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# Comprehensive Analysis on Critical Factors for the Operation of Advanced High Gain DC-DC Converters Used in Renewable Energy Applications

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**Abstract -** Renewable energy is identified as a potential alternative to conventional utility grid-based electricity to meet the present-day requirements of a variety of consumers. However, the inadequacy of matching the generated voltage to the customer required rating is still a major constraint. So, to meet the required energy requirements in terms of voltage ratings, power electronics-based DC-DC boost converters are generally used. But the voltage gain produced by traditional DC-DC boost converter may not be sufficient for the renewable energy application, where, the source voltage ratings produced are usually low. Hence, an effective DC-DC boost converter circuit with high gain has to be identified for this purpose. In line with this, many studies have proposed different topologies. Even though there were some studies presented in the literature, all those did not consider various key performance metrics viz., ripple current, voltage stress, voltage gain, number of components used, efficiency, output quality, switching frequency, etc., for the analysis. The effectiveness of any topology has to be evaluated in terms of the above-mentioned factors to understand its usefulness. Hence, keeping this gap in view, this paper presents a detailed theoretical and simulation analysis on state-of-the-art topologies in view of all the key performance metrics. A comparative analysis concerning the number of components used, performance metrics, output quality, transient response analysis, gain factor achieved, switch rating requirement, voltage/current stresses has been conducted. Based on this analysis of the advanced topologies, a better DC-DC converter topology is suggested as the conclusion of this paper.

**Keywords** DC-DC boost converter, High-gain converter, Power quality, Renewable energy, Switch stress, Transient response.

## 1. Introduction

Population growth and industrial development have led to high demand for energy in recent years. The consumption of energy is extremely increasing, where, saving energy becomes one of the biggest challenges. As consumption increases, the amount of fossil fuel resources required for generating energy also increasing. So, the world is focusing on renewable energy sources for providing energy without depending on fossil resources [82], [83]. However, the voltage ratings produced by these renewable energy sources is normally lower than the required level of the consumers. Besides, different kinds of consumers require a variety of voltage ratings with reliable power to meet their applications [84]. The traditional DC-DC converters have limitations to boost up the voltages to much higher levels to meet all these versatile requirements. In these scenarios, high-gain DC-DC boost converters serve the purpose of boosting the voltage to a much higher level, thereby, helps in achieving the full use of renewable energy sources [85], [86].

### *1.1. Operation of the Basic DC-DC Boost Converter*

A boost converter steps up the input DC voltage to the desired level based on the applied duty cycle. Usually, a lower output DC voltage generated from a renewable source is fed to the input of the step-up converter, which in turn converts it to the high output DC voltage. The basic model of the DC-DC boost converter is shown in Fig. 1. It consists of a semiconductor switch such as MOSFET (*M*) and energy storage elements such as inductor (*L*) and capacitor (*C*). A diode (*D*) is also used to protect the source from the reverse current flow. The control signal (pulse of a certain duty cycle) is fed to the gate of MOSFET, which decides the gain of the converter. The duty cycle (*d*) is defined as the ratio of the switch-on time ($T_{SON}$) of MOSFET and total time period (sum of switch-on time ($T_{SON}$) and switch-off time ($T_{SOFF}$)) as given by (1). There are two modes of operation for the MOSFET switch as given follows.

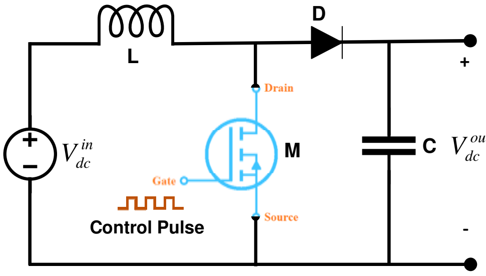

**Fig. 1.** The basic circuit of the boost converter.

- Switch-on state: The MOSFET acts as short-circuited. So, the current flows through the *L*, thereby, it gets charged up to the value of source voltage ($V_{dc}^{in}$).
- Switch-off state: The *L* discharges in this operation as the impedance offered by the MOSFET is very high. Hence, the current flows from *L* to the output (load). The *C* acts as the filter at the output to reduce the output ripples.

The continuous switching of MOSFET with a certain duty cycle provides continuous charging and discharging of *L*. The overall output voltage ($V_{dc}^{out}$) of this converter is equal to the average of these two operations, which is derived as given by (2). The voltage gain ($A_V$) of this converter is given by (3), which is always limited practically. Hence, it is required to investigate the high-gain topologies that can meet the requirement of high voltage supply of different practical applications without comprising the power quality.

$$d = \frac{T_{SON}}{T_{SON} + T_{SOFF}} \tag{1}$$

$$V_{dc}^{out} = \frac{V_{dc}^{in}}{1-d} \tag{2}$$

$$A_V = \frac{Output\ Voltage}{Input\ Voltage} = \frac{V_{dc}^{out}}{V_{dc}^{in}} \tag{3}$$

### *1.2. Literature Review and Contribution of this Paper*

Based on the importance of high-gain DC-DC converters, various researchers tried to investigate the efficacy of key topologies available in the literature. However, the effective topology depends upon various typical factors for its fruitful operation. Such typical factors that are needed to be considered while designing the high-gain converters are described as follows.

