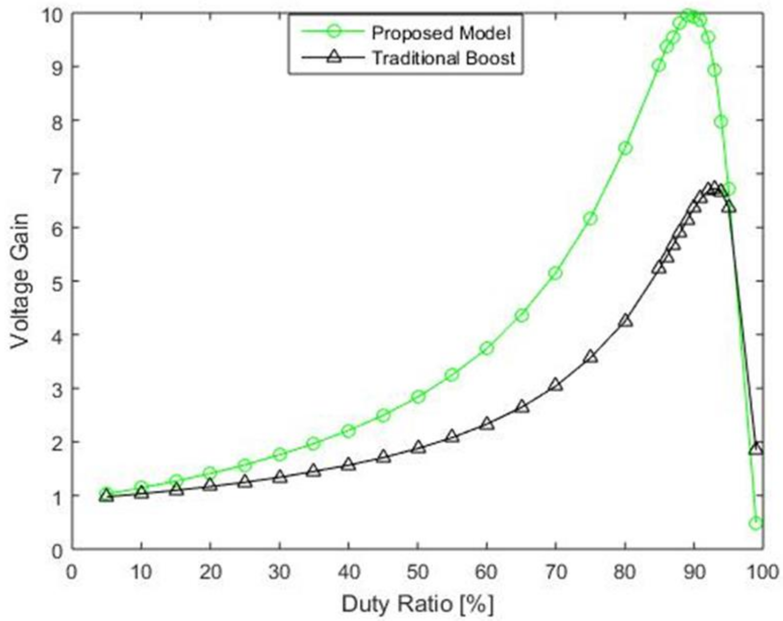

FIGURE 4. Voltage gain comparison for V_i = 12 V, R/R_L = 200

Fig. 5 and Fig. 6 illustrate the performance improvement of the proposed converter in the presence of higher load-inductor inner resistance ratio. According to these figures, the effect of increase in load-inductor inner resistance ratio on the proposed converter is more than traditional boost converter. Thereby, the modified circuit provides more voltage gains when circuit is operated at higher R/R_L ratios.

