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A Review on Coupled Inductor-Based High Step-Up DC-DC Converters for Renewable Energy Sources

Harwan M. Taha[1], Yasir M.Y. Ameen[2] , Emad Hussen Sadiq[3],Nizar Jabar Faqishafyee[4]
harwan.taha@dpu.edu.krd, yasir_752000@uomosul.edu.iq, emad.sadiq@dpu.edu.krd, nizar.jabar@auas.edu.krd
[1]Department of Energy Engineering, Technical College of Engineering, Duhok Polytechnic University, Duhok, Iraq
[2]Department of Electrical Engineering, College of Engineering, University of Mosul, Mosul, Iraq
[3]Department of Energy Engineering, Dept. Technical College of Engineering, Duhok Polytechnic University, Duhok, Iraq
[4]Department of Information Technology, Technical College of Informatics-Akre, Akre University for Applied Sciences

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Abstract

Renewable energy sources are increasingly being embraced due to their environmental advantages, characterized by clean energy production, including solar energy, fuel cells, and wind turbines. High step-up DC-DC converters are commonly employed in conjunction with these sources to elevate their unregulated output voltage to a high and regulated level. This is especially true for converters based on coupled inductors, which are able to achieve high voltage with a low duty cycle. This paper provides a comprehensive review on the coupled inductor-based high step-up DC-DC converters. This review involves five widely used topologies, namely stacked converters, cascaded converters, multi-winding converters, interleaved converters, and integrated converters. It is evident that the researchers proposing these converters aim to enhance the overall efficiency of the renewable energy system by achieving a high voltage gain with a low duty cycle, thereby reducing conduction losses, mitigating stress on switches, alleviating voltage spikes across the main switches, and recycling the leakage energy. However, it is noteworthy that some of the proposed circuit designs are complex and involve a high number of components resulting in increase in cost and size of packaging. Additionally, some proposed circuits could not effectively achieve the aforementioned objectives. This paper serves as a valuable resource for researchers, offering an overview of the latest developments in the high step-up converters based on coupled inductor, which may help them to identify potential research gaps.

A. Introduction

Recently the demand for the renewable energy systems increased due to their environmental benefits, including solar photovoltaic (PV) panels, fuel cells, and wind turbines. As the aforementioned sources depends on the weather conditions, their output power is not constant [1], [2]. Thus, the DC-DC converters are employed to regulate the output power, consequently enhance the overall performance of the renewable systems. In general, with the increasing demand on these sustainable sources, the power electronic device became more important as they play a crucial role in such system, particularly DC-DC converters. The integration of renewable energy systems into the electrical utility is expected to be greatly expedited by the growing adoption of high step-up DC-DC converters. Ensuring the dependability and efficiency of these converters is paramount for the successful transformation of renewable energy sources into electric power for the grid [3], [4]. A typical renewable energy system is shown in Figure 1, which includes renewable energy sources, an DC-DC converter, DC-AC inverter, grid and loads.

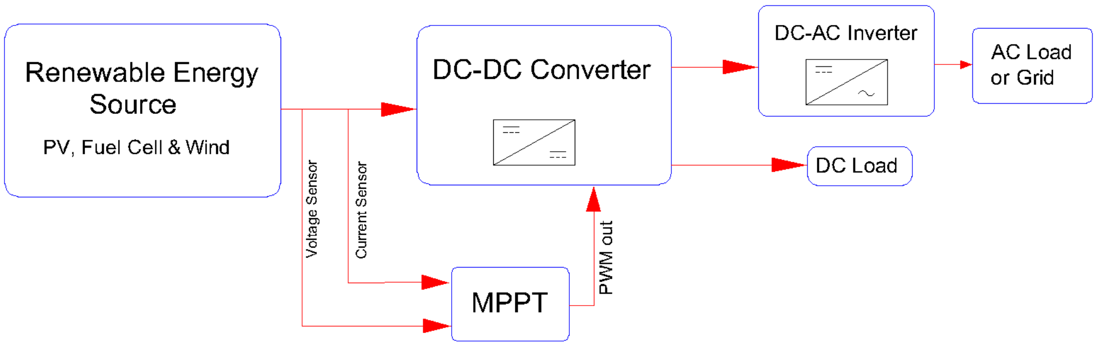

Figure 1. Typical renewable energy system

In order to connect the renewable energy sources with the grid, often the step-up (boost) DC-DC converter is utilized to regulate output voltage of these sources and higher its level so it can be easily inverted to a specific AC voltage. A conventional boost converter is not a convenient option in high step-up applications as they require an extreme duty cycle to achieve a high voltage gain, which lower their conversion efficiency. Therefore, the high step-up converters based on coupled inductor are employed instead of conventional boost converter to obtain a high voltage gain with low duty cycle which in turn improve the overall efficiency of converter.

The idea of coupled inductors is to couple two or more inductors magnetically together allowing the energy transfer between them. These converters offer several benefits, for example, achieving high voltage gain with low duty cycle, reducing switching losses, reducing voltage and current stress on the switches, and reducing current ripple [5][6]. In contrast, these converters face some challenges, such as introducing the inductor leakage energy which cause voltage spike across the main switches. To address these challenges the active and passive clamp circuits have been employed by part of researchers which help to recycle leakage energy to the output terminal as will be discussed later.

Researchers proposed numerous coupled inductor converters topologies to overcome the limitations of conventional boost converters, as discussed in section 3, including stacked converters, cascaded converters, multi winding converters, interleaved and integrated converters.

In this paragraph some related works are illustrated. After reviewing it can be noticed that the majority of the proposed converters used the interleaved topologies. For instance, references [5], [6] proposed the high step-up interleaved DC-DC converters with coupled inductor. According to their results, they achieved high efficiency, reduced voltage stress on the switch, recycled leakage energy, and alleviated voltage spike across the main switches. Additionally, references [7], [8], [9], [10], [11], [12], [13], presented interleaved converters with Voltage Multiplier Cells (VMC) using coupled inductors, resulting in high efficiency, high voltage gain, and low switching losses and low voltage stress on switches. However, a number of the proposed circuits suffered from the high input current ripple. Thus, the researchers of the aforementioned studies tried to lower the level of the input current ripple.

In other studies [14], [15], [16] the multi-winding configuration have been presented. In this approach, they utilized a multi-winding coupled inductor, specifically three windings. Their results showed that they achieved high efficiency, high voltage gain, low input current triple, low voltage spike across the main switches, low conduction losses, low voltage and current stress, and recycling of leakage energy to the output; however, this resulted in an increasing in number of components and circuit complexity.

Furthermore, the high step-up switched capacitor DC-DC converter with coupled inductor proposed in references [17], [18] both achieved high efficiency with an effective performance. These studies also suffered from the leakage energy. Nevertheless, after adding a passive clamp circuit to their proposed converters the leakage energy recycled to the output terminal.