**Table 1.** Comparison of Various State-of-the-art Review Works

| Contribution Title | Year | Comparison Metrics | | | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Gain | Voltage Stress | Ripple Current | Switching frequency | Number of Components | Output Quality | Efficiency | Number of Sources | Duty Cycle | |
| Review of dc boost non-isolated converters | 2014 | ✓ | ✓ | × | × | × | × | × | × | × | [1] |
| Performance assessment of dc-dc converters | 2016 | ✓ | ✓ | ✓ | × | ✓ | ✓ | ✓ | ✓ | ✓ | [2] |
| Analysis of dc converters on power losses, ripple current, and efficiency | 2016 | × | × | ✓ | × | × | ✓ | ✓ | × | × | [3] |
| Review of dc high gain non-isolated converters | 2016 | ✓ | ✓ | × | × | ✓ | ✓ | × | × | × | [4] |
| Overview of coupled inductor based boost converters | 2016 | ✓ | ✓ | × | × | ✓ | ✓ | ✓ | × | × | [5] |
| Overview of dc converters based on the voltage conversion ratio | 2017 | × | × | × | × | × | × | ✓ | × | ✓ | [6] |
| Review of step-up dc converters | 2017 | ✓ | ✓ | × | × | ✓ | × | × | × | × | [7] |
| High gain interleaved dc-dc bidirectional converter | 2018 | ✓ | × | × | ✓ | × | ✓ | ✓ | × | ✓ | [8] |
| Overview of switched-capacitor based dc boost converters | 2018 | ✓ | ✓ | ✓ | ✓ | ✓ | × | ✓ | × | ✓ | [9] |
| Performance assessment of dc boost converters | 2019 | × | × | ✓ | ✓ | × | × | × | × | × | [10] |

(1) *Number of components used:* As the quantity of components increases, very high input power is required to switch ON all the components.
(2) *Voltage stress:* The increased voltage on a particular component affects the working of that component.
(3) *Efficiency:* The output must be more efficient in terms of the gain and purity of the waveform.
(4) *Waveform quality:* The quality of the expected output waveform must be very precise without any distortions or noise.
(5) *Ripples:* There should not be any ripple content i.e., the output should not contain any noise or undesired voltage or current.
(6) *Switching frequency:* As the MOSFETs are controlled by a pulse that is related to frequency, the output will be affected as the switching of MOSFETs might affect.
(7) *Gain:* The gain must be higher as the application of this boost converter is to step up or add suitable gain to the input ultimately.
(8) *Duty cycle:* The duty cycle of the MOSFET must be calculated properly so that it might not affect the gain and output of the waveform. Ultimately, the duty cycle decides the gain of the converter.
(9) *No of sources:* As the number of sources increases, the cost of the application will increase.

Hence, this section summarizes the available literature review works on high-gain converters. By considering the comparison matrix given in Table 1, even though, some papers cover all the key quality factors, it is observed that many are missing some of the main comparison factors among gain, voltage stress, ripple current, switching frequency, number of components, output quality, efficiency, number of sources, duty cycle. Quantitative analysis is also having not been done in these review papers. Comparing and finding the most efficient topology in every aspect is very important for elucidating the best topology.

Hence, based on the gaps present in the existing review papers, this paper conducts a comprehensive review in terms of both qualitative and quantitative analysis by considering all key performance parameters. Hence, the proposed analysis in this paper helps to identify a better-advanced topology for high voltage gain applications.

## 2. Theoretical (or Qualitative) Analysis

To identify a better high-gain DC-DC converter, this section performs detailed qualitative analysis on state-of-the-art high-gain boost converter configurations by considering all the abovementioned key performance parameters. This analysis is presented in Table 2 and Table 3. Here, Table 2 gives the analysis with respect to the number of components used for the topology development and Table 3 gives the analysis with respect to various performance quality metrics. Since, the load is common in all of these topologies, it is not considered in the count of the total number of components. All the parameters as validated in the available works are considered for the comparison, where, the parameters that were not validated are indicated as "NV" in the tables.

