cigre Turkey

TEPES
TURKISH JOURNAL OF
ELECTRICAL POWER
AND ENERGY SYSTEMS

TEPES, Vol. 4, Issue. 2, 96-107, 2024 **DOI:** 10.5152/tepes.2024.22029

REVIEW

Performance Analysis of LLC Resonant and Pulse Width Modulation Direct Current- Direct Current Converters for Buck and Boost Operation

Mohammad Mustafizur Rahman, Rashed Abdullah, Arif Ahammad, Ifte Khairul Amin

Department of Electrical & Electronic Engineering, Shahjalal University of Science and Technology, Sylhet, Bangladesh

Cite this article as: M. M. Rahman, R. Abdullah, A. Ahammad and I. K. Amin, “Performance analysis of LLC resonant and pulse width modulation direct current-direct current converters for buck and boost operation,” *Turk J Electr Power Energy Syst.*, 2024; 4(2), 96-107.

ABSTRACT

This paper accentuates the study of LLC resonant converter by a comparative analysis of the properties of LLC resonant and pulse width modulation direct current-direct current converters. Lately, LLC resonant converters have become more appealing and desirable in many applications than other pulse width modulation converters (e.g., Buck, Boost, Cuk) for their soft-switching techniques like zero voltage switching, zero current switching as well as low electromagnetic interference. This paper presents an analysis of efficiency variation, output voltage's ripple, and various transient performances like percentage overshoot, and the settling time with the variation of load current in a comparative way between LLC resonant converter's buck, boost operation, and conventional pulse width modulation converter's buck, boost operation. Feedback proportional-integral-derivative duty cycle controller is used in all converter topologies for some specific analysis. A fixed input voltage of 100 V is selected for simulation and an output voltage of 24 V for buck operation and 120 V for boost operation are chosen. For simulation purposes, MATLAB/SIMULINK software is used.

Index Terms—DC-DC converter, LLC resonant converter, pulse width modulation, switched-mode power supply, zero voltage switching

I. INTRODUCTION

Modernized electronic devices do require high-quality, compact, lightweight, reliable, and energy efficient power supplies [1–4]. As the demand for high performing, cost efficient systems, and portable electronics continues to rise, the design of power electronics system has become more challenging and complex than ever. DC power supplies are used in most of the appliances requiring a constant voltage, so the role played by direct current-direct current (DC-DC) converter is becoming more significant [5, 6]. One of the core concerns of DC converters is its efficiency along with other parameters like its output voltage regulation, ripple in the output load voltage, overshoot, settling time, voltage and current stress in the circuit components, etc. Among various topologies of DC-DC converters, switched-mode power supply (SMPS) devices are getting enough attention among researchers for satisfactory efficiency, compact form-factor, soft switching, higher frequency switching, and higher power densities [7–10]. These are just some of the current trends in DC-DC converters [11]. In this paper, three of the popular SMPS topologies named LLC resonant converter, pulse width modulation (PWM) buck converter and PWM boost converter are taken to study. The aforementioned parameters in this section are graphed versus load current for comparative assessment. In a study, Steigerwald [12] showed a comparison among half bridge resonant converters. Output power vs. efficiency graphs had been shown among series, parallel and series parallel networks of resonant converters. Jung and Kwon in [13] have shown a method for the optimal design of LLC resonant converter. A greater visualization is provided in by S. Abdel-Rahman in terms of designing both LLC resonant converter and its controller [14]. Steigerwald [12] compared among DC-DC soft switched converter topologies (series/parallel resonant, dual active bridge, phase-shifted bridge, auxiliary resonant commutated bridge, hard-switched PWM, etc.) which were mostly among isolating topologies. Efficiency study only for an LLC resonant converter with another isolating topology, flyback converter was analyzed by Cheng et al in [15]. Comparison of a buck converter with a slightly modulated buck topology is also conducted in many papers [16, 17]. Comparison among buck and boost converters incorporated with LLC resonant topology is not covered by researchers in their studies

Received: May 13, 2023
Revision Requested: July 3, 2023
Last Revision Received: April 5, 2024
Accepted: April 24, 2024
Publication Date: June 20, 2024

Corresponding Author: Mohammad Mustafizur Rahman, mustafizmr07@gmail.com

so far, especially for efficiency analysis. In this paper, the efficiency performance is demonstrated among the converters for various input or load conditions. Although they belong to the same class of converter which is a switched mode power supply, it is observed that this comparison gives a good insight about their performance and application over various loading conditions. In this study, Buck, Boost, LLC Buck and LLC Boost topologies are analyzed bringing up as many combinations of comparison as possible to show a complete overview of similarities, dissimilarities, advantages, disadvantages, best field of operations etc. The performance indicating variables for the devices are shown in two designs i.e., 100/24 V for buck operation and 100/120 V for boost operation.

II. METHODS

A. General Block Diagram and Working Principle of PWM Converters

A workflow block diagram of DC-DC conventional PWM converters (buck, boost) is given in Fig. 1. The working process of both converter topologies (buck converter, boost converter) is about the same based on the principle and components used, but converting elements are in different combinations in each of them. Both topologies work on the principle of storing energy and controlling and releasing the stored energy in a certain way which is performed by opening and closing the switching elements repeatedly. It is fed with a DC input voltage at first. Then its converting elements (switch, diode, inductor) step the voltage up (boost converter)/down (buck converter). There is a filter circuit for greater regulation of the output voltage. The proportional integral derivative (PID) controller and PWM generator are used to control the converting process by taking feedback from output. If the output voltage changes from its desired value, PID controller senses it and produces a new duty ratio (D). Then PWM generator taking D and f_s (switching frequency) as inputs generate new pulses to maintain the desired output value.

B. Working Principle and Block Diagram of LLC Resonant Converter

The working principle of the LLC resonant converter is quite simple. Like other SMPS converters, it also has to switch metal–oxide–sem iconductor field-effect transistors (MOSFETs). The duty ratio of the gate pulse should be selected in a proper manner so that the switches get enough dead time to fulfill the zero voltage switching (ZVS) condition to reduce switching losses and to avoid any shoot-through current which can be very destructive for switches. Although in this paper a duty cycle PID controller is used to regulate the converter's output voltage, when a pure DC voltage enters the bridge inverter, it gets inverted. Then the inverted square wave becomes nearly a pure sine wave because of the filtering process of the LLC resonant tank circuit. This tank circuit also gives a slight gain (positive or negative). This slight gain is a must for the proper tuning of the output. Next, this sinusoid propagates through a linear center-tapping transformer. The main step-down operation for buck operation and step up for boost operation is carried out by this transformer. The design of this transformer is a sensitive issue since it directly affects the efficiency and output shape. In the Simulink model, the magnetizing resistance and capacitance are kept considerably high so that it consumes low power. The secondary voltage of the transformer gets rectified by diodes and then supplied to load. The capacitor connected to the resistive load helps to reduce the ripple. A control system is necessary to regulate the output voltage with load variation. So, the output voltage is fed back to a PID controller which supplies a controlled duty cycle (D) to the PWM generator. The switching action of the MOSFETs is controlled by using the output of the PWM generator as a gate pulse. The workflow block diagram of the LLC resonant converter is depicted in Fig. 2.

Main Points

- A comparative analysis is done between LLC resonant and PWM DC-DC converters.
- Analysis is done in two modes of LLC resonant converters—buck mode and boost mode.
- At the end of the analysis, it is found that LLC resonant converters show better results than PWM DC-DC converters in some parameters.

C. Usage of PWM Generator and PID Controller for Processing

As a duty ratio controlled PID controller is used, it is necessary that the duty ratio of the gate pulses of the MOSFETs is changed accordingly. To have a changed duty ratio, a PWM generator is used, which is shown in Fig. 3. It takes the switching frequency f_s and the PID controller's generated duty ratio (D) as inputs. Then, it produces a pulse which acts as the MOSFETs gate pulse.