This paper presents a review of high step-up DC-DC converters based on coupled inductor as their foundational principle. In Section 2, a theoretical background of the configuration of DC-DC converters in renewable energy systems is provided. In Section 3, a brief background about conventional high step-up DC-DC converters is given. In Section 4, a background theory is presented about coupled inductor-based high step-up DC-DC converter. In section 5 classification of these converters are discussed. While, in Section 6, a table of performance comparison of high step-up converters with coupled inductors is presented. Finally, the main findings are summarized in the conclusion section.

B. Configuration of DC–DC Converters in Renewable Energy Systems

Renewable energy sources, like solar energy, fuel cells and wind energy, face several constraints when it comes to harnessing energy. The efficiency of PV panels in converting energy is significantly impacted by the radiation received on their surface, while wind energy generation is influenced by the conditions of the wind that affect the turbine blades. Consequently, climate change has a significant impact on the production of power (current and voltage) from these sustainable sources. Therefore, a power converter with high efficiency is required to handle variations in voltage level and maintain fixed voltage levels to meet the load demand [19]. As it has mentioned earlier that the renewable energy sources depend on the weather conditions, so their output power is not constant and changes with the weather. That is why the power electronics, especially DC-DC converters, play a highly effective role in the configuration of renewable energy systems, due to their ability to optimize the output power of renewable sources, resulting in an increasing in the efficiency of such systems. These converters manage power flow withing the renewable energy systems.

The configuration of DC-DC converters in renewable energy systems is shown in Fig. 1. The DC-DC converters work as a charger control if the battery charging is needed or to regulate the level of output voltage of the renewable sources with the help of Maximum Power Point Tracking (MPPT). The MPPT technique generate the Pulth Width Modulation (PWM) signal of the main switch of the dc-dc converts to optimize the performance of the system. The principle of this control technique is to sense the DC output current and voltage from the renewable sources and track the maximum point to extract maximum power from them.

For DC loads and battery storage systems, the output voltage of DC-DC converters is directly used. Meanwhile, in most cases, renewable energy sources are utilized to feed the AC loads or to integrate with the public electrical utility through the DC-AC inverter. Thus, the output voltage of these sources is raised and adjusted to a higher level to meet the required level by using boost or high step-up dc-dc converters. For this reason, this research reviewed these converters to provide an overview of the latest developments in this field. The output voltages generated by renewable energy sources, such as photovoltaic panels and fuel cells usually fall within the range of 20 to 50 V. It is clear that these output voltages are considerably lower than what is needed for a grid-connected inverter. Therefore, incorporating a high step-up DC/DC converter is essential for the proper functioning of a grid-connected inverter system [20], [21].

C. High Step-up DC-DC Converter

Conventional DC-DC boost converters are non-isolated step-up converters, and the voltage gain tends to approach infinity as the duty cycle approaches one [16]. However, a large duty cycle can lead to high voltage stresses on switches, pose reverse recovery challenges for diodes, and result in low efficiency. Additionally, due to parasitic parameters, the voltage gain decreases with an increasing duty cycle, making it unsuitable for meeting the demands of high-step-up DC-DC conversion. To address these issues and fulfill the requirements of high step-up applications, numerous researchers have dedicated their efforts to develop converters with high voltage gain, low cost, and high efficiency. These advancements fall into various categories, such as high step-up converters with coupled inductors, converters incorporating switched capacitors, configurations combining inductors and switched capacitors for high step-up, and designs that integrate coupled inductors with switched capacitors, among others. The overarching goal remains achieving increased step-up ratio while ensuring affordability and efficiency in these converters to optimize their performance in renewable energy applications.

D. High Step-up DC-DC Converter with Coupled Inductor

The idea of dc-dc converters based on coupled inductor is to couple two or more inductor magnetically together with permitting the energy transfer between these coupled inductors. Thus, they work as a transformer to achieve high voltage gain in high step-up DC-DC converters resulting in an improvement in performance of the converters[22]. The level of voltage gain can be controlled by choosing proper number of turns-ratio of the coupled inductors. The basic equivalent circuit of a coupled inductor-based high step-up DC-DC converter is shown in Figure 2. According to the characteristics of the circuit, the voltage gain can be calculated using the expression in (1), this equation is when the converter operating in Continuous Conduction Mode (CCM).

$$M = \frac{V_O}{V_{in}} = \frac{1+ND}{1-D} \tag{1}$$

Here, D represents the duty cycle, and N denotes the turn-ratio. One advantage of this configuration is its ability to achieve higher voltage gains with a lower duty cycle compared to conventional converters, reducing stress on components. Moreover, coupled inductors promote continuous energy transfer, enhancing overall converter efficiency. However, limitations include increased complexity in control circuitry and potential for electromagnetic interference. Despite these challenges, the high step-up DC-DC converter with coupled inductor stands as a promising technology, offering improved voltage gain and efficiency, particularly in applications requiring significant voltage elevation, such as renewable energy systems.

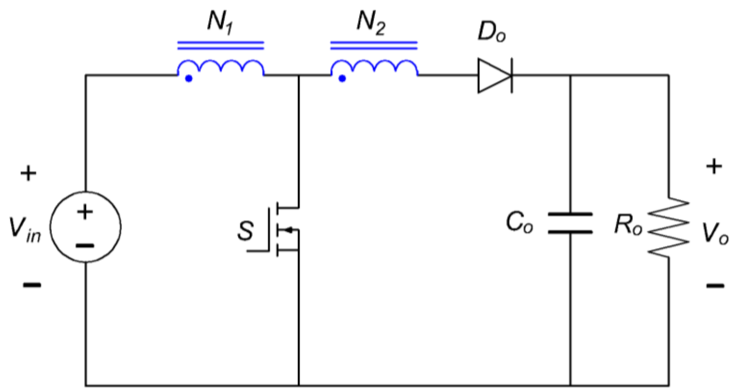

Figure 2. Basic High step-up DC-DC converter with coupled inductor

E. Classification of High Step-up DC-DC Converters Based on Coupled Inductor

As has been mentioned earlier, several coupled inductor converters have been proposed by the researchers. They shared the same objectives to enhance the efficiency of these converters. Yet, the circuit arrangement, component numbers and performance are different. Figure 3 presents the classification of the commonly used couple inductor-based converters. This chapter will give a brief theoretical background of the mentioned converters in Figure 3.