**Table 2.** Qualitative Comparison of Various State-of-the-art Topologies in Terms of Number of Components

| S.No | Name of the Topology | Comparison Metrics | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | **No. of Switches** | **No. of Inductors** | **No. of Capacitors** | **No. of Diodes** | **No. of Sources** | **No. of Transformers** | **Total No. of Components** | |
| 1 | Dual inductor-based isolated boost converter | 2 | 2 | 2 | 2 | 2 | 1 | 11 | [11] |
| 2 | Dual inductor-based non-isolated boost converter | 2 | 2 | 3 | 4 | 2 | 1 | 14 | [11] |
| 3 | 4-level boost DC-DC converter | 3 | 1 | 3 | 3 | 2 | 0 | 12 | [12] |
| 4 | Boost-2 Zeta converter | 1 | 1 | 3 | 2 | 2 | 1 | 10 | [13] |
| 5 | DC-DC converter for soft switching | 1 | 1 | 5 | 5 | 2 | 2 | 16 | [14] |
| 6 | ZCS Bidirectional DC–DC converter | 5 | 3 | 3 | 0 | 2 | 0 | 13 | [15] |
| 7 | Interleaved boost with Cockroft Walton and Dickson cell | 2 | 2 | 5 | 5 | 2 | 0 | 16 | [16] |
| 8 | Boost converter with capacitor cell and a switched inductor | 1 | 2 | 4 | 5 | 2 | 0 | 14 | [17] |
| 9 | High gain DC-DC converter | 1 | 3 | 4 | 6 | 2 | 0 | 16 | [18] |
| 10 | Single switch DC-DC converter | 1 | 2 | 4 | 5 | 2 | 0 | 14 | [19] |
| 11 | Converter with IBC interleaved boost converter and voltage multiplier circuit | 4 | 0 | 11 | 10 | 2 | 4 | 31 | [20] |
| 12 | Two-module converter | 2 | 2 | 2 | 2 | 2 | 0 | 10 | [21] |
| 13 | High step converter | 1 | 2 | 4 | 5 | 2 | 0 | 14 | [22] |
| 14 | Double-input converter | 2 | 5 | 3 | 2 | 2 | 0 | 14 | [23] |
| 15 | DC-DC converter with high gain | 1 | 4 | 2 | 4 | 2 | 0 | 13 | [24] |
| 16 | DC-DC circuit with Z-source and switched inductor network | 2 | 4 | 3 | 9 | 2 | 0 | 20 | [25] |
| 17 | SEPIC DC-DC converter | 1 | 3 | 3 | 1 | 2 | 0 | 10 | [26] |
| 18 | DC-to-DC boost converter with tapped inductor | 1 | 3 | 2 | 3 | 2 | 0 | 11 | [27] |
| 19 | Flying-capacitor boost converter | 2 | 2 | 3 | 4 | 2 | 0 | 13 | [28] |
| 20 | Multilevel boost converter | 1 | 1 | 5 | 6 | 2 | 0 | 15 | [29] |
| 21 | High-gain bi-directional DC-DC converter | 4 | 1 | 2 | 4 | 2 | 2 | 15 | [30] |
| 22 | Interleaved DC to DC boost converter | 2 | 2 | 1 | 3 | 3 | 0 | 11 | [31] |
| 23 | Two-stage converter | 2 | 4 | 2 | 8 | 2 | 0 | 18 | [32] |
| 24 | Boost converter with coupled- inductor | 1 | 2 | 4 | 3 | 2 | 1 | 13 | [33] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | switching cell | | | | | | | | |
| 25 | High-gain DC-DC voltage converter circuit with VM stage and single input source | 2 | 2 | 4 | 4 | 2 | 0 | 14 | [34] |
| 26 | DC-DC converter having voltage lift switched inductor module | 1 | 3 | 3 | 5 | 2 | 0 | 14 | [35] |
| 27 | Boost converter with VLSI module | 1 | 3 | 3 | 5 | 2 | 0 | 14 | [35] |
| 28 | Boost converter with MBCVLSI-XY | 1 | 4 | 4 | 7 | 2 | 0 | 18 | [35] |
| 29 | Boost converter for the n-stage | 2 | 2 | 2 | 3 | 2 | 0 | 11 | [36] |
| 30 | High efficiency DC/DC boost converter | 1 | 3 | 3 | 2 | 2 | 1 | 12 | [37] |
| 31 | High gain DC-DC converter where DC buses are substituted by loads | 3 | 2 | 2 | 3 | 2 | 0 | 12 | [38] |
| 32 | Dual boost converter | 4 | 4 | 2 | 4 | 2 | 0 | 16 | [39] |
| 33 | Boost converter circuit with voltage multiplier | 1 | 2 | 3 | 3 | 2 | 0 | 11 | [40] |
| 34 | High gain DC-DC converter | 2 | 2 | 4 | 6 | 2 | 0 | 16 | [41] |
| 35 | Voltage multiplier and coupled inductor based DC-DC converter | 1 | 5 | 5 | 4 | 1 | 0 | 16 | [42] |