Loss calculation in the components of the converter is a very important part of the efficiency calculation. Chun-An Cheng in [15] has given some ideas about calculating various losses for LLC resonant converter. In this paper, the calculation process for all the losses in the buck converter, boost converter, and LLC resonant converter is done by using a power measurement block provided by the MATLAB SIMULINK library. This block takes voltage and the current flowing through an element as input through a mux and calculates the active and reactive power up to the fourth harmonic. Mean values of the active and reactive power are then added through an adder and delivered as output. The efficiency calculation formula used in the following study is:

$$\eta = \frac{P_{out}}{P_{out} + losses} \tag{1}$$

For efficiency calculations, all kinds of losses in switches and diodes (where main losses occur) including transformer losses are calculated by the aforementioned power measurement block. In PID controller, transfer function-based (PID tuner app) is used for tuning method. For meeting the soft switching requirement and to avoid shoot through current, the PID controller's upper saturation limit is set to a specific limit for LLC resonant converter usually less than 0.50. This PID controller takes 2 inputs. One is the reference voltage value, and another is the feedback voltage value. And it gives a duty ratio, hence called a duty cycle controller, to keep the output voltage at the reference value. Then its output is fed to the PWM generator. In comparison section, controller is not used.

III. CIRCUIT DESCRIPTION AND A BRIEF ANALYSIS OF LLC RESONANT CONVERTER TOPOLOGY

A schematic diagram of a half-bridge LLC resonant converter is depicted in Fig. 4. Half-bridge in the topology works as an inverter

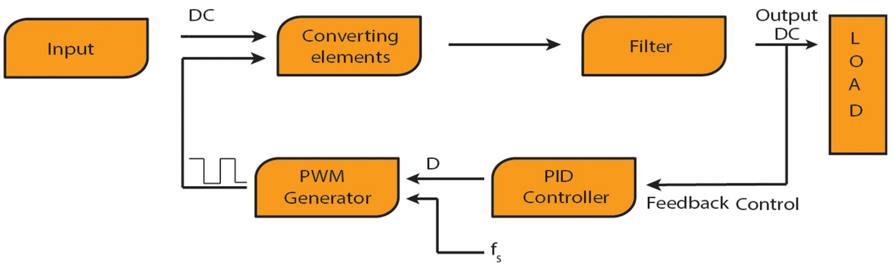

Fig. 1. Block diagram of the conventional PWM converter (buck, boost) cyto-histopathological features.

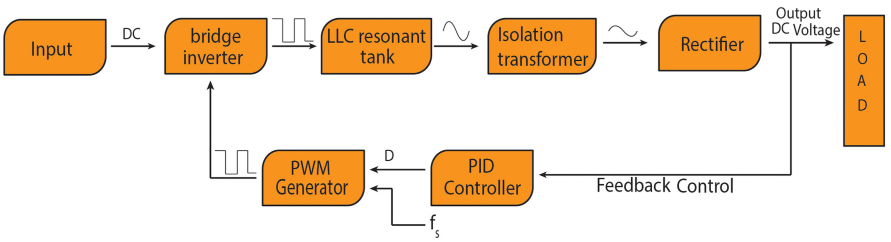

Fig. 2. General workflow diagram of LLC resonant converter.

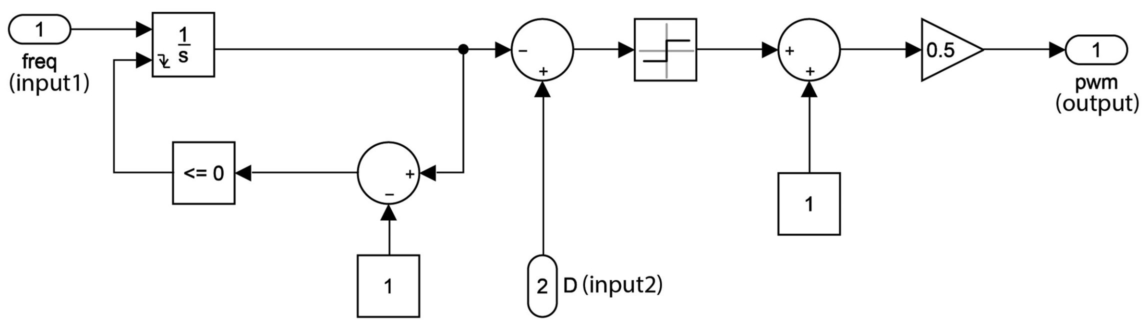

Fig. 3. PWM generator in Simulink.

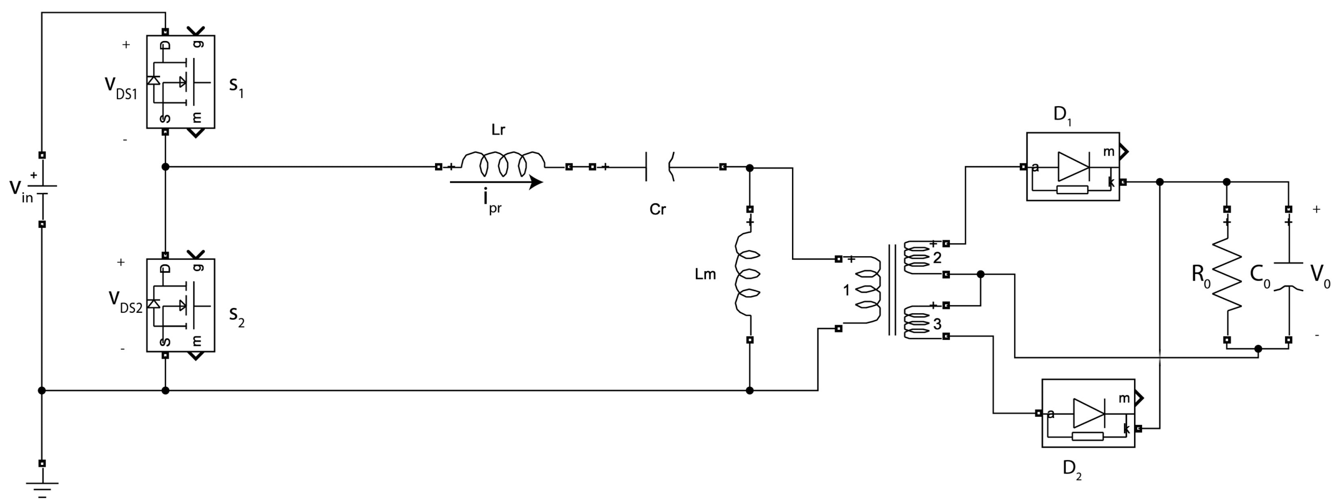

Fig. 4. Schematic diagram of a half-bridge LLC resonant converter.

to produce a square wave and the resonant circuit in the middle controls the conversion mode, e.g., buck, boost, resonance. Finally, the full-wave circuit on the right side rectifies the transformer's secondary voltage. The capacitor used in parallel reduces the output ripple voltage. L_r, L_m, C_r are the three passive resonant components of an LLC resonant converter. C_r, the resonant capacitor and L_r, the resonant inductor makes automatic flux balancing and high resonant frequency, and C_r and $L_r + L_m$ introduces another low resonant frequency. The highest gain of this system can be achieved by operating at this frequency. The LLC resonant converter does have two resonant frequencies both playing crucial role in the operation of the converter. Two resonant frequencies addressed as f_{r1} and f_{r2} can be defined as follows:

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{2}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m)*C_r}} \tag{3}$$

The quality factor Q could be expressed as:

$$Q = \frac{1}{R_{ac}} \cdot \sqrt{\frac{L_r}{C_r}} \tag{4}$$

From the LLC converter's DC characteristic, it can be seen that variations in load cause a shift in the gain peak. This peak moves towards f_{r2} resonant frequency when the load becomes lighter and for heavier loads, the peak shifts towards f_{r1} resonant frequency. The load has an inversely proportional relationship with resistance. The gain at f_{r1} is quite close to unity, regardless of the change in load. Gain against normalized switching frequency for several load resistances in different regions is shown in Fig. 5. For a particular load, if the switching frequencies are selected higher than the peak gain frequency, the resonant circuit faces an inductive load and the resonating current lags, and the switching current alternates its direction when the switching voltage is zero, offering ZVS. Similarly, switching frequency below the peak gain frequency offers zero current switching (ZCS).