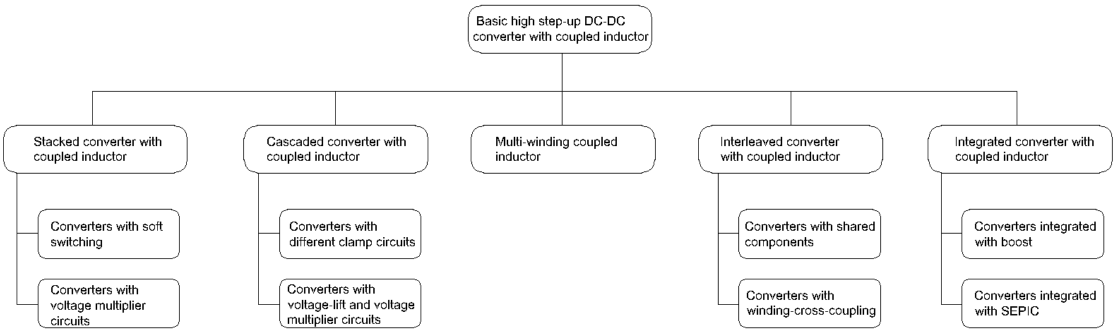

Figure 3. Classification of high step-up dc-dc converters based on coupled inductor

1) Stacked converter with coupled inductor

This converter can be conceptualized as a combination of a boost converter and a flyback converter. The passive clamp circuit is formed by the diode Do1 and capacitor Co1. The half-wave voltage multiplier consists of the secondary winding N2, along with Do2 and Co2. The primary benefit of this converter stems from its relatively uncomplicated and compact design, allowing for the direct recycling of leakage energy into the output. Topological enhancements within this category primarily concentrate on implementing soft-switching techniques to minimize switching losses and incorporating voltage multipliers to enhance the voltage gain even further [23]. The primary drawback of this converter is the presence of parasitic oscillations at the secondary side of the rectifier diode.

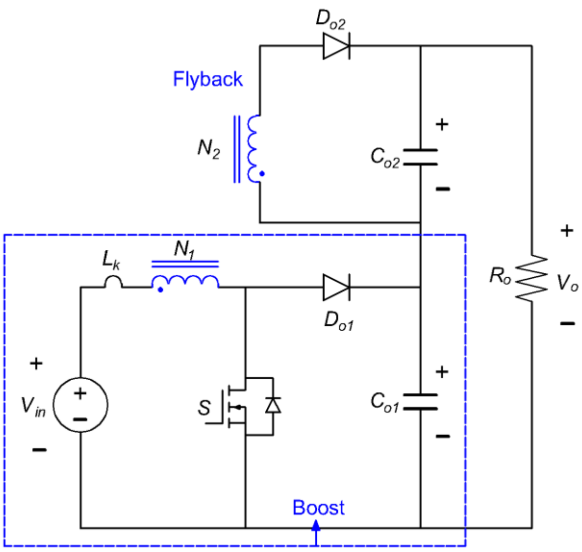

Figure 4. Basic Stacked converter with coupled inductor [24]

2) Cascaded converter with coupled inductor

Cascaded DC-DC converters with coupled inductor topologies offer several advantages in terms of efficiency and compact design. It consists of multiple power stages connected in series, each containing a DC-DC converter with a dedicated coupled inductor. The benefits of cascaded converters with coupled inductors include enhanced efficiency, modularity for scalability, and reduced voltage stress, resulting in improved reliability. Moreover, the flexible design ensures that the output voltage remains stable and low-ripple for specific applications. Despite this, utilizing cascaded DC-DC converters with coupled inductors has some disadvantages. Among these disadvantages are intricate control requirements, increased component counts that increase costs and may raise reliability concerns, as well as restrictions in applications with low power or space requirements. In order to protect against cascading failures, robust fault detection mechanisms must be implemented. A careful consideration of specific application requirements is essential to determining the most appropriate deployment.

3) Multi-winding coupled inductor

In specific situations where higher voltage gains are required, it becomes necessary to have a larger turn ratio in the coupled inductor. This is done to avoid excessively high duty cycles, which can lead to increased leakage inductance. As a result, the voltage stress on rectifier diode Dc1 may rise significantly, potentially exceeding the output voltage.

In this paper, the circuit from two sources is illustrated; one is presented in [25], as shown in Figure 5. In this proposed circuit, the N2 and N3 windings are not connected in series with the primary winding, unlike in cascaded converters. This design choice eliminates the need for additional clamp circuits, enabling the direct release of leakage energy into the output load. Nonetheless, there is a reduction in the voltage conversion ratio. To minimize the reverse recovery current of the output diode, the delay time of the primary and secondary overlap currents can be adjusted. The second circuit, introduced in [15] for renewable applications, specifically fuel cells, involves the adaptation of the voltage multiplier designed for the tertiary winding into a voltage doubler, as shown in Figure 6.

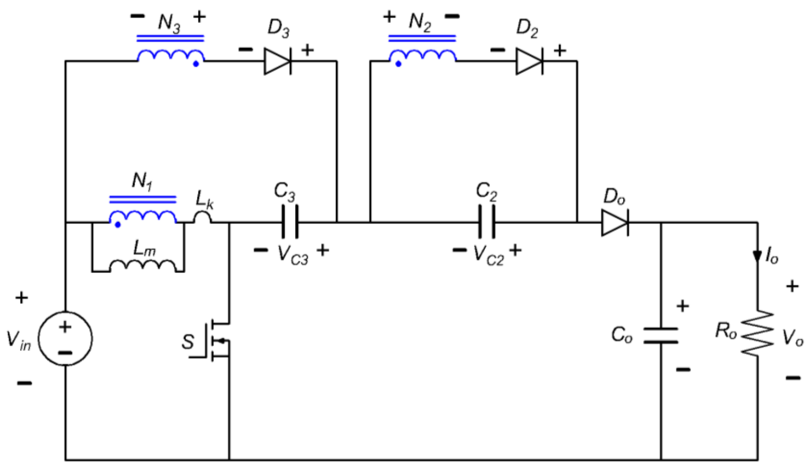

Figure 5. Multi-winding converter with coupled inductor proposed in [25]

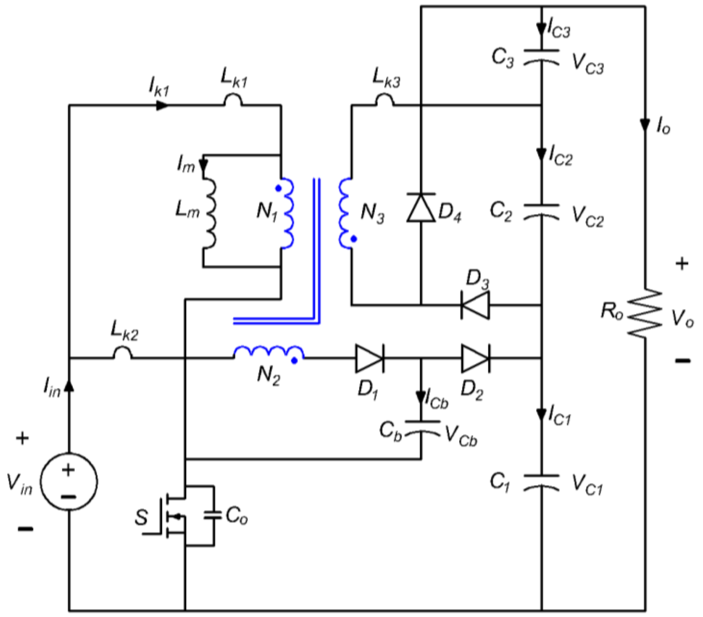

Figure 6. Multi-winding converter with coupled inductor proposed in [15]

4) Interleaved converter with coupled inductor

Interleaving coupled inductor step-up converters allows for achieving high-step-up power conversion without the need for extreme duty ratio operation, effectively managing high input currents. These converters are recognized for their capability to minimize input current ripple. When dealing with higher power ratings, it is often more advantageous to interconnect converters in parallel. This parallel configuration serves to evenly distribute switch current and thermal stresses, thereby enhancing overall efficiency and reliability. It also effectively doubles the switching frequency, enabling the use of smaller inductors and capacitors [25].