| 36 | DC boost converter with high voltage gain | 2 | 2 | 5 | 5 | 2 | 0 | 16 | [43] |
| 37 | High gain DC converter using 4 VM stages | 2 | 2 | 5 | 5 | 2 | 0 | 16 | [44] |
| 38 | High-step up SEPIC boost DC-DC converter | 1 | 1 | 4 | 4 | 1 | 2 | 13 | [45] |
| 39 | Transformer-less DC-DC converter for high voltage gain | 3 | 3 | 4 | 3 | 3 | 0 | 16 | [46] |
| 40 | Modular and hybrid switched capacitor based converter with high gain | 4 | 4 | 8 | 0 | 4 | 0 | 20 | [47] |
| 41 | Dual coupled inductors based DC converter for high gain input and parallel output | 2 | 2 | 4 | 4 | 2 | 2 | 16 | [48] |
| 42 | Voltage multiplier for the interleaved boost converter | 2 | 2 | 4 | 4 | 2 | 0 | 14 | [49] |
| 43 | High step-up DC-DC converter | 2 | 2 | 7 | 7 | 2 | 2 | 22 | [50] |
| 44 | High step-up non-isolated DC-DC converter | 3 | 1 | 3 | 4 | 3 | 0 | 14 | [51] |
| 45 | High step-up converter with ZVS switching | 4 | 4 | 5 | 4 | 4 | 1 | 22 | [52] |
| 46 | Modified Dickson charge pump based DC-DC converter | 2 | 2 | 5 | 4 | 2 | 0 | 15 | [53] |
| 47 | Hybrid boosting converter | 1 | 1 | 4 | 4 | 1 | 0 | 11 | [54] |
| 48 | Isolated single-switch hybrid boost converter for high-gain | 1 | 1 | 6 | 7 | 1 | 1 | 17 | [55] |
| 49 | Switched-capacitor-based dual-switch (SCDS) converter | 2 | 1 | 3 | 4 | 2 | 0 | 12 | [56] |
| 50 | DC/DC high step-up converter with switched-capacitor and coupled inductor | 1 | 4 | 4 | 4 | 1 | 0 | 14 | [57] |
| 51 | Switched LC-network for ultra-gain DC-DC converter | 1 | 2 | 3 | 4 | 1 | 0 | 11 | [58] |
| 52 | Transformer-less high step-up gain converter | 1 | 2 | 3 | 1 | 1 | 0 | 8 | [59] |
| 53 | Ultra-high voltage gain hybrid DC-DC converter | 1 | 3 | 7 | 7 | 1 | 0 | 19 | [60] |
| 54 | High step up soft switched converter | 2 | 2 | 3 | 3 | 2 | 1 | 13 | [61] |
| 55 | High gain DC-DC converter for PVs | 1 | 3 | 5 | 5 | 1 | 0 | 15 | [62] |
| 56 | Non isolated high gain DC converter | 2 | 2 | 3 | 3 | 2 | 0 | 12 | [63] |
| 57 | Non isolated boost converter for microgrids | 3 | 2 | 1 | 2 | 3 | 0 | 11 | [64] |
| 58 | LCL resonant DC-DC converter | 4 | 3 | 6 | 0 | 4 | 0 | 17 | [65] |
| 59 | Soft switching bidirectional DC converter | 6 | 5 | 3 | 0 | 6 | 0 | 20 | [66] |
| 60 | Interleaved high gain DC converter | 2 | 2 | 2 | 4 | 2 | 2 | 14 | [67] |
| 61 | Non isolated interleaved DC-DC converter | 4 | 0 | 4 | 2 | 4 | 4 | 18 | [68] |
| 62 | DC boost converter for PV sources | 1 | 4 | 3 | 1 | 1 | 1 | 11 | [69] |
| 63 | Double boost sepic DC converter | 1 | 2 | 5 | 4 | 1 | 0 | 13 | [70] |
| 64 | DC-DC converter for PV energy utilization | 1 | 3 | 5 | 4 | 1 | 0 | 14 | [71] |
| 65 | Single switch DC-DC converter | 1 | 4 | 3 | 4 | 1 | 1 | 14 | [72] |
| 66 | DC converter for micro- inverter | 2 | 1 | 4 | 2 | 2 | 2 | 13 | [73] |
| 67 | DC-DC topology for grid-connected PV plant | 4 | 0 | 3 | 2 | 4 | 3 | 16 | [74] |
| 68 | Interleaved converter for renewable energy systems | 2 | 0 | 5 | 5 | 2 | 4 | 18 | [75] |
| 69 | Active switched network based DC-DC converter | 2 | 2 | 2 | 2 | 2 | 0 | 10 | [76] |
| 70 | Scalable high-gain and non-isolated DC-DC converter | 4 | 10 | 1 | 17 | 4 | 0 | 36 | [77] |
| 71 | Dual switches DC/DC converter | 2 | 3 | 4 | 4 | 1 | 0 | 14 | [78] |
| 72 | SEPIC-based high step-up converter | 1 | 2 | 5 | 4 | 1 | 2 | 15 | [79] |
| 73 | Single switch high step-up converter | 1 | 2 | 4 | 4 | 1 | 0 | 12 | [80] |
| 74 | High gain Re Boost-Luo converter | 1 | 0 | 4 | 3 | 1 | 1 | 10 | [81] |