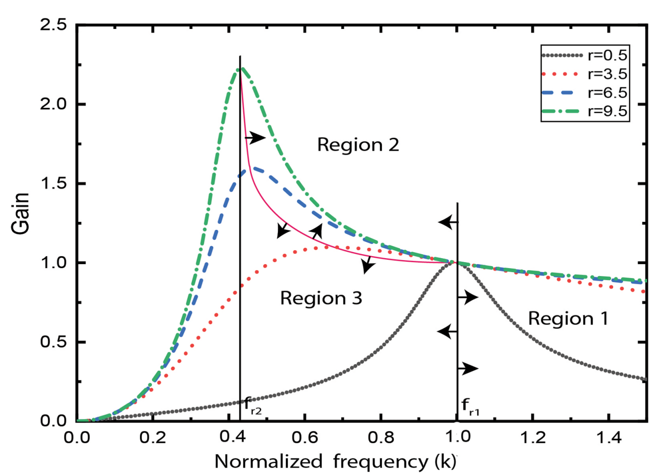

Fig. 5. Gain against normalized switching frequency for several load resistances in a different region. (In this study $r = 6$ has been used).

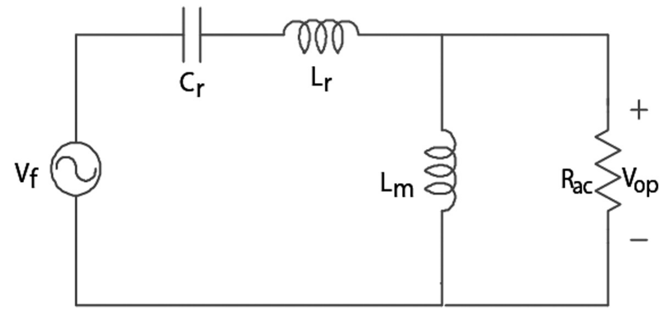

Fig. 6. An equivalent circuit diagram of an LLC resonant converter.

But in general, ZCS operation is avoided in this region. Because below peak gain frequency, the current in the intrinsic body diode of MOSFETs on the primary side faces a hard commutation which could cause a failure condition in the MOSFETs. Region 1 of Fig. 5 is the operation region of series resonant circuit. The state of ZVS is often ensured as magnetizing inductance is not involved in the resonance. Region 2 is the region of operation of multi resonant converter. The condition of load will determine the converter's performance between the frequencies of f_{r1} and f_{r2}, under ZVS and ZCS conditions. The energy contained in the magnetic components in this region causes the opposite MOSFET to have ZVS. Region 3 is an overloaded region. The converter does enter the ZCS mode in this region. Regions 1 and 2 are where the LLC resonant converter is intended to operate due to output regulation with ZVS operation. The range of operation is kept above f_{r2} to ensure ZVS operation. Fundamental harmonic approximation (FHA) is a commonly used technique in the analysis of resonant converters [20–23]. R.L.Steigerwald derived an analysis process in [12]. An equivalent model can be derived which is shown in Fig. 6.

Equivalent model parameters can be derived from the original schematic of LLC resonant circuit as:

$$V_f = \frac{2V_{in}}{\pi} \tag{5}$$

$$R_{ac} = \frac{8}{\pi^2} \cdot \frac{N_p^2}{N_s^2} \cdot R_o \tag{6}$$

$$I_o = \frac{\pi V_{op}}{4R_o} \tag{7}$$

$$V_o = \frac{\pi V_{op}}{4n} \tag{8}$$

Now, converter gain = switching bridge gain × resonant tank gain × transformer turn ratio (N_s/N_p) [14]. Here the gain of the switching bridge for a full bridge is 1 and for a half bridge it is 0.5. Analyzing the equivalent resonant circuit depicted in Fig. 6 yields the gain of resonant tank, and it is equal to the magnitude of its transfer function. If gain is defined as G then it will be a function of Q, *r* and k [14].

$$G(Q,r,k) = \left|\frac{V_{0\_ac}(s)}{V_{in\_ac(s)}}\right| = \frac{k^2(m-1)}{\sqrt{(m \cdot k^2 - 1)^2 + k^2 \cdot (k^2-1)^2 \cdot (m-1)^2 \cdot Q^2}} \tag{9}$$

$$k = \frac{f_s}{f_{r1}} \tag{10}$$

$$r = \frac{L_m + L_r}{L_r} \quad (11)$$

With the help of nodal analysis of the equivalent model shown in Fig. 6, the transfer ratio of input–output of the FHA model, $T_{FHA}(V_{op}/V_f)$ in the Laplace transformation form, can be obtained,

$$\frac{V_{op}}{R_{ac}} + \frac{V_{op}}{sL_m} + \frac{V_{op} - V_f}{\frac{1}{sC_s} + sL_r} = 0 \quad (12)$$

$$T_{FHA} = \frac{s^2 L_m C_r R_{ac}}{s^3 L_m C_r L_r + s^2 R_{ac} L_m C_r + sL_m + R_{ac}} \quad (13)$$

Highest acceptable operating frequency, changes in load, range of input voltage, and short circuit characteristics play an important role in designing resonant components [13]. Design characteristics that are given in [13] are followed in this paper. The dead time, t_{dt} calculating formula from [13] is given as:

$$t_{dt} = 16 C_s f_{s(max)} L_m \quad (14)$$

C_s is defined as the snubber capacitance of MOSFETs and $f_{s(max)}$ as the maximum switching frequency.

IV. SIMULATION RESULTS

A. PWM Buck Converter

Buck converter's parameters are given in Table I. Its output voltage plot is given in Fig. 7. Its controller's control signal is shown in Fig. 8. This operation's block diagram of this operation is depicted in Fig. 1.

B. PWM Boost Converter

The boost converter's parameters are given in Table II. Its output voltage plot is given in Fig. 9(a). Its workflow diagram is shown in Fig. 1. And its controller's control signal is shown in Fig. 9(b). From its output voltage, it can be seen it has a very high initial overshoot because of inductive kickback, which is converting current into voltage in an attempt to keep the current constant. The more abruptly the current decreases, the larger the voltage it generates [24].

It can be seen from Fig. 9(b) that the controller's signal remains zero for some instances, then it starts contributing to keeping output

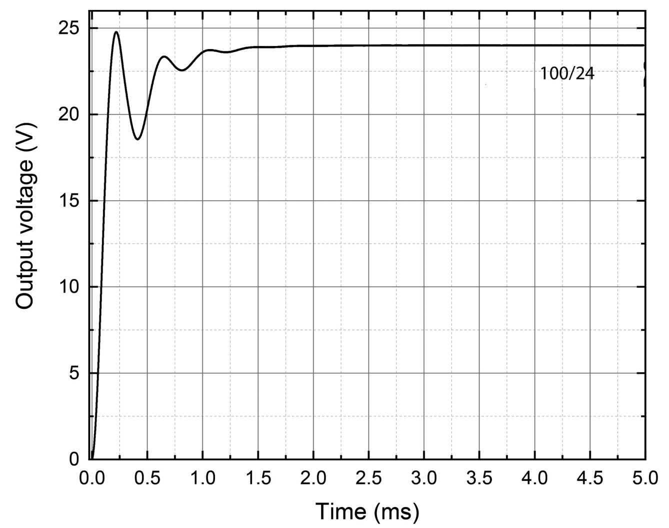

Fig. 7. PWM buck converter's output voltage.