The interleaved converter based on coupled inductors, while effective, often involves a substantial number of components. In an effort to mitigate this, several circuits proposed by researchers aim to reduce the component count. One such approach, presented in [26], involves the sharing of common components. It introduces a circuit that shares active clamp circuits after interleaving basic coupled inductor converters, as depicted in Figure 7. This active clamp circuit recycled the leakage energy from coupled inductor back to the output through the boost converter utilizing a common clamp capacitor. The result showed that, with low voltage rated switches, the recycled leakage energy increased the efficiency, due to the decrease in losses.

An additional illustration of component sharing is demonstrated in the work presented in [27], which introduces a groundbreaking interleaved converter based on coupled inductors with a jointly utilized voltage multiplier, tailored for photovoltaic applications. This converter interleaves conventional boost converters, attaining a noteworthy high voltage gain without requiring an extensive duty cycle. A noteworthy benefit of this design is the integration of an active clamp, efficiently alleviating voltage spikes across power switches and enhancing the overall efficiency of the converter.

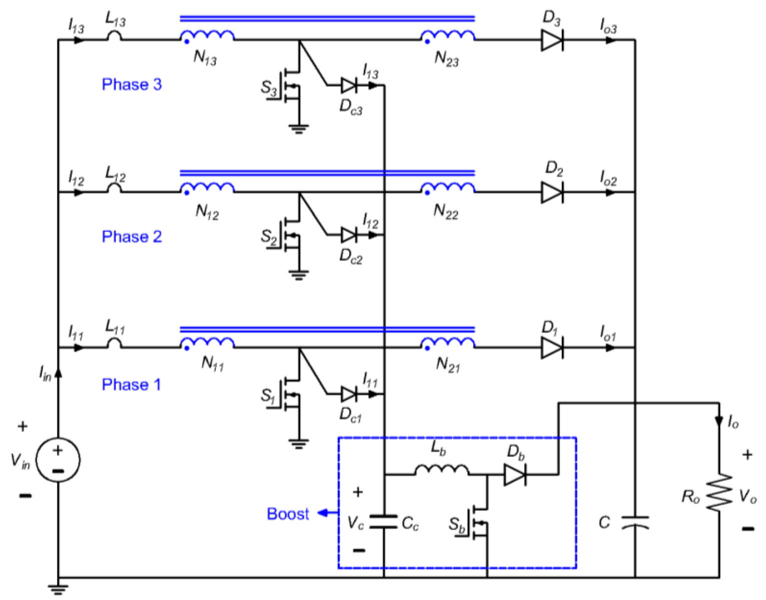

Figure 7. Interleaved converter based on coupled inductor with shared active clamp circuits

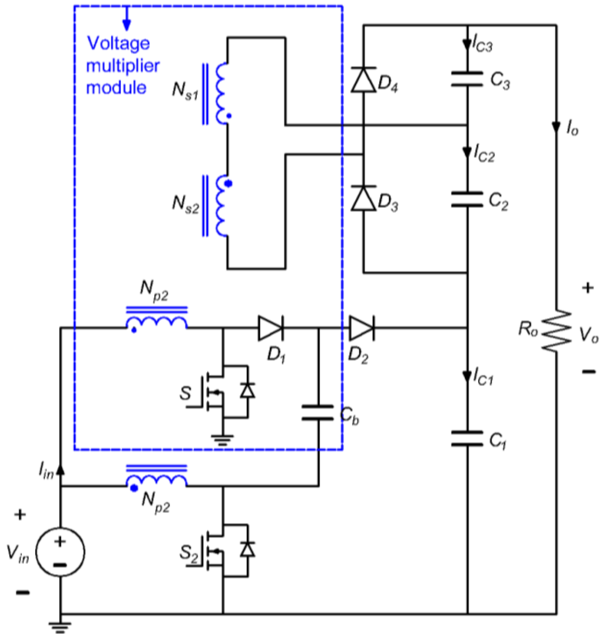

Figure 8. Interleaved converter based on coupled inductor with shared voltage multiplier

In the realm of interleaved coupled inductor converters, another distinctive topology is exemplified by the interleaved converter with winding-cross-coupled inductors. Addressing this configuration, reference [28] introduces an interleaved high step-up converter designed specifically for photovoltaic applications (see Figure 9). This converter achieves both a commendable high voltage gain and a reduction in the voltage stress experienced by power switches. Notably, the design incorporates measures to clamp voltage spikes on the MOSFETs, ensuring enhanced reliability. Additionally, the system efficiently recycles leakage energy through the utilization of voltage multiplier cells.

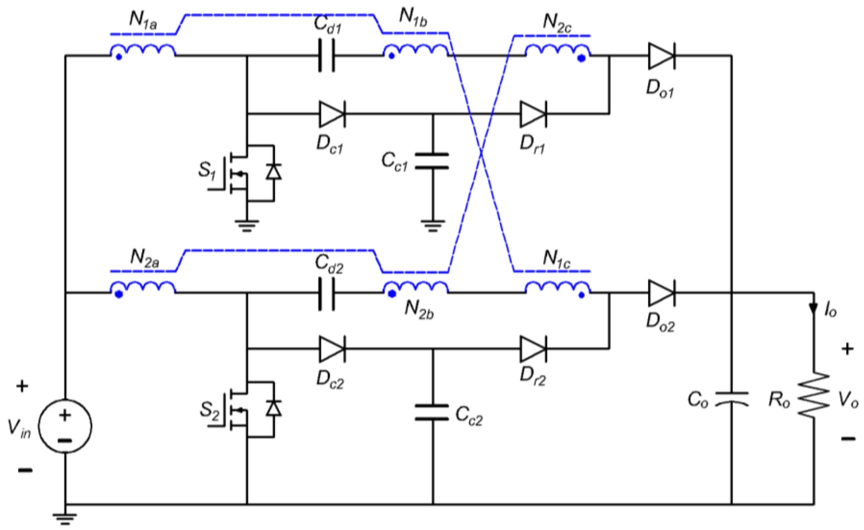

Figure 9. Interleaved converter with winding-cross-coupling inductors

5) Integrated converter with coupled inductor

Integrating coupled inductor-based converters with other DC-DC converters offers several advantages, particularly in reducing input current ripple. This review paper discusses the integration with boost converters and integration with SEPIC as follows:

First, integrating with boost converter, the configuration depicted in Fig. 10 by reference [29], noteworthy characteristics of this converter include minimal input current ripples and a quadratic voltage gain. Similarly, stacked coupled inductors, can be integrated with the boost converter as well. Figure 11 illustrates one such typical topology, as in [30]. The coupled-inductor boost converters shown in Figure 10 and Figure 11 exhibit minimal input current fluctuations and achieve a quadratic voltage conversion ratio. However, in the main power branch, there are essentially two diodes, contributing to elevated conduction losses. Furthermore, the converters essentially function as two units in series, leading to a less-than-optimal overall system efficiency.