**Table 3.** Qualitative Comparison of Various State-of-the-art Topologies in Terms of Performance Metrics

| S.No | Name of the Topology | Comparison Metrics | | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | Voltage Gain | Voltage Stress (V/s) | Ripple Current (A) | Switching frequency (kHz) | Output Quality | Efficiency (%) | Duty Cycle | |
| 1 | Dual inductor-based Isolated boost converter | NV | NV | NV | 20 | NV | 94.7 | 0.6 | [11] |
| 2 | Dual inductor-based Non-isolated boost converter | NV | NV | NV | 20 | NV | 94.3 | 0.6 | [11] |
| 3 | 4-level boost DC-DC converter | 2 | NV | 55 | 100 | NV | NV | 0.5 | [12] |
| 4 | Boost-2Zeta | (240/30) = 8 | NV | NV | 100 | NV | NV | 0.5 | [13] |
| 5 | DC-DC converter for soft switching | (460/25) = 18.4 | NV | NV | 100 | NV | NV | NV | [14] |
| 6 | ZCS Bidirectional DC–DC converter | (300/70) = 4.2 | NV | NV | 50 | NV | NV | NV | [15] |
| 7 | Interleaved boost with Cockroft Walton and Dickson cell | (400/20) = 20 | NV | NV | 100 | NV | NV | 0.75 | [16] |
| 8 | Converter with capacitor cell and switched inductor | (384/34) = 11.2 | NV | NV | 50 | NV | NV | 0.65 | [17] |
| 9 | High gain DC-DC converter | NV | NV | NV | 50 | NV | NV | NV | [18] |
| 10 | Single switch DC-DC converter | (400/20) = 20 | NV | NV | 40 | NV | NV | 0.058 | [19] |
| 11 | Converter with IBC interleaved boost converter and voltage multiplier circuit | (1000/40) = 25 | NV | NV | 25 | NV | 94 | 0.66 | [20] |
| 12 | Two-module converter | NV | NV | NV | 10 | NV | NV | NV | [21] |
| 13 | High step converter | (240/24) = 10 | NV | NV | 90 | NV | 93 | NV | [22] |
| 14 | Double-input converter | (40/10) = 4 | NV | NV | 20 | NV | NV | NV | [23] |
| 15 | DC converter with high gain | NV | NV | NV | 50 | NV | 96 | NV | [24] |
| 16 | DC circuit with Z-source and switched inductor | NV | NV | NV | NV | NV | NV | NV | [25] |
| 17 | SEPIC DC-DC converter | (149.1/15)=9.9 | NV | NV | 150 | NV | NV | 0.1-0.9 | [26] |
| 18 | DC-DC boost converter with tapped inductor | (120/24) = 5 | NV | NV | 20 | NV | NV | 0.5 | [27] |
| 19 | Flying-capacitor boost converter | (384/48) = 8 | NV | NV | 10 | NV | NV | NV | [28] |
| 20 | Multilevel Boost converter | (1000/100) = 10 | NV | NV | 20 | NV | NV | NV | [29] |
| 21 | High-gain bidirectional dc–dc converter | (400/40) = 10 | NV | NV | NV | NV | 94.5 | NV | [30] |
| 22 | Interleaved DC to DC boost converter | (56.2/12) = 4.68 | NV | NV | NV | NV | 77.64 | NV | [31] |
| 23 | Cascaded DC to DC boost converter | (62.15/12) = 5.2 | NV | NV | NV | NV | 91.21 | NV | [31] |
| 24 | Two-stage converter | (114/24) = 4.75 | NV | NV | 25 | NV | NV | NV | [32] |
| 25 | High- gain dc–dc voltage converter circuit with VM stage and single input source | (360/12) = 30 | NV | NV | 20 | NV | 96.5 | 0.8 | [33] |
| 26 | DC-DC converter having voltage lift switched inductor module | (400/15) = 26.6 | NV | NV | 50 | NV | NV | 0.67 | [34] |
| 27 | DC-DC converter having voltage lift switched inductor module | (221/66.4) = 3.32 | NV | NV | 50 | NV | 98.38 | 0.7 | [35] |
| 28 | Boost converter with VLSI module | (221.6/33.1)=6.69 | NV | NV | 50 | NV | 98.96 | 0.7 | [35] |
| 29 | Boost converter with MBCVLSI-XY | (443/65.5) = 6.76 | NV | NV | 50 | NV | 98.34 | 0.7 | [35] |
| 30 | Boost converter for the n-stage | (48/12) = 4 | NV | NV | 10 | NV | 93.5 | 0.5 | [36] |
| 31 | High efficiency DC/DC boost converter | NV | NV | NV | 10 | NV | 98.21 | NV | [37] |
| 32 | High gain DC-DC converter where DC buses are substituted by loads | NV | NV | NV | 10 | NV | NV | 0.36 | [38] |
| 33 | Dual boost converter | (700/120)=5.83 | NV | NV | 20 | NV | NV | NV | [39] |
| 34 | Boost converter with voltage multiplier circuit | (185/36) =5.13 | NV | NV | 150 | NV | NV | 0.1-0.9 | [40] |
| 35 | High gain DC-DC converter | (200/43)=4.65 | 38 | 5 | 40 | NV | 90 | 0.1-0.16 | [41] |
| 36 | Voltage multiplier and coupled inductor based DC-DC converter | (120/24) = 5 | NV | NV | 20 | NV | NV | 0.5 | [42] |
| 37 | DC-DC boost converter with high voltage gain | (400/80) = 5 | NV | NV | 20 | NV | NV | 0.4 | [43] |
| 38 | High gain DC-DC converter using 4 VM stages | NV | NV | 9 | NV | NV | 94.2 | NV | [44] |