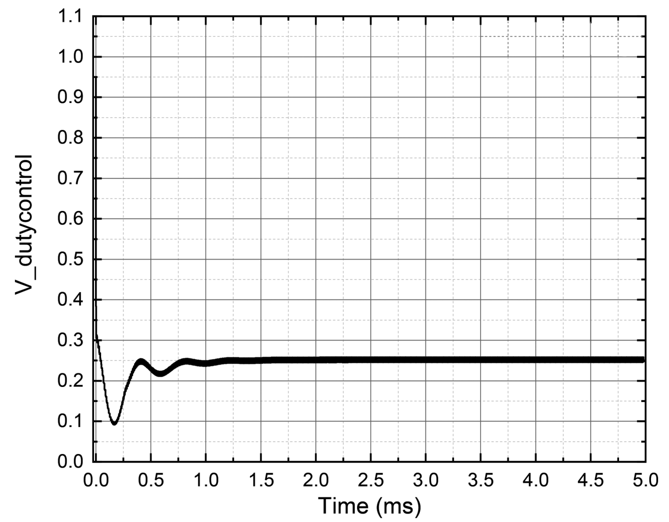

Fig. 8. PID controller's control signal of Buck converter.

TABLE I.
DEVICE PARAMETERS DESCRIPTION FOR BUCK CONVERTER

Parameters	Value
Nominal power, P_o	300 W
Rated input voltage, V_i	100 V
Rated output voltage	24 V
Switching frequency, f_s	100 KHz
Inductor, H	35 µH
Filter capacitor, C	250 µF

TABLE II.
DEVICE PARAMETERS DESCRIPTION FOR BOOST CONVERTER

Parameters	Value
Nominal power, P_o	300 W
Rated input voltage, V_i	100 V
Rated output voltage	120 V
Switching frequency, f_s	100 KHz
Inductor, H	80 µH
Filter capacitor, C	50 µF

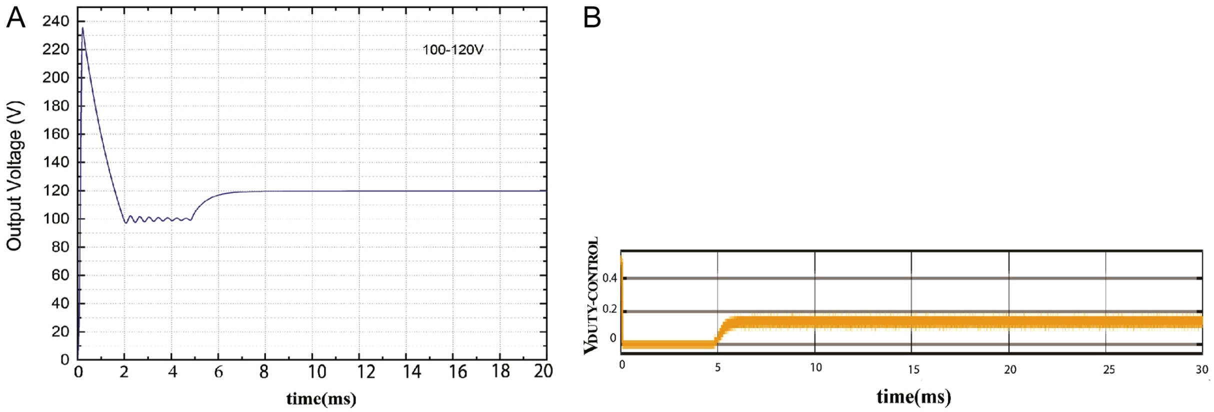

Fig. 9. (a) Boost converter's output voltage. (b) PID controller's control signal of boost converter.

voltage at the desired level. It is also clear that it has a quite large frequency.

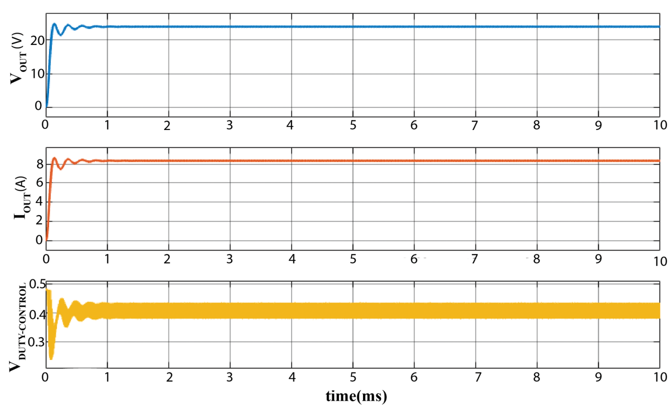

Fig. 10. Output voltage, load current, and controller's signal of LLC converter's buck operation.

C. LLC Resonant Converter's Buck Operation

When configured as a buck converter, LLC resonant converter can perform buck operation. Its specifications for buck operation are shown in Table III. The output voltage, load current, and PID controller's control signal are shown in Fig. 10. This operation's block diagram of this operation is depicted in Fig. 2. In the circuit of the LLC resonant buck converter's circuit, a half-bridge inverter, a center-tapped transformer, and diodes as secondary rectifiers are used.

D. LLC Resonant Converter's Boost Operation

Like LLC converter's buck operation, when set as a boost converter, LLC resonant converter can do boost operation. Its specification for boost operation are shown in Table IV. Its output voltage, load current, and PID controller's control signal are shown in Fig. 11.

TABLE III.
DEVICE PARAMETERS DESCRIPTION FOR LLC CONVERTER'S BUCK OPERATION

Parameters	Value
Nominal power, P_o	300 W
Rated input voltage, V_i	100 V
Rated output voltage	24 V
Switching frequency, f_s	100 KHz
Resonant frequency, fr_r	104 KHz
Filter capacitor, C	100 µF
Resonant capacitor, C_r	66 nF
Resonant inductor, L_r	35 µH
Magnetizing inductor, L_m	175 µH
Transformer turn ratio, n	2
Snubber capacitor, C_s	900 pF

TABLE IV.
DEVICE PARAMETERS DESCRIPTION FOR LLC CONVERTER'S BOOST OPERATION

Parameters	Value
Nominal power, P_o	300 W
Rated input voltage, V_i	100 V
Rated output voltage	120 V
Switching frequency, f_s	100 KHz
Resonant frequency, fr_r	104 KHz
Filter capacitor, C	100 µF
Resonant capacitor, C_r	66 nF
Resonant inductor, L_r	35 µH
Magnetizing inductor, L_m	175 µH
Transformer turn ratio, n	1
Snubber capacitor, C_s	900 pF

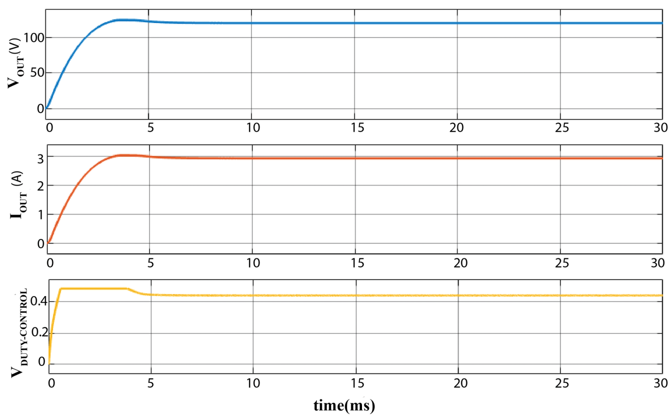

Fig. 11. Output voltage, load current, and controller's signal of LLC converter's boost operation.

In LLC resonant boost converter's circuit, a full-bridge inverter, center-tapped transformer, and diodes as secondary rectifiers are used.

E. Efficiency Vs. Duty Cycle Graphs

Fig. 12(a, b) and Fig. 13(a, b) show how efficiency changes as a function of the duty cycle for these topologies.

For LLC resonant converter, if the switches are not given proper dead time, then its requirement for zero voltage switching does not fulfilll. So, there will be a lot of switching losses resulting in a fall in efficiency. Fig. 12(a) shows that for LLC resonant converter's buck and boost operation, after a certain point of duty cycle efficiency keeps dropping because ZVS cannot occur after that certain point of duty cycle. It shows a very significant theoretical concept about the importance of dead time in an LLC resonant converter.

F. Comparative Graphs of LLC Resonant Converter's Buck Operation Vs. PWM Buck Converter

Comparisons between these two topologies are done with respect to load for percentage overshoot, ripple voltage, settling time, and terminal voltage. Graphs of those studies are depicted from Fig. 14 and Fig. 15(a-c). PID controller was set off for this study as the frequency was fixed.