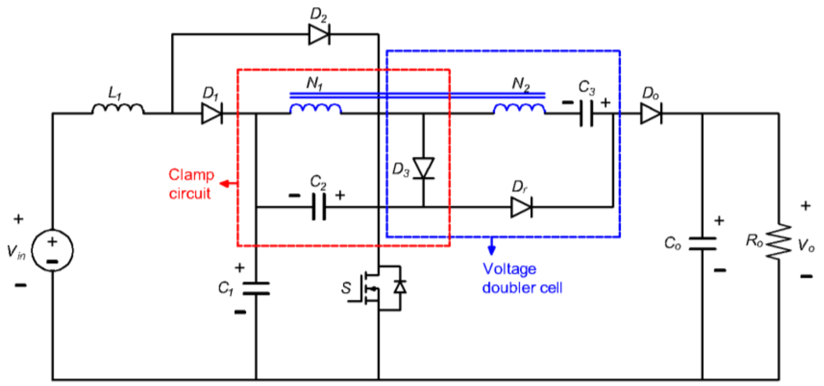

Figure 10. Coupled inductor-based converter integrated with boost

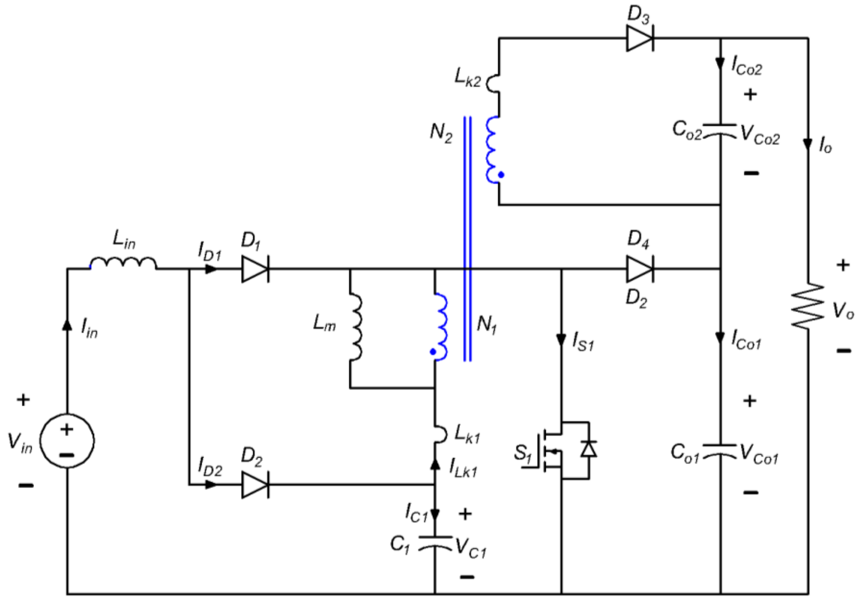

Figure 11. Coupled inductor-based converter integrated with boost

Secondly, the integration of coupled inductor-based converter with SEPIC as shown in Figure 12 which is proposed by reference [31], an investigation is conducted on a single-switch high step-up converter with a built-in transformer. This converter can be conceptualized as a combination of the SEPIC converter and the converter based on coupled inductor. A similar configuration is presented in [32], where an active clamp circuit is implemented to achieve zero-voltage switching (ZVS) for the switch. Additionally, the converter in Figure 13 employs the stacked output concept, as in [33]. This design yields advantages such as a high step-up ratio and low input current ripple. Various topological variations, including the use of a multi-winding structure, are also feasible.

The primary benefit of the topologies depicted in Figure 12 and Figure 13 is their ability to minimize input current ripple. Compared to the boost converter integrated circuits shown in Fig. 10 and Fig. 11, these two proposed circuits were more efficient as the used only one diode in the main power branch, contributing to a reduction in conduction losses. However, their voltage conversion ratio is not quadratic and is lower than that of the integrated converter with boost. Furthermore, these both integrated topologies are similar in terms of the magnetizing energy of transformer N1:N2. This implies multi-stage energy transfer and additional conduction loss.

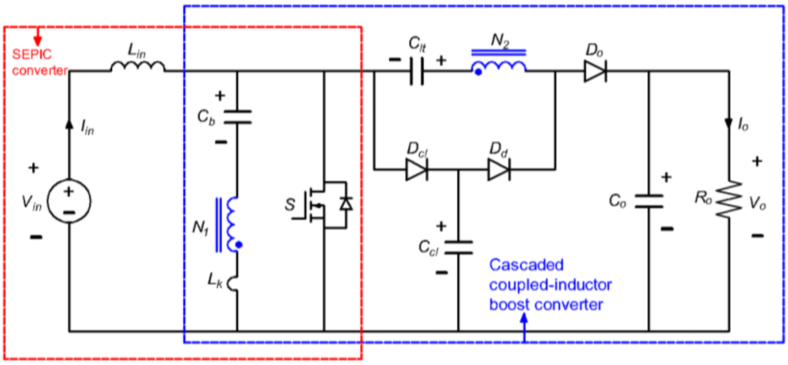

Figure 12. Coupled inductor-based converter integrated with SEPIC [31]

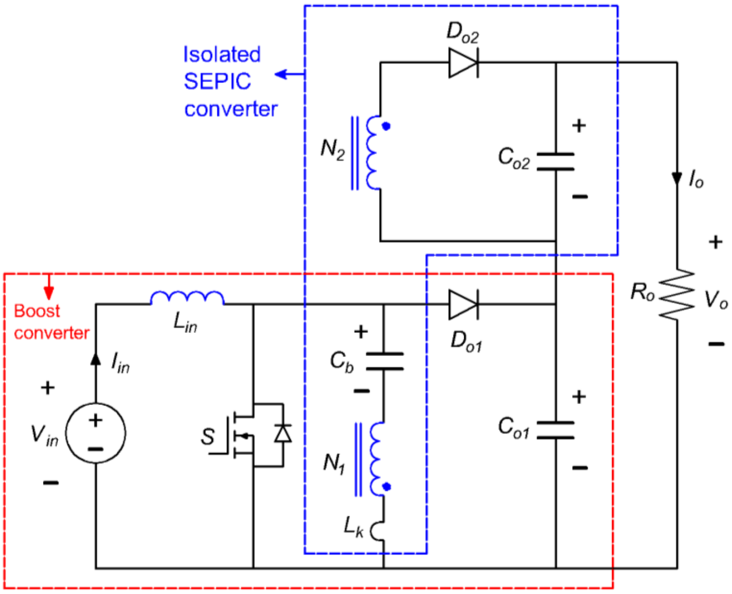

Figure 13. Coupled inductor-based converter integrated with SEPIC [33]