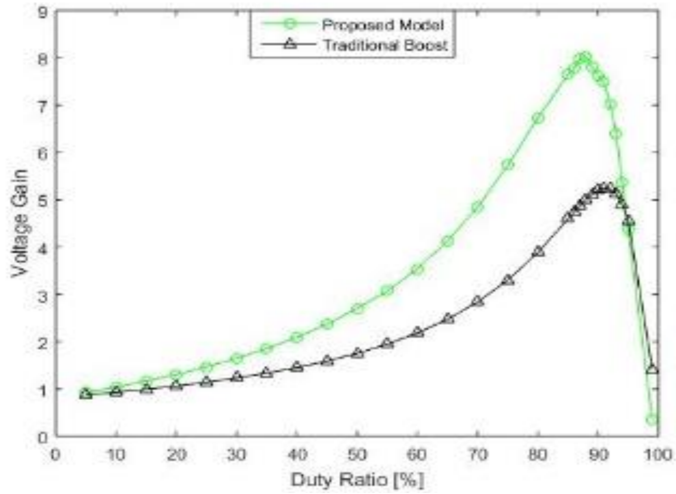

FIGURE 5. Voltage gain comparison for $V_i = 5$ V, $R/R_L = 125$

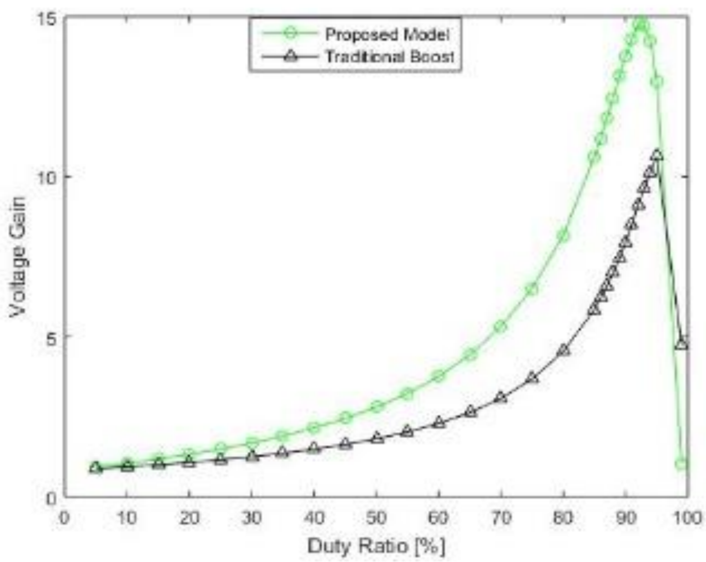

FIGURE 6. Voltage gain comparison for $V_i = 5$ V, $R/R_L = 500$

The additional semiconductor switches of the proposed circuit can be considered as a drawback. However, when the recent advancements in the semiconductor switches considered, these additional losses and the complexity of proposed circuit become negligible. Also, it is better to use GaN based HEMT instead of diodes, as diodes cause more voltage drop and switching losses on them. Accordingly, this enhanced converter becomes suitable candidate for dc/dc conversion part of weight restricted devices, applications and systems.

When output current decreases, voltage drop that is caused by imperfections of the elements becomes less effective and for that reason if higher voltage gains are aimed the proposed circuit should be operated at low currents. Thus, the voltage gain of the proposed circuit can be enhanced with using a new generation low inner-resistance semiconductor element.

With ideal elements, the expected output voltage gain of this circuit is $(1+D)$ times of the traditional boost converter as obtained from (9). However, in non-ideal cases, this ratio becomes lower because of the imperfection of non-ideal circuit elements. As this kind of imperfections (such as inner resistances) may cause voltage drop on the circuit elements, thus output voltage decreases.

The proposed converter provides approximately *1.3-1.7* times more voltage gain than the traditional one. This gain changes according to inner resistances of the circuit elements and the capacity of the input capacitance. To provide more voltage gain, semiconductor switches and diodes with lower inner resistances and lower forward voltage drop rates can be used.

Consequently, if the mathematical analyzes and modeling results are considered, optimum (maximum voltage gain) working condition of this proposed converter can be obtained when the circuit works in low output current and approximately between *0.8* and *0.9* duty ratios.

For practical applications, if transistors without body diode do not exist, two blocking diodes might be used that are connected in series to T_1 and T_2 in addition to prevent C_i from short circuit case. However, it is important to consider that these additional elements will change the gain function of modified converter.

6. Conclusions

Voltage gain is the main performance metric for boost type converters. In almost all studies, authors aim to increase the gain of the boost type converters by using transformer based approaches, silicon based diodes and inductor based schemes. But, recent years, there is a rapid improvement in semiconductor switch technology. These switches provide lower inner resistances, lower switching losses and compatibility to new generation devices and systems. Therefore, in this study, I aim to use these kind of semiconductors to improve the voltage gain performance of the traditional boost converter for high voltage gain applications such as renewable energy systems, drone applications, PV applications. The additional semiconductor switches of the proposed topology can be perceived as an issue. But, when the current developments in the semiconductors technology considered, these increased losses and the complexities of the proposed converters become negligible. Moreover, it is prefered to utilize GaN based HEMT instead of diodes, as diodes cause more voltage drops and switching losses on the components. Therefore, the proposed converter in this study becomes suitable candidate for dc/dc conversion part of weight restricted applications and technologies. Results of the analyses and modelling illustrate that proposed converter provides approximately *1.7* times more voltage gain than traditional boost converter. This gain varies due to the inner resistances of the circuit components and the capacity of the input capacitance. To provide more voltage gain, semiconductor switches and diodes with lower inner resistances and lower forward voltage drop rates can be used. The proposed topology provides a considerable gain and a wide output voltage range with lower turn ratios compared with other topologies. For future studies, to increase gain of enhanced converter, switches with lower on-state resistance can be used. In addition, I aim to make real-time experiments of the proposed converter to verify its performance improvements.

References

[1] Tofoli, F. L., Pereira, D. C., Paula, W.J., Oliviera Junior, D.S., Survey on non-isolated high-voltage step-up dc-dc topologies based on the boost converter. *IET Power Electronics*, 8(10) (2015), 2044–2057.