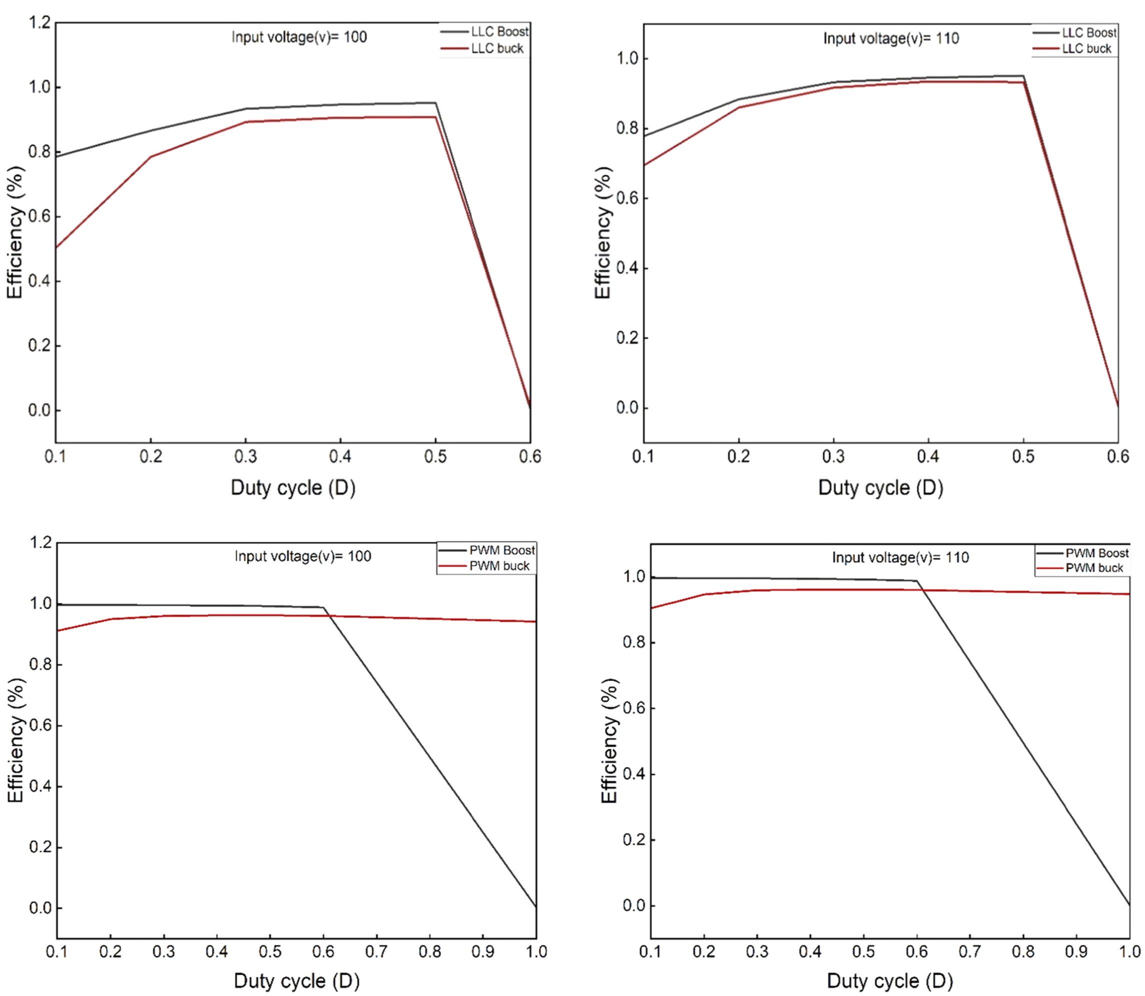

Fig. 12. (a) Efficiency vs. duty cycle for LLC resonant topology. (b) Efficiency vs. duty cycle for PWM boost and buck topology.

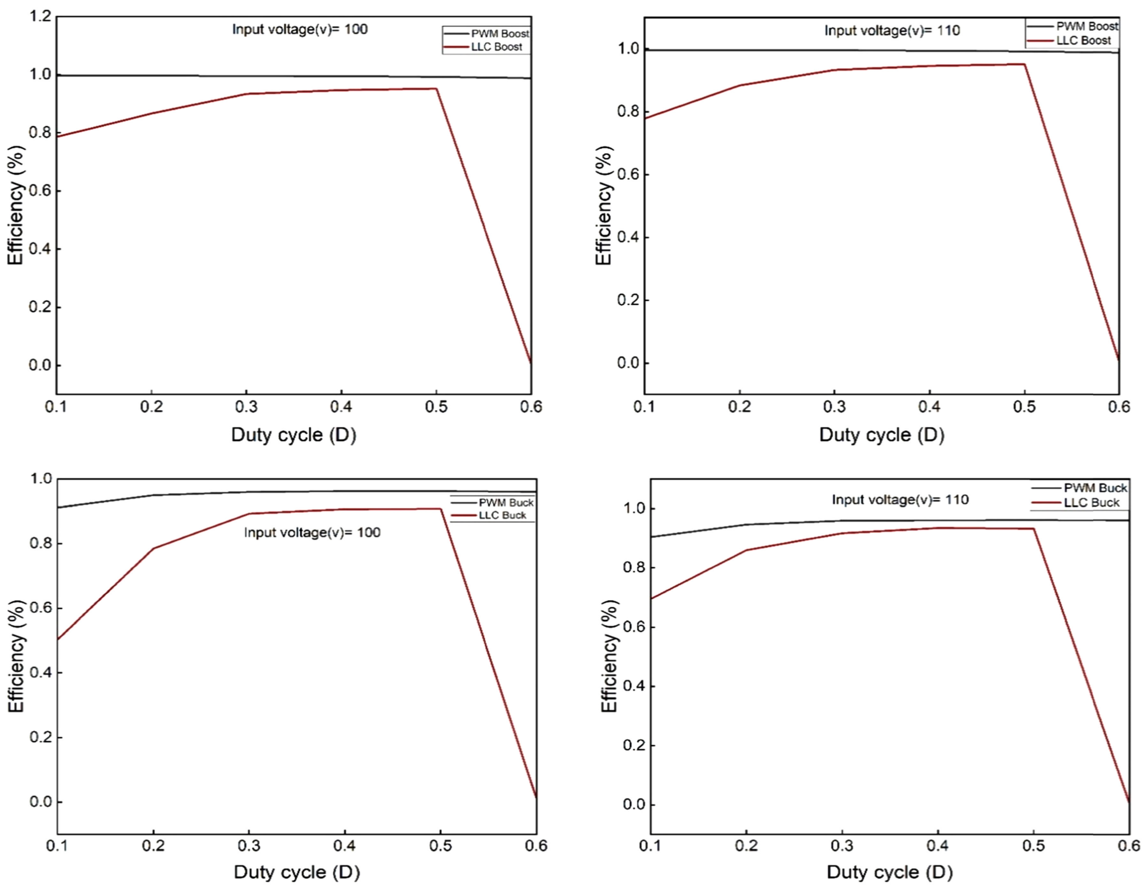

Fig. 13. (a) Efficiency vs. duty cycle between LLC resonant converter and PWM buck converter. (b) Efficiency vs. duty cycle between LLC resonant converter and PWM boost converter.