| 39 | High-step up SEPIC boost DC-DC converter | (200/24~30) = 6.66 ~ 8.33 | NV | NV | 50 | NV | 94.2 | 0.42 | [45] |
| 40 | Transformer-less DC-DC converter for high gain | (381/12) = 31.7 | 180 | NV | 50 | NV | NV | 0.33 ~ 0.66 | [46] |
| 41 | Modular and hybrid switched capacitor based converter with high gain | (48/2.5) = 19.2 | NV | NV | 100 | NV | 96.5 | 0.5 | [47] |
| 42 | Dual coupled inductors based DC/DC converter for high gain input and parallel output | (200/36) = 5.55 | NV | NV | 40 | NV | NV | 0.5 | [48] |
| 43 | Voltage multiplier for the interleaved boost topology | (400/24) = 16.6 | NV | NV | NV | NV | NV | 0.81 | [49] |
| 44 | High step-up DC-DC converter | (800/32) = 25 | NV | NV | 118 | NV | 96.7 | 0.68 | [50] |
| 45 | High step-up non-isolated DC-DC converter | (394/20) = 19.7 | NV | NV | 46 | NV | 95.85 | 0.35, 0.5 | [51] |
| 46 | High step-up converter with ZVS switching | (531.25/50)=10.62 | 125 | NV | 100 | NV | 95.32 | 0.6 | [52] |
| 47 | Modified dickson charge pump based DC converter | (400/20) = 20 | NV | 1.2 | NV | NV | NV | 0.8 | [53] |
| 48 | Hybrid Boosting Converter | (380/35) = 10.8 | NV | NV | 40 | NV | 95.44 | 0.8 | [54] |
| 49 | Isolated single-switch hybrid boost converter for high-gain | (400/35) = 11.4 | NV | NV | 50 | NV | 94 | 0.8 | [55] |
| 50 | Switched-capacitor-based dual-switch converter | (200/50) = 4 | NV | NV | 50 | NV | NV | NV | [56] |
| 51 | DC/DC high step-up converter with switched-capacitor and coupled inductor | (400/40) = 10 | NV | NV | 60 | NV | 96 | NV | [57] |
| 52 | Switched LC-network for ultra-gain DC converter | (325/20) = 16.2 | NV | NV | 50 | NV | 91.2 | 0.71 | [58] |
| 53 | Transformer-less high step-up gain converter | (250/20) = 12.5 | NV | NV | 40 | NV | 74.2 | 0.8 | [59] |
| 54 | Ultra-high voltage gain hybrid DC-DC converter | 12 | NV | NV | 48 | NV | 93.27 | NV | [60] |
| 55 | High step up soft switched converter | (400/48) = 8.33 | NV | NV | 100 | NV | 95.92 | NV | [61] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 56 | High gain DC-DC converter for PVs | (700/45) = 15.5 | NV | NV | 60 | NV | 95 | NV | [62] |
| 57 | Non isolated High gain DC-DC converter | (300/20) = 15 | NV | NV | 50 | NV | 96.2 | 0.75 | [63] |
| 58 | Non isolated boost converter for microgrids | (200/20) = 10 | NV | NV | 50 | NV | 87.5 | 0.5, 0.35 | [64] |
| 59 | LCL resonant DC-DC converter | (380/48) = 7.92 | NV | NV | 105 | NV | 95.5 | 0.5 | [65] |
| 60 | Soft switching bidirectional DC-DC converter | (400/48) = 8.33 | NV | NV | 100 | NV | 96.5 | NV | [66] |
| 61 | Interleaved high gain DC-DC converter | (380/24) = 15.83 | NV | 2 | 50 | NV | 95 | NV | [67] |
| 62 | Non isolated interleaved DC-DC converter | (120/14) = 8.57 | NV | NV | 50 | NV | 91.2 | 0.5 | [68] |
| 63 | DC boost converter for PV sources | (311/17) = 18.2 | NV | NV | 50 | NV | 50 | 0.29 | [69] |
| 64 | Double boost sepic DC-DC converter | (240/24) = 10 | 84 | NV | 200 | NV | 93.5 | 0.86 | [70] |
| 65 | DC-DC converter for PV utilization | (60/10) = 6 | NV | NV | 50 | NV | 97.68 | 0.69 | [71] |
| 66 | Single switch DC-DC converter | (200/12) = 16.6 | NV | NV | 100 | NV | 95.5 | 0.644 | [72] |
| 67 | DC-DC converter for micro- inverter | (350/80) = 4.37 | NV | NV | 50 | NV | 97.5 | 0.35 | [73] |
| 68 | DC-DC converter for Grid-connected PV systems | (400/40) = 10 | NV | NV | 50 | NV | 96.6 | 0.85 | [74] |
| 69 | Interleaved converter for renewable energy systems | (380/40) = 9.5 | NV | NV | 40 | NV | 97.1 | 0.5 | [75] |
| 70 | Active switched network based DC-DC converter | (200/20) = 10 | NV | NV | 50 | NV | 95.6 | 0.65 | [76] |
| 71 | Scalable high-gain and non-isolated DC converter | (160/20) = 8 | NV | NV | 20 | NV | 95.6 | 0.5 | [77] |
| 72 | Dual switches DC/DC converter | (400/50) = 8 | NV | NV | 50 | NV | 96.4 | 0.6 | [78] |
| 73 | SEPIC-based high step-up converter | (300/26) = 11.5 | NV | NV | 30 | NV | 94 | NV | [79] |
| 74 | Single switch high step-up converter | (300/30) = 10 | NV | NV | 24 | NV | 92.3 | 0.81 | [80] |
| 75 | High gain Re Boost-Luo converter | (200/70) = 2.85 | NV | NV | 100 | NV | NV | 0.5 | [81] |