F. Perfurmance Comparison of High step-up Converters with Coupled Inductors

This section presents the performance comparison between the reviewed papers. The comparison is based on the equation of the voltage gain, number of parameters used in their circuits, and the obtained efficiency, as given in Table 1. It is clear from the results that the reviewed papers have achieved more than 90% efficiency. While the number of components and voltage gain level is different. Some proposed converters employed more than 15 components as is shown in references [10], [13], [34], [35], [36], [37], [38]. They all attained high step-up voltage but some of them faced some specific challenges including stress on the main switch, effect of leakage energy, voltage spike across main switches, switching losses and input current ripple. For instance, proposed converters in references [17], [18], [39] suffered from the high input current ripple. In addition, many proposed circuits suffered from the stored energy of leakage inductance which cause the voltage spike on the switches. However, they employed active and passive clam circuits to address this problem as it shown in references [11], [18], [40].

Ref.	Voltage gain (M) (Vout/Vin)	Maximum Efficiency (%)	Number of components Coupled inductor/C/S/D/L	Total number of components
[41]	$\frac{(8N+2)+2D(1-4N)}{1-D}$	95.96	3/5/2/5	15
[8]	$\frac{4}{1-D}$	94.16	2/5/2/5	14
[9]	$\frac{3N+1}{1-D}$	97.3	2/4/2/5	13
[10]	$\frac{2(N+1)}{1-D}$	96.7	2/7/2/7	18
[11]	$\frac{2(n+1)}{1-D}$	97.1	2/5/2/6	15
[12]	$\frac{2(n+1)}{1-D}$	97.2	2/5/2/6	15
[13]	$\frac{2(N+1)}{1-D}$	96.8	3/5/4/4/2	18
[14]	$\frac{N+2+D(N-1)}{1-D}$	96.5	2/5/2/6	15
[16]	$\frac{3n}{1-D}$	95.38	2/4/1/3	10
[17]	$\frac{1+(1+D)n}{1-D}$	96.4	1/4/1/4	13
[18]	$\frac{2+n+nD}{1-D}$	96	1/4/1/4	10
[42]	$\frac{2+n+D}{1-D}$	94	1/4/1/4/1	11
[39]	$\frac{2(1+nD)}{1-D}$	92.8	1/2/2/4	9
[43]	$\frac{n+1}{1-D}$	96	1/3/1/3	8
[44]	$\frac{2(N+1)}{1-D}$	94.37	2/4/2/4	12
[45]	$\frac{1+ND}{1-D}$	96.43	1/3/1/2/1	8
[46]	$\frac{1+n}{1-2D}$	96.37	1/1/5/1/4	12
[47]	$\frac{2+D}{1-D}+\frac{N_s}{N_p}$	95	1/3/2/1/1	8
[48]	$n_2+\frac{1+(n_2+n_3)D}{1-D}$	96.7	1/5/1/5	12
[49]	$\frac{2(n+1)}{1-D}$	96.6	2/3/4/2	11
[50]	$\frac{2N+4}{1-D}$	94.9	2/4/2/4	12
[40]	$\frac{nD+1}{1-D}$	92	2/4/2/3	11
[34]	$\frac{2(N+1)+n}{1-D}$	97.65	3/5/2/6/2	18
[35]	$\frac{2(n+N+1)}{1-D}$	97.77	3/7/2/8	20

Table 1. Performance Comparison of Coupled Inductor Converters

[36]	$\frac{3N+1}{1-D}$	97	2/7/2/8	19
[37]	$\frac{2(N+1)}{1-D}$	96.5	3/5/2/6/2	18
[38]	$\frac{3+D}{1-D}$	96.9	6/8/6/14	34

G. Conclusion

Renewable energy sources, such as solar energy, fuel cells, and wind turbines, have gained widespread use due to their environmental benefits. High step-up DC-DC converters are commonly employed with these sources to boost and regulate their output voltage. This paper provides an overview of high step-up DC-DC converters based on coupled inductors, highlighting their advantages in delivering high voltage gain with low duty cycles. The paper classifies five topologies of high step-up converters with coupled inductors, including stacked converters, cascaded converters, integrated converters, interleaved converters, and multi-winding converters. The primary objectives of these proposed converters are to achieve high voltage with low duty cycles, reduce switching losses, alleviate voltage and current stress on the main switches, suppress voltage spikes, and recycle leakage energy. Despite these advantages, some challenges are identified in certain proposed converters, such as an increased number of components leading to higher costs and circuit complexity. The paper contributes to the understanding of these high step-up converters, emphasizing their potential benefits and acknowledging the trade-offs associated with specific designs.

H. References

[1] H. M. Taha and S. Hameed, "Optimization of Tilt Angle of a PV System to Get Maximum Generated Power: a Case Study," *Kurdistan Journal of Applied Research*, pp. 71–81, Dec. 2020, doi: 10.24017/science.2020.2.7.

[2] I. R. Alnaab, H. M. Taha, Z. A. Abdulwahab, and M. S. Al-Radhi, "Performance comparison between fixed tilt angle and solar tracking systems at Basra governorate: A case study," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 26, no. 1, pp. 184–193, Apr. 2022, doi: 10.11591/ijeecs.v26.i1.pp184-193.

[3] E. H. Sadiq, R. K. Antar, and S. T. Ahmed, "Power losses evaluation in low voltage distribution network: a case study of 250 kVA, 11/0.416 kV substation," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 25, no. 1, pp. 35–41, Jan. 2022, doi: 10.11591/ijeecs.v25.i1.pp35-41.

[4] O. A. Al-Ani, A. M. A Sabaawi, M. Farhan Mosleh, O. Ahmed Al-ani, E. H. Sadiq, and M. F. Mosleh, "EFFECT OF STRUCTURAL DEFECTS AND IMPURITIES ON ELECTRICAL CHARACTERISTICS OF PHOTOVOLTAIC CELLS: MULTISCALE MODELLING," 2021. [Online]. Available: https://www.researchgate.net/publication/350135105

[5] S. Dwari and L. Parsa, "An efficient high-step-up interleaved DC-DC converter with a common active clamp," *IEEE Trans Power Electron*, vol. 26, no. 1, pp. 66–78, 2011, doi: 10.1109/TPEL.2010.2051816.