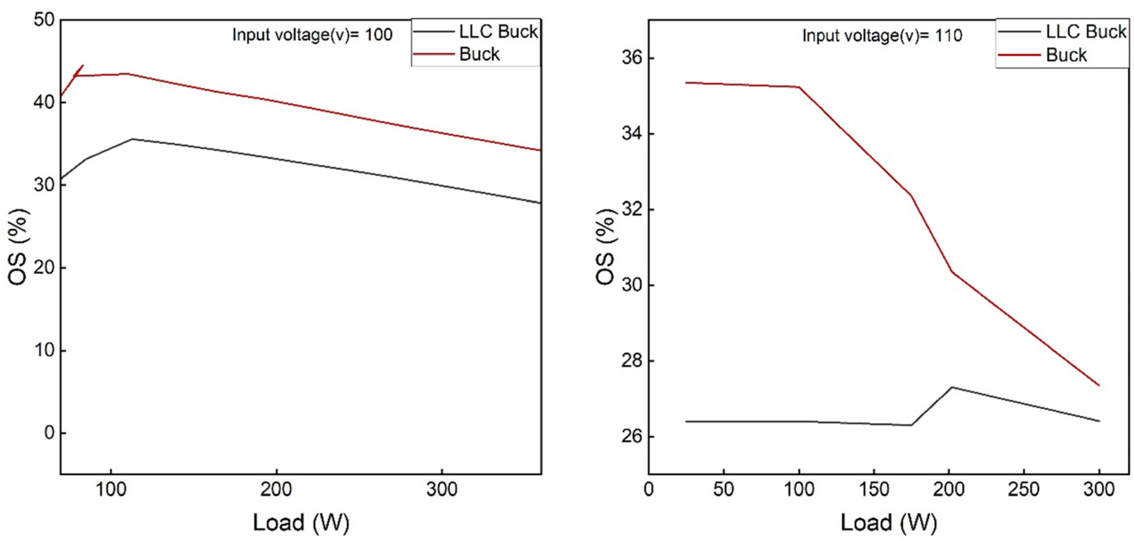

Fig. 14. Percentage OS comparison between PWM buck converter and LLC resonant converter's buck operation.

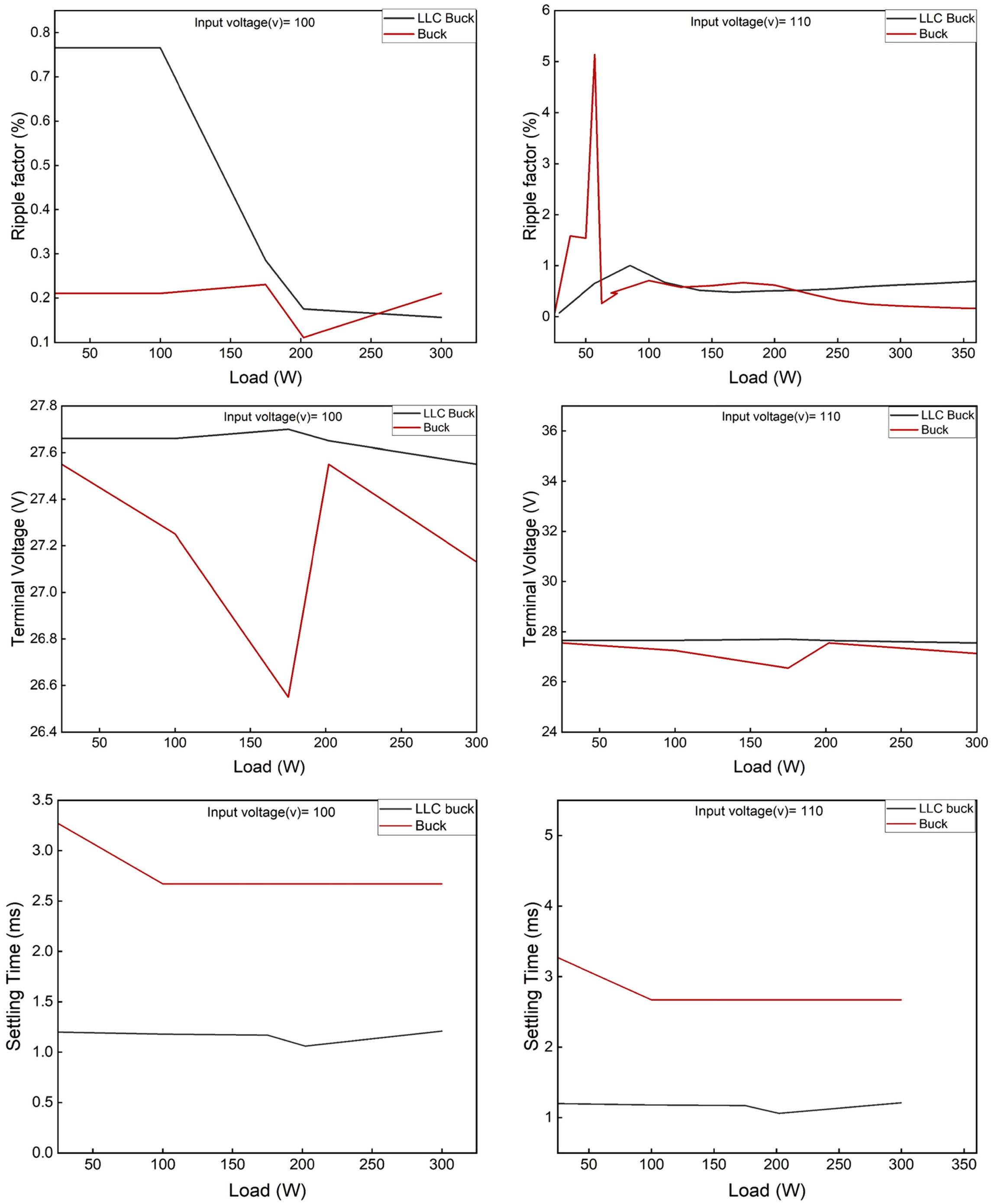

Fig. 15. (a) Ripple voltage comparison between PWM buck converter and LLC resonant converter's buck operation. (b) Terminal voltage comparison between buck converter and LLC resonant converter's buck operation. (c) Settling time comparison between PWM buck converter and LLC resonant converter's buck operation.

Percentage overshoot decreases with the load current in the buck converter for both topologies which are shown in Fig. 14, but the ripple voltage increases with the load as shown in Fig. 15(a). The output ripple voltage of the LLC buck converter increases more rapidly than the PWM buck converter. Although the LLC buck converter's output ripple voltage is more than the PWM buck converter, it is in a permissible range for many applications. As a result, there should be a trade-off between ripple voltage and the percentage overshoot. By observing the ripple voltage graph in Fig. 15(a), ripple voltage has an inverse relation with the load resistance. In other words, ripple voltage is proportional to the load. Heavy load requires a high load current, which causes the filter capacitor to charge or discharge quickly,