[2] Li, W., He, X., Review of nonisolated high-step-up dc/dc converters in photovoltaic grid-connected applications, *IEEE Trans. On Industrial Electronics*, 58(4) (2011), 1239–1250.

[3] Chen, T. M., Chan, C.L., Analysis and design of asymmetrical half bridge flyback converter, *IEE Proc.-Elect. Power Appl.*, 149(6) (2002), 433-440.

[4] Soltanzadeh, K., Khalilian, H., Dehghani, M., Analysis, design and implementation of a zero voltage switching two-switch CCM flyback converter, *IET Circuits, Devices & Systems*, 10(1) (2015), 20-28.

[5] Murthy-Bellur, D., Kondrath, N., Kazimierczuk, M.K., Transformer winding loss caused by skin and proximity effects including harmonics in pulse-width modulated dc-dc

flyback converters for the continuous conduction mode, *IET Power Electronics,* 4(4) (2010), 363-373.

[6] Yan, Z., Ai-ming, S., Simplified ferrite core loss separation model for switched mode power converter, *IET Power Electronics,* 9(3) (2015), 529-535.

[7] GaN Systems. Top-side cooled 100 V E-mode GaN transistor, *GS61008T datasheet,* (2017).

[8] Zhu, B., Wang, H., Vilathgamuwa, D.M., Single-switch high step-up boost converter based on a novel voltage multiplier, *IET Power Electronics*, 12(14) (2019), 3732-3738.

[9] Choi, K., Kim, Y., Kim, K., Kim, S., Output voltage tracking controller embedding auto-tuning algorithm for DC/DC boost converters, *IET Power Electronics,* 12(14) (2019), 3767-3773.

[10] Aghdam Meinagh, F. A., Babaei, E., Tarzamni, H., Kolahian, P., Isolated high step-up switched-boost DC/DC converter with modified control method, *IET Power Electronics,* 12(14) (2019), 3635-3645.

[11] Appikonda, M., Kaliaperumal, D., Modelling and control of dual input boost converter with voltage multiplier cell, *IET Circuits, Devices & Systems,* 13(8) (2019), 1267-1276.

[12] Spiazzi, G., Analysis and design of the soft-switched clamped-resonant interleaved boost converter, *CPSS Transactions on Power Electronics and Applications,* 4(4) (2019), 276-287.

[13] Shaneh, M., Niroomand, M., Adib, E., Ultrahigh-Step-Up Nonisolated Interleaved Boost Converter, *IEEE Journal of Emerging and Selected Topics in Power Electronics,* 8(3) (2020), 2747-2758.

[14] Yang, F., Li, C., Cao, Y., Yao, K., Two-Phase Interleaved Boost PFC Converter With Coupled Inductor Under Single-Phase Operation, *IEEE Transactions on Power Electronics,* 35(1) (2020), 169-184.

[15] Zheng, Y., Smedley, K.M., Analysis and Design of a Single-Switch High Step-Up Coupled-Inductor Boost Converter, *IEEE Transactions on Power Electronics,* 35(1) (2020), 535-545.

[16] Radin, R.L., Sawan, M., Galup-Montoro, C., Schneider, M.C., A 7.5-mV-Input Boost Converter for Thermal Energy Harvesting With 11-mV Self-Startup, *IEEE Transactions on Circuits and Systems II: Express Briefs*, 67(8) (2020), 1379-1383.

[17] Janabi, A., Wang, B., Switched-Capacitor Voltage Boost Converter for Electric and Hybrid Electric Vehicle Drives, *IEEE Transactions on Power Electronics,* 35(6) (2020), 5615-5624.

[18] Matei, C., Urbonas, J., Votsi, H., Kendig, D., Aaen, P.H., Dynamic Temperature Measurements of a GaN DC–DC Boost Converter at MHz Frequencies, *IEEE Transactions on Power Electronics,* 35(8) (2020), 8303-8310.

[19] Eskandari, R., Babaei, E., Sabahi, M., Ojaghkandi, S.R., Interleaved high step-up zero-voltage zero-current switching boost DC–DC converter, *IET Power Electronics,* 13(1)

(2020), 96-103.