[6] Y. Zheng, W. Xie, and K. M. Smedley, "Interleaved high step-up converter with coupled inductors," *IEEE Trans Power Electron*, vol. 34, no. 7, pp. 6478–6488, Jul. 2019, doi: 10.1109/TPEL.2018.2874189.

[7] S. M. Hashemzadeh, S. H. Hosseini, E. Babaei, and M. Sabahi, "Design and modelling of a new three winding coupled inductor based high step-up DC–DC converter for renewable energy applications," *IET Power Electronics*, vol. 15, no. 13, pp. 1322–1339, Oct. 2022, doi: 10.1049/pel2.12307.
[8] B. P. Baddipadiga and M. Ferdowsi, "A High-Voltage-Gain DC-DC Converter Based on Modified Dickson Charge Pump Voltage Multiplier," *IEEE Trans Power Electron*, vol. 32, no. 10, pp. 7707–7715, Oct. 2017, doi: 10.1109/TPEL.2016.2594016.
[9] T. Liu, M. Lin, and J. Ai, "High Step-Up Interleaved dc-dc Converter with Asymmetric Voltage Multiplier Cell and Coupled Inductor," *IEEE J Emerg Sel Top Power Electron*, vol. 8, no. 4, pp. 4209–4222, Dec. 2020, doi: 10.1109/JESTPE.2019.2931634.
[10] M. L. Alghaythi, R. M. O'Connell, N. E. Islam, M. M. S. Khan, and J. M. Guerrero, "A High Step-Up Interleaved DC-DC Converter with Voltage Multiplier and Coupled Inductors for Renewable Energy Systems," *IEEE Access*, vol. 8, pp. 123165–123174, 2020, doi: 10.1109/ACCESS.2020.3007137.
[11] "High Step-Up, High Efficiency Interleaved Converter with Voltage Multiplier Module for Renewable Energy System," 2013.
[12] L. He and Y. Liao, "An Advanced Current-Autobalance High Step-Up Converter with a Multicoupled Inductor and Voltage Multiplier for a Renewable Power Generation System," *IEEE Trans Power Electron*, vol. 31, no. 10, pp. 6992–7005, Oct. 2016, doi: 10.1109/TPEL.2015.2509159.
[13] W. Li, X. Xiang, C. Li, W. Li, and X. He, "Interleaved high step-up ZVT converter with built-in transformer voltage doubler cell for distributed PV generation system," *IEEE Trans Power Electron*, vol. 28, no. 1, pp. 300–313, 2013, doi: 10.1109/TPEL.2012.2199771.
[14] K. C. Tseng, J. Z. Chen, J. T. Lin, C. C. Huang, and T. H. Yen, "High step-up interleaved forward-flyback boost converter with three-winding coupled inductors," *IEEE Trans Power Electron*, vol. 30, no. 9, pp. 4696–4703, Sep. 2015, doi: 10.1109/TPEL.2014.2364292.
[15] K. C. Tseng, J. T. Lin, and C. C. Huang, "High step-up converter with three-winding coupled inductor for fuel cell energy source applications," *IEEE Trans Power Electron*, vol. 30, no. 2, pp. 574–581, Feb. 2015, doi: 10.1109/TPEL.2014.2309793.
[16] S. M. Hashemzadeh, S. H. Hosseini, E. Babaei, and M. Sabahi, "Design and modelling of a new three winding coupled inductor based high step-up DC–DC converter for renewable energy applications," *IET Power Electronics*, vol. 15, no. 13, pp. 1322–1339, Oct. 2022, doi: 10.1049/pel2.12307.
[17] T. J. Liang, S. M. Chen, L. S. Yang, J. F. Chen, and A. Ioinovici, "Ultra-large gain step-up switched-capacitor DC-DC converter with coupled inductor for alternative sources of energy," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 59, no. 4, pp. 864–874, 2012, doi: 10.1109/TCSI.2011.2169886.
[18] A. Ajami, H. Ardi, and A. Farakhor, "A Novel High Step-up DC/DC Converter Based on Integrating Coupled Inductor and Switched-Capacitor Techniques for Renewable Energy Applications," *IEEE Trans Power Electron*, vol. 30, no. 8, pp. 4255–4263, 2015, doi: 10.1109/TPEL.2014.2360495.
[19] T. Sutikno, H. S. Purnama, N. S. Widodo, S. Padmanaban, and M. R. Sahid, "A review on non-isolated low-power DC-DC converter topologies with high output gain for

solar photovoltaic system applications," *Clean Energy*, vol. 6, no. 4, pp. 557–572, Aug. 2022, doi: 10.1093/ce/zkac037.
[20] W. Li and X. He, "Review of nonisolated high-step-up DC/DC converters in photovoltaic grid-connected applications," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4. pp. 1239–1250, Apr. 2011. doi: 10.1109/TIE.2010.2049715.
[21] F. L. Tofoli, D. de C. Pereira, W. J. de Paula, and D. de S. Oliveira Júnior, "Survey on non-isolated high-voltage step-up dc-dc topologies based on the boost converter," *IET Power Electronics*, vol. 8, no. 10, pp. 2044–2057, Oct. 2015, doi: 10.1049/iet-pel.2014.0605.
[22] C. Y. Inaba, Y. Konishi, and M. Nakaoka, "High frequency PWM controlled step-up chopper type DC-DC power converters with reduced peak switch voltage stress," *IEE Proceedings: Electric Power Applications*, vol. 151, no. 1, pp. 47–52, Jan. 2004, doi: 10.1049/ip-epa:20031059.
[23] H. Liu, H. Hu, H. Wu, Y. Xing, and I. Batarseh, "Overview of High-Step-Up Coupled-Inductor Boost Converters," *IEEE J Emerg Sel Top Power Electron*, vol. 4, no. 2, pp. 689–704, Jun. 2016, doi: 10.1109/JESTPE.2016.2532930.
[24] Q. Zhao and F. C. Lee, "High Performance Coupled-Inductor DC-DC Converters," 2003.
[25] R.-J. Wail, C.-Y. Linz, and R.-Y. Duan3, "High-efficiency DC-DC Converter with High Voltage Gain and Reduced Switch Stress."
[26] S. Dwari and L. Parsa, "An efficient high-step-up interleaved DC-DC converter with a common active clamp," *IEEE Trans Power Electron*, vol. 26, no. 1, pp. 66–78, 2011, doi: 10.1109/TPEL.2010.2051816.
[27] K. C. Tseng, C. C. Huang, and W. Y. Shih, "A high step-up converter with a voltage multiplier module for a photovoltaic system," *IEEE Trans Power Electron*, vol. 28, no. 6, pp. 3047–3057, 2013, doi: 10.1109/TPEL.2012.2217157.
[28] W. Li, Y. Zhao, J. Wu, and X. He, "Interleaved High Step-Up Converter with Winding-Cross-Coupled Inductors and Voltage Multiplier Cells," *IEEE Trans Power Electron*, vol. 27, no. 1, pp. 133–143, 2012, doi: 10.1109/TPEL.2009.2028688.
[29] X. Hu and C. Gong, "A high voltage gain DC-DC converter integrating coupled-inductor and diode-capacitor techniques," *IEEE Trans Power Electron*, vol. 29, no. 2, pp. 789–800, 2014, doi: 10.1109/TPEL.2013.2257870.
[30] S. M. Chen, T. J. Liang, L. S. Yang, and J. F. Chen, "A cascaded high step-up DCDC converter with single switch for microsource applications," *IEEE Trans Power Electron*, vol. 26, no. 4, pp. 1146–1153, 2011, doi: 10.1109/TPEL.2010.2090362.
[31] Y. Deng, Q. Rong, W. Li, Y. Zhao, J. Shi, and X. He, "Single-switch high step-up converters with built-in transformer voltage multiplier cell," *IEEE Trans Power Electron*, vol. 27, no. 8, pp. 3557–3567, 2012, doi: 10.1109/TPEL.2012.2183620.
[32] W. Li, W. Li, Y. Deng, and X. He, "Single-stage single-phase high-step-up ZVT boost converter for fuel-cell microgrid system," *IEEE Trans Power Electron*, vol. 25, no. 12, pp. 3057–3065, 2010, doi: 10.1109/TPEL.2010.2079955.
[33] K. B. Park, G. W. Moon, and M. J. Youn, "Nonisolated high step-up boost converter integrated with sepic converter," *IEEE Trans Power Electron*, vol. 25, no. 9, pp. 2266–2275, 2010, doi: 10.1109/TPEL.2010.2046650.
[34] T. Nouri, N. Vosoughi, S. H. Hosseini, E. Babaei, and M. Sabahi, "An interleaved high step-up converter with coupled inductor and built-in transformer voltage