**Table 4.** Summary and Order of Superiority of the State-of-the-art Topologies

| **Order of Superiority Based on Total Number of Components** | | **Order of Superiority Based on Total Gain Produced** | | **Order of Superiority Based on Switching Frequency Used** | |
|---|---|---|---|---|---|
| **Total No. of Components Used** | **References** | **Voltage Gain Produced** | **References** | **Switching Frequency (kHz)** | **References** |
| 8 | [59] | 31.78 | [46] | 10 | [21], [28], [36], [37], [38] |
| 10 | [13], [21], [26], [76], [81] | 26.6 | [34] | 20 | [11], [23], [27], [29], [33], [39], [42], [43], [77] |
| 11 | [27], [31], [36], [40], [54], [58], [64], [69] | 25 | [20], [50] | 24 | [80] |
| 12 | [12], [37], [38]. [56], [63], [80] | 20 | [16], [19], [53] | 25 | [20], [32] |
| 13 | [15], [24], [28], [33], [45], [61], [70], [73] | 19-20 | [47], [51] | 30 | [79] |
| 14 | [11], [17], [19], [22], [23], [34], [35]. [49], [51], [57], [67], [71], [72], [78] | 18-19 | [69], [14] | 40 | [16], [19]. [41], [48], [54], [59], [75] |
| 15 | [29], [30], [53], [62], [79] | 16-17 | [58], [49], [72] | 46 | [51] |
| 16 | [14], [16], [18], [39], [41], [42], [43], [44]. [46], [48], [74] | 15-16 | [63], [62], [67] | 48 | [60] |
| 17 | [55], [65] | 12-13 | [60], [59] | 50 | [15], [17], [18], [24], [34], [35], [45], [46], [55], [56], [58], [63], [64], [67], [68], [69], [71], [73], [74], [76], [78] |
| 18 | [32], [68], [75] | 11-12 | [17], [55], [79] | 60 | [57], [62] |
| 19 | [60] | 10-11 | [22], [29], [26], [30], [33], [52], [54], [57], [64], [70], [74], [76], [80] | 90 | [22] |
| 20 | [47], [66] | 8-10 | [13][28],[37],[11], [61], [65], [66], [68], [75], [77], [78] | 100 | [12], [13], [14], [16], [47], [52], [61], [66], [72], [81] |
| 22 | [50], [52] | 6-7 | [35], [45], [71] | 105 | [65] |
| 31 | [20] | 5-6 | [39], [38], [31], [40], [27], [42], [43], [48] | 118 | [50] |
| 36 | [77] | 4-5 | [32], [15], [23], [36], [41], [56], [73] | 150 | [26], [40] |
| | | 2-3 | [12], [21], [81] | 200 | [70] |

### *2.1. Summary of the Qualitative Analysis*

From the qualitative analysis presented in this paper, the superior topologies have been decided based on three important factors, viz., the total number of components, gain produced, and switching frequency used. Always, it is desired to use a lower number of components and less switching frequency while producing the maximum possible voltage gain. To identify the topologies with these desired features, all the topologies analyzed in Table 2 and Table 3 are summarized and arranged sequentially according to their features in Table 4. From this summary, the superior converter is identified based on the following approach.

For example, the topology presented in [46] is producing a gain of 31.78, which is the highest among all the other topologies. However, this topology uses 16 components and needs a higher switching frequency at least of 50kHz, which is violating the desired features. Hence, this topology is not considered for further quantitative analysis. Similarly, the topology given in [34] is producing a gain of 26.6, which is the second-highest among all other topologies. However, this topology also uses 14 components and needs a higher switching frequency of 50kHz. Hence, this topology is also not considered for further quantitative analysis. Further, the topologies that are given in [12], [15], [21], [23], [27], [31], [32], [35], [36], [38], [39], [40], [41], [42], [43], [45], [48],

[56], [71], [73], and [81] are producing less voltage gain when compared to other topologies. So, those are also not considered for quantitative analysis. In the same way, the analysis is carried for all the topologies reviewed in this paper. As a result of this qualitative summary presented in Table 4, the topologies presented in [11], [28], [29], [33] and [37] are identified as superior topologies when compared to the other state-of-the-art high-gain DC-DC converter topologies with respect to the desired features.

## 3. Simulation-Based (or Quantitative) Analysis

The qualitative analysis extracts some of the useful topologies among the advanced DC converter topologies available in the literature. To further extend the investigation to identify the best topology, this section provides a quantitative analysis. This quantitative analysis is carried out by conducting an extensive simulation study. The simulation circuits developed for the analysis are given through Fig. 2 to Fig. 6 with respect to the topologies identified in Section 2.1 (i.e., for topologies given in [11], [28], [29], [33] and [37] respectively). The specifications used for the circuits' simulation are given in Table 5. These quantitative analysis results are discussed in Section 4.

**Table 5.** Specifications Used in the Simulation Study

| Topology Reference | Capacitance | | Inductance | | Load (Ω) |
|---|---|---|---|---|---|
| | Name | Value (μF) | Name | Value (μH) | |
| [11] | C1, C2, C3 | 22 | L1, L2 | 70 | 58 |
| [28] | C0 | 25 | L1 | 11.7 | 58 |
| | C1, C2 | 4 | L2 | 46.87 | |
| [29] | C1, C2, C3, C4, C5 | 35 | L1 | 1200 | 1000 |
| [33] | C1, C2, C4 | 4.7 | L1 | 270 | 360 |
| | C3 | 0.47 | L2 | 400 | |
| [37] | C1 | 680 | L1 | 0.011 | 18.89k |
| | C2 | 0.0012 | L2 | 9.82 | |
| | C3 | 18 | L3 | 0.031 | |
| | Cout | 220 | | | |