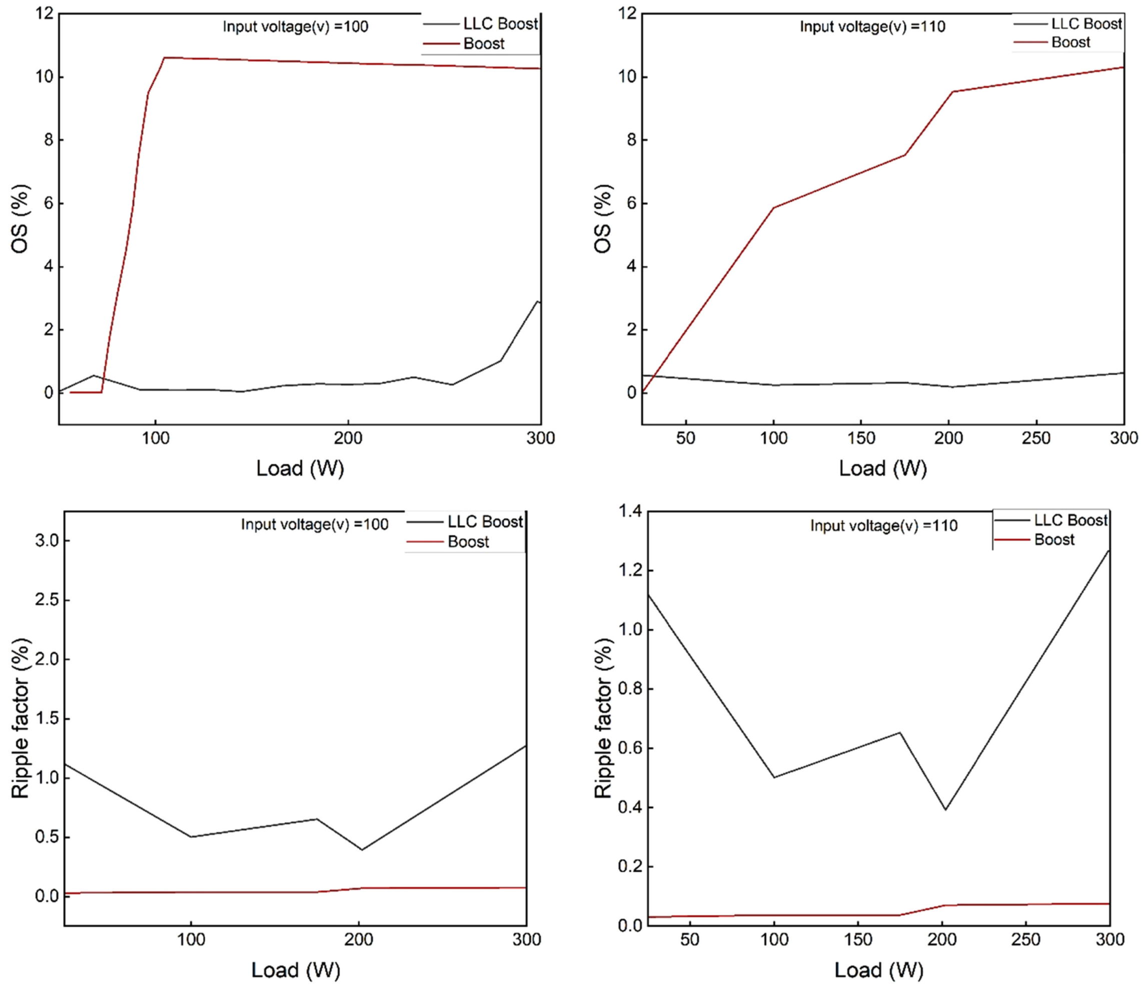

Fig. 16. (a) Percentage OS comparison between boost converter and LLC resonant converter's boost operation. (b) Ripple voltage comparison between boost converter and LLC resonant converter's boost operation.

hence higher the ripple. Settling time for all loads is less than the buck converter for LLC converter's buck operation shown in Fig. 15(c).

G. Comparative Graphs of LLC Resonant Converter's Boost Operation vs PWM Boost Converter

Comparisons between these two topologies are done with respect to load for percentage overshoot, ripple voltage, settling time, and terminal voltage. Graphs of those studies are depicted in Fig. 16(a, b) to Fig. 17(a, b). The PID controller was set off for this study as the frequency was fixed.

From the PWM boost converter and LLC boost converter comparison, it can be found that one of the big disadvantages of the PWM boost converter is the very high percentage of overshoot, which is shown in Fig. 16(a), which can be very harmful and dangerous for many applications. The high overshoot in the output voltage of the PWM boost DC-DC converter is due to a phenomenon known as inductive kickback/fly-back. The inductor initially produces high voltage to compensate for the effect of switching, causing a high change in current in this case. In contrast, the LLC circuit shows almost zero overshoot. Output ripple voltage is also higher for the PWM boost converter compared to the LLC boost converter at any point of load application, as depicted in Fig. 16(b). The LLC resonant converter also has a lower settling time compared to the PWM boost topology as shown in Fig. 17(a).

H. Efficiency Comparison

A graph showing the variation of efficiency concerning load variation for the PWM buck converter, PWM boost converter, LLC converter's boost and buck operation is depicted in Fig. 18, for the load variations from 100 W to 300 W. For efficiency calculation, losses in switches, diodes, and transformer were taken into consideration. PID controller was set off for this study too.

V. CONCLUSION

Performance analysis of LLC resonant converter's buck and boost operation in comparison with conventional PWM converter's buck and boost operation was done in detail showing the variation of efficiency, output ripple voltage, percentage overshoot, and settling time. LLC resonant buck converter has almost similar efficiency and a lower percentage of overshoot than the conventional PWM buck converter. Another significant advantage of the LLC resonant buck

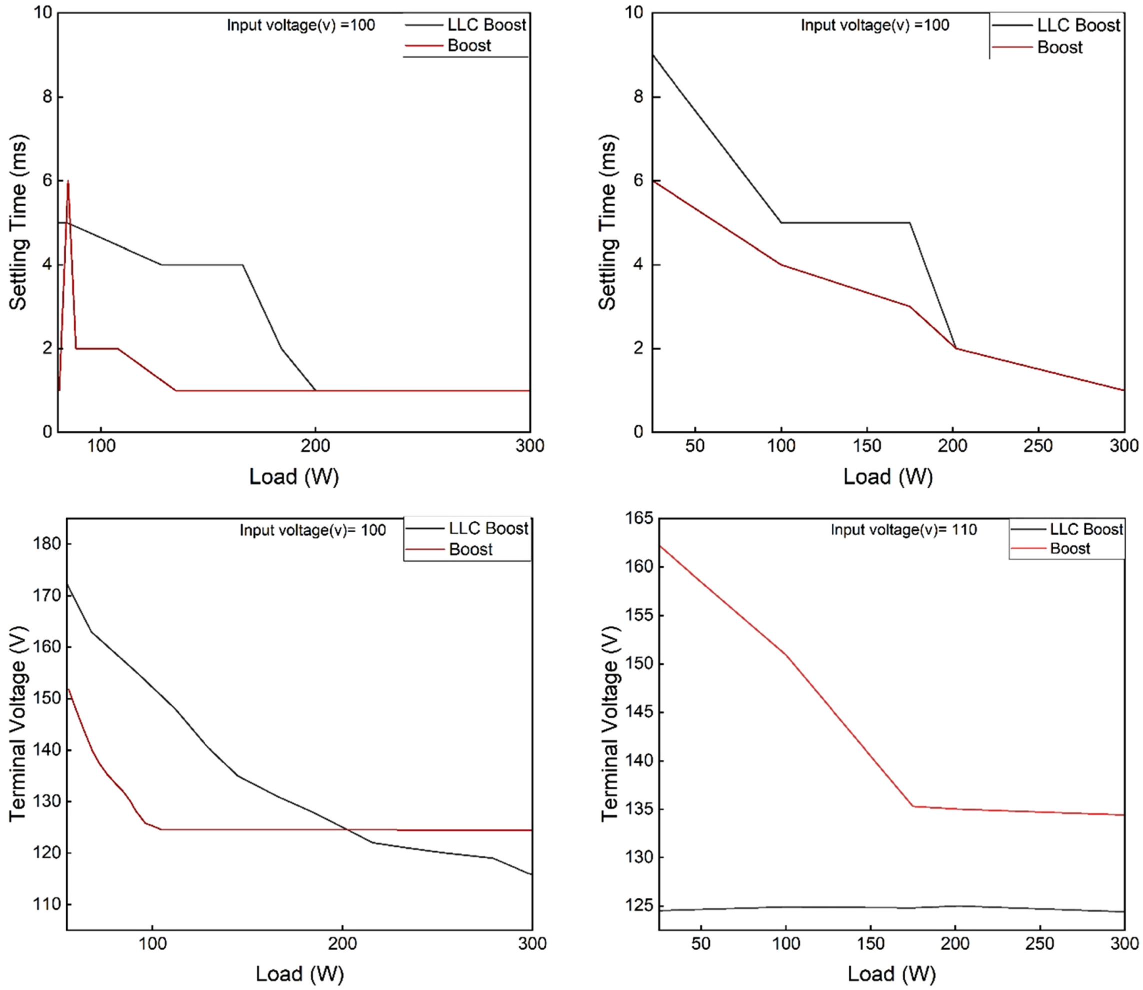

Fig. 17. (a) Settling time comparison between boost converter and LLC resonant converter's boost operation. (b) Terminal voltage comparison between boost converter and LLC resonant converter's boost operation.