[20] Yuan, Y., Zhang, Z., Mei, X., Boost-integrated LCL resonant converter with high voltage gain, *IET Power Electronics,* 13(2) (2020), 332-339.

[21] Hu, X., Liu, X., Ma, P., Jiang, S., An Ultrahigh Voltage Gain Hybrid-Connected Boost Converter With Ultralow Distributed Voltage Stress, *IEEE Transactions on Power Electronics,* 35(10) (2020), 10385-10395.

[22] Jhang, J., Wu, H., Hsu, T., Wei, C., Design of a Boost DC–DC Converter With 82-mV Startup Voltage and Fully Built-in Startup Circuits for Harvesting Thermoelectric Energy, *IEEE Solid-State Circuits Letters*, 3 (2020), 54-57.

[23] Sedaghati, F., Pourjafar, S., Analysis and implementation of a boost DC–DC converter with high voltage gain and continuous input current, *IET Power Electronics*, 13(4) (2020), 798-807.

[24] AlZawaideh, A., Boiko, I., Analysis of a Sliding Mode DC–DC Boost Converter Through LPRS of a Nonlinear Plant, *IEEE Transactions on Power Electronics*, 35(11) (2020), 12321-12331.

[25] Li, G., Jin, X., Chen, X, Mu, X, A novel quadratic boost converter with low inductor currents, *CPSS Transactions on Power Electronics and Applications,* 5(1) (2020), 1-10.

[26] Zhang, K., Ye, T., Yan, Z., Song, B., Hu, A.P., Obtaining Maximum Efficiency of Inductive Power-Transfer System by Impedance Matching Based on Boost Converter, *IEEE Transactions on Transportation Electrification,* 6 (2) (2020), 488-496.

[27] Leng, M., Zhou, G., Tian, Q., Xu, G., Blaabjerg, F., Small Signal Modeling and Design Analysis for Boost Converter With Valley V2 Control, *IEEE Transactions on Power Electronics,* 35(12) (2020), 13475-13487.

[28] Guo, J. et al. A Comprehensive Analysis for High-Power Density, High-Efficiency 60 kW Interleaved Boost Converter Design for Electrified Powertrains, *IEEE Transactions on Vehicular Technology,* 69(7) (2020), 7131-7145.

[29] Meraj, M., Bhaskar, M.S., Iqbal, A., Al-Emadi, N., Rahman, S., Interleaved Multilevel Boost Converter With Minimal Voltage Multiplier Components for High-Voltage Step-Up Applications, *IEEE Transactions on Power Electronics,* 35(12) (2020), 12816-12833.

[30] Hu, R., Zeng, J., Liu, J., Guo, Z., Yang, N., An Ultrahigh Step-Up Quadratic Boost Converter Based on Coupled-Inductor, *IEEE Transactions on Power Electronics,* 35(12) (2020), 13200-13209.

[31] Lopez-Santos, O., Mayo-Maldonado, J.C., Rosas-Caro, J.C., Valdez-Resendiz, J.E., Zambrano-Prada, D.A, Ruiz-Martinez, O.F., Quadratic boost converter with low-output-voltage ripple, *IET Power Electronics,* 13(8) (2020), 1605-1612.

[32] Santos Spencer Andrade, A. M., da Silva Martins, M.L., Isolated boost converter based high step-up topologies for PV microinverter applications, *IET Power Electronics*, 13(7) (2020), 1353-1363.

[33] Wang, L., Wu, Q., Tang, W., Improved Energy Balance Control for Boost Converters Without Estimating Circuit Energy Losses, *IEEE Access,* 8 (2020), 146323-146330.

[34] Zeng, Y., Li, H., Wang, W., Zhang, B., Zheng, T.Q., Cost-effective clamping capacitor boost converter with high voltage gain, *IET Power Electronics*, 13(9) (2020), 1775-1786.

[35] Rostami, S., Abbasi, V., Talebi, N., Kerekes, T., Three-port DC-DC converter based on quadratic boost converter for stand-alone PV/battery systems, *IET Power Electronics*, 13(10) (2020), 2106-2118.