multiplier cell techniques," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 3, pp. 1894–1905, Mar. 2019, doi: 10.1109/TIE.2018.2835420.

[35] T. Nouri, N. Nouri, and N. Vosoughi, "A Novel High Step-Up High Efficiency Interleaved DC-DC Converter with Coupled Inductor and Built-In Transformer for Renewable Energy Systems," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 8, pp. 6505–6516, Aug. 2020, doi: 10.1109/TIE.2019.2938483.

[36] T. Nouri, S. H. Hosseini, E. Babaei, and J. Ebrahimi, "Interleaved high step-up DC-DC converter based on three-winding high-frequency coupled inductor and voltage multiplier cell," *IET Power Electronics*, vol. 8, no. 2, pp. 175–189, Feb. 2015, doi: 10.1049/iet-pel.2014.0165.

[37] W. Li, W. Li, X. Xiang, Y. Hu, and X. He, "High step-up interleaved converter with built-in transformer voltage multiplier cells for sustainable energy applications," *IEEE Trans Power Electron*, vol. 29, no. 6, pp. 2829–2836, Jun. 2014, doi: 10.1109/TPEL.2013.2273977.

[38] M. Maalandish, S. H. Hosseini, S. Ghasemzadeh, E. Babaei, R. Shalchi Alishah, and T. Jalilzadeh, "Six-phase interleaved boost dc/dc converter with high-voltage gain and reduced voltage stress," *IET Power Electronics*, vol. 10, no. 14, pp. 1904–1914, Nov. 2017, doi: 10.1049/iet-pel.2016.1029.

[39] L. S. Yang, T. J. Liang, H. C. Lee, and J. F. Chen, "Novel high step-up dc-dc converter with coupled-inductor and voltage-doubler circuits," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 4196–4206, Sep. 2011, doi: 10.1109/TIE.2010.2098360.

[40] T.-F. Wu, Y.-S. Lai, J.-C. Hung, and Y.-M. Chen, "Boost Converter with Coupled Inductors and Buck-Boost Type of Active Clamp."

[41] S. M. Hashemzadeh, E. Babaei, S. H. Hosseini, and M. Sabahi, "Design and Analysis of a New Coupled Inductor-Based Interleaved High Step-Up DC-DC Converter for Renewable Energy Applications," *International Transactions on Electrical Energy Systems*, vol. 2022, 2022, doi: 10.1155/2022/7618242.

[42] R. Moradpour, H. Ardi, and A. Tavakoli, "Design and implementation of a new SEPIC-based high step-up DC/DC converter for renewable energy applications," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1290–1297, 2017, doi: 10.1109/TIE.2017.2733421.

[43] M. Das and V. Agarwal, "Design and Analysis of a High-Efficiency DC-DC Converter with Soft Switching Capability for Renewable Energy Applications Requiring High Voltage Gain," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 5, pp. 2936–2944, May 2016, doi: 10.1109/TIE.2016.2515565.

[44] X. Hu and C. Gong, "A high gain input-parallel output-series DC/DC converter with dual coupled inductors," *IEEE Trans Power Electron*, vol. 30, no. 3, pp. 1306–1317, 2015, doi: 10.1109/TPEL.2014.2315613.

[45] W. Hassan, D. D. C. Lu, and W. Xiao, "Analysis and experimental verification of a single-switch high-voltage gain ZCS DC–DC converter," *IET Power Electronics*, vol. 12, no. 8, pp. 2146–2153, Jul. 2019, doi: 10.1049/iet-pel.2019.0076.

[46] A. Samadian, S. H. Hosseini, M. Sabahi, and M. Maalandish, "A New Coupled Inductor Nonisolated High Step-Up Quasi Z-Source DC-DC Converter," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 7, pp. 5389–5397, Jul. 2020, doi: 10.1109/TIE.2019.2934067.

[47] K. I. Hwu and W. Z. Jiang, "Voltage Gain Enhancement for Step-Up Converter Constructed by KY and Buck-Boost Converters," 2013.
[48] S. K. Changchien, T. J. Liang, J. F. Chen, and L. S. Yang, "Novel high step-up DCDC converter for fuel cell energy conversion system," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 6, pp. 2007–2017, Jun. 2010, doi: 10.1109/TIE.2009.2026364.
[49] M. Forouzesh, Y. Shen, K. Yari, Y. P. Siwakoti, and F. Blaabjerg, "High-Efficiency High Step-Up DC-DC Converter with Dual Coupled Inductors for Grid-Connected Photovoltaic Systems," IEEE Trans Power Electron, vol. 33, no. 7, pp. 5967–5982, Jul. 2018, doi: 10.1109/TPEL.2017.2746750.
[50] Y. Zheng and K. M. Smedley, "Interleaved High Step-Up Converter Integrating Coupled Inductor and Switched Capacitor for Distributed Generation Systems," IEEE Trans Power Electron, vol. 34, no. 8, pp. 7617–7628, Aug. 2019, doi: 10.1109/TPEL.2018.2878409.