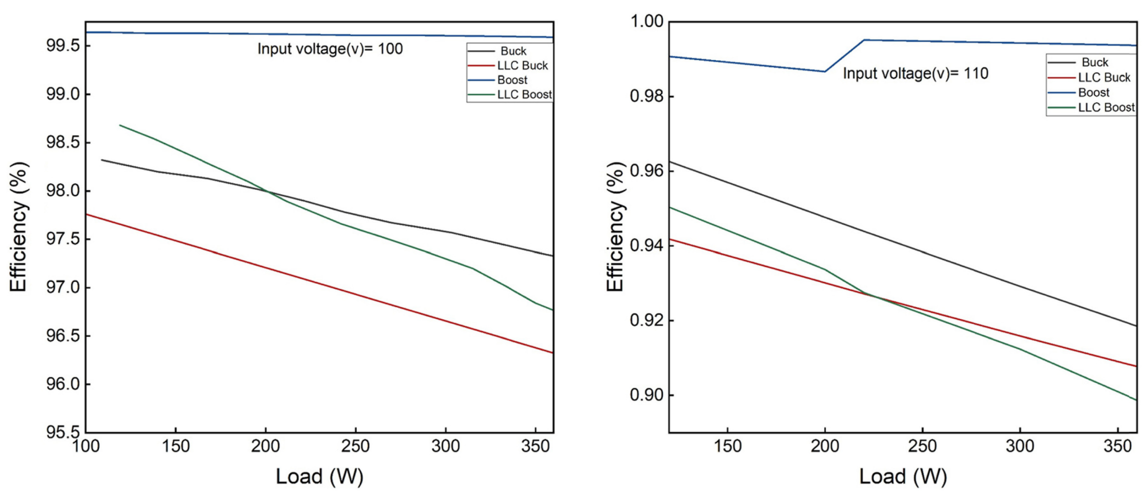

Fig. 18. Efficiency vs. Load for all three topologies (four operations).

converter is that it has a much shorter settling time than conventional PWM buck converters. Ripple factor for them is well under 1%. However, the efficiency and settling time (for a lower load range) of the LLC resonant boost converter are lower than those of the PWM boost converter. The LLC resonant boost converter has almost no overshoot, whereas the PWM boost converter has a higher overshoot. Analyzing the result, it is justified to say that the LLC resonant converter can give a preferable output in many demanding aspects for both buck and boost operation.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – R.A., M.M.R.; Design – R.A., M.M.R.; Supervision – A.A., I.K.A.; Resources – M.M.R., R.A.; Materials – R.A., M.M.R.; Data Collection and/or Processing – R.A.; Analysis and/or Interpretation – R.A., M.M.R., T.R.; Literature Search – A.A., I.K.A.; Writing – M.M.R., Critical Review – I.K.A.

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: This study received no funding.

REFERENCES

1. J. G. Kassakian, M. F. Schlecht, and G. C. Verghese, *Principles of Power Electronics*. Graphis, 2000.
2. F. A. Silva, "Power electronics handbook, (Rashid, mh; 2011) [book news]," *IEEE Ind. Electron. Mag.*, vol. 5, no. 2, pp. 54–55, 2011. [CrossRef]
3. A. Aminian, and M. K. Kazimierczuk, *Electronic Devices: A Design Approach*. Prentice Hall, 2004.
4. S. E. Reza, A. S. M. Kaikobad, A. A. F. I. Mahabub, M. M. H. Nahid, A. Ahammad, and M. J. Rahimi, "A study on the reactive power control mechanism of current source boost inverter for Photovoltaic power system," in International Conference on Electrical Engineering and Information Communication Technology (ICEEICT). IEEE PUBLICATIONS, 2015, pp. 1–5. [CrossRef]
5. A. Radic, S. M. Ahssanuzzaman, B. Mahdavikhah, and A. Prodic, "High-power density hybrid converter topologies for low-power Dc-Dc SMPS," in International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), 18–21 May, 2014, pp. 3582–3586. [CrossRef]
6. G. R. Walker, and P. C. Sernia, "Cascaded DC-DC converter connection of photovoltaic modules," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1130–1139, 2004. [CrossRef]
7. Y. S. Kim, and J. Ko, "Development of a sensor network- based SMPS system: A smart LED monitoring application based on wireless sensor network," in *Int. J. Distrib. Sens. Netw.*, vol. 10, No. 6, no. 12, 2014. [CrossRef]
8. J. Abu-Qahouq, and I. Batarseh, "Generalized analysis of soft- switching DC-DC converters," International Symposium on Circuits And Systems (ISCAS- IEEE), 2000.
9. A. Elasser, and D. A. Torrey, "Soft switching active snubbers for DC/DC converters," in *IEEE Trans. Power Electron.*, vol. 11, no. 5, pp. 710–722, 1996. [CrossRef]
10. G. Hua, C. S. Leu, Y. Jiang, and F. C. Y. Lee, "Novel zerovoltagetransition PWM converters," *IEEE Trans. Power Electron.*, vol. 9, no.2, pp. 213–219, 1994. [CrossRef]
11. K. Gunawardane, N. Padmawansa, N. Kularatna, K. Subasinghage, and T. T. Lie, "Current context and research trends in linear DC–DC converters," *Appl. Sci. (Switzerland)*. Multidisciplinary Digital Publishing Institute (MDPI), vol. 12, No. 9, 2022. [CrossRef]
12. R. L. Steigerwald, "A comparison of half-bridge resonant converter topologies," *IEEE Trans. Power Electron.*, vol. 3, no. 2, pp. 174–182, 1988. [CrossRef]
13. J.-h. Jung, and J.-g. Kwon, "Theoretical analysis and optimal design of llc resonant converter," in European Conference on Power Electronics and Applications. *IEEE Publications*, 2007, pp. 1–10.
14. S. Abdel-Rahman, "Resonant LLC converter: Operation and design," *Infineon Technol. N. Am.*, 2012.
15. C.-A. Cheng, H.-W. Chen, E.-C. Chang, C.-H. Yen, and K.-J. Lin, "Efficiency study for a 150w llc resonant converter," in International conference on power electronics and drive systems (PEDS), *IEEE Publications*, 2009, pp. 1261–1265. [CrossRef]
16. P. S. Shenoy, M. Amaro, J. Morroni, and D. Freeman, "Comparison of a buck converter and a series capacitor buck converter for high-frequency, high-conversion-ratio voltage regulators," *IEEE Trans. Power Electron.*, vol. 31, no. 10, 2016.
17. P. S. Shenoy, M. Amaro, D. Freeman, and J. Morroni, "Comparison of a 12V, 10A, 3MHz buck converter and a series capacitor buck converter," IEEE Applied Power Electronics Conference and Exposition, 2015, pp. 461–468. [CrossRef]
18. D. W. Hart, *Power Electronics*. McGraw-Hill Education, 2011.
19. R. L. Steigerwald, R. W. De Doncker, and H. Kheraluwala, "A comparison of high-power dc-dc soft-switched converter topologies," *IEEE Trans. Ind. Appl.*, vol. 32, no. 5, pp. 1139–1145, 1996. [CrossRef]
20. S. De Simone, C. Adragna, C. Spini, and G. Gattavari, "Design-oriented steady-state analysis of llc resonant converters based on fha," *SPEEDAM* International Symposium on Power Electronics, Electrical Drives, Automation and Motion, *IEEE Publications*, 2006, pp.200–207. [CrossRef]
21. H. Huang, "'Fha-based voltage gain function with harmonic compensation for llc resonant converter' in2010" Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC). *IEEE Publications*, 2010, pp. 1770–1777.
22. M. Hao, and Q. Feng, "An improved design method for resonant tank parameters of llcresonant converter," *Proceedings of the CSEE*, vol. 28, no. 33, pp. 6–11, 2008.
23. G. Ivensky, S. Bronshtein, and A. Abramovitz, "Approximate analysis of resonant llc dc-dc converter," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3274–3284, 2011. [CrossRef]
24. "Cipparrone, Flavio AM and Beccaro, Wesley and kaiser, Walter," *Model. Anal. Inductive*Kickback" in "Low voltage circuits," in *IEEE Trans. Educ.*, vol. 63, no. 1, pp. 17–23, 2019.