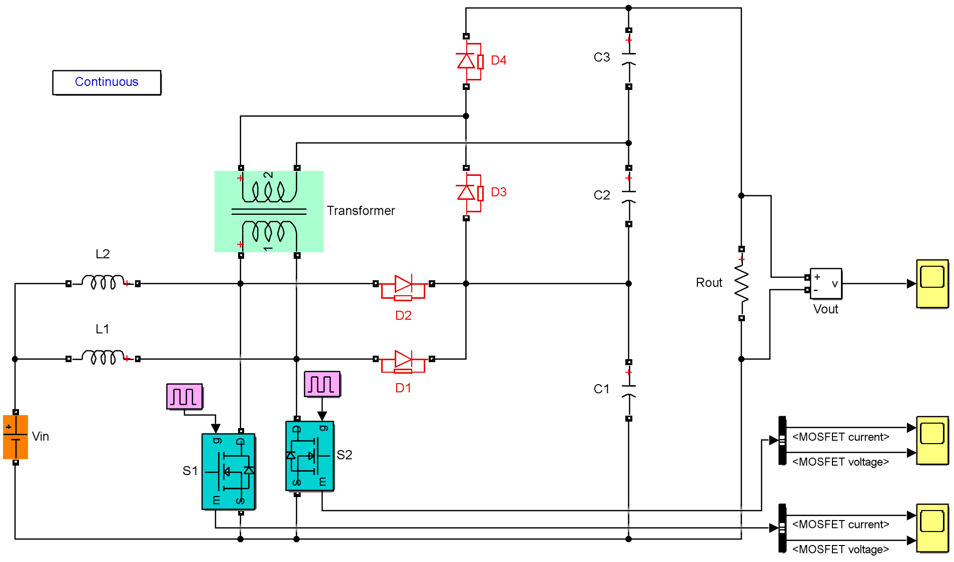

**Fig. 2.** The simulation model of the high gain DC-DC converter topology given in [11].

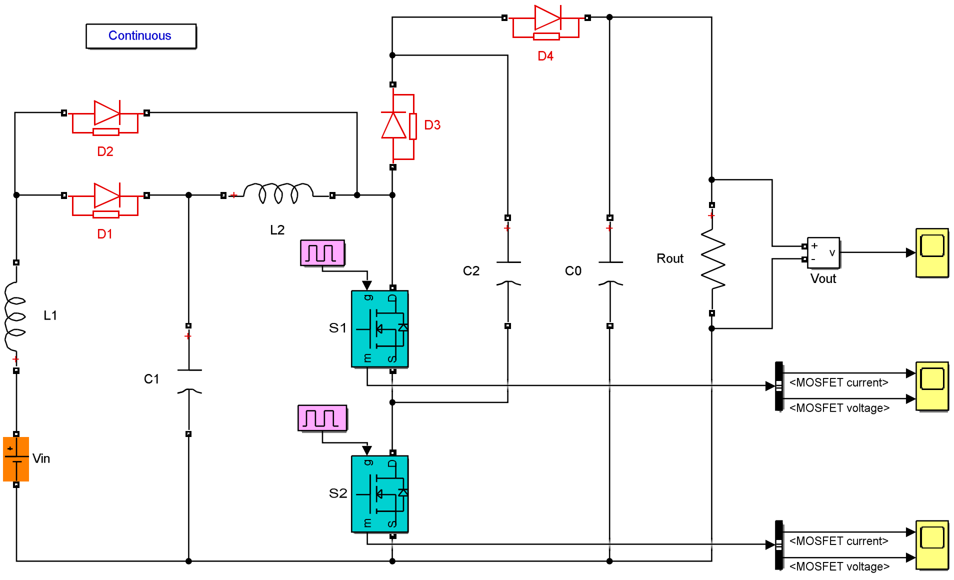

**Fig. 3.** The simulation model of the high gain DC-DC converter topology given in [28].

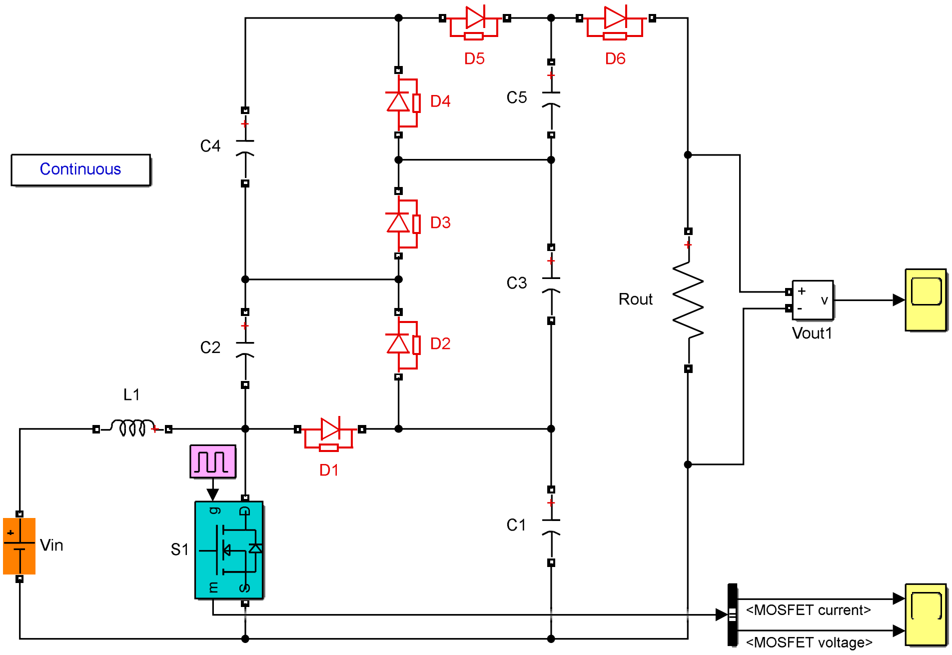

**Fig. 4.** The simulation model of the high gain DC-DC converter topology given in [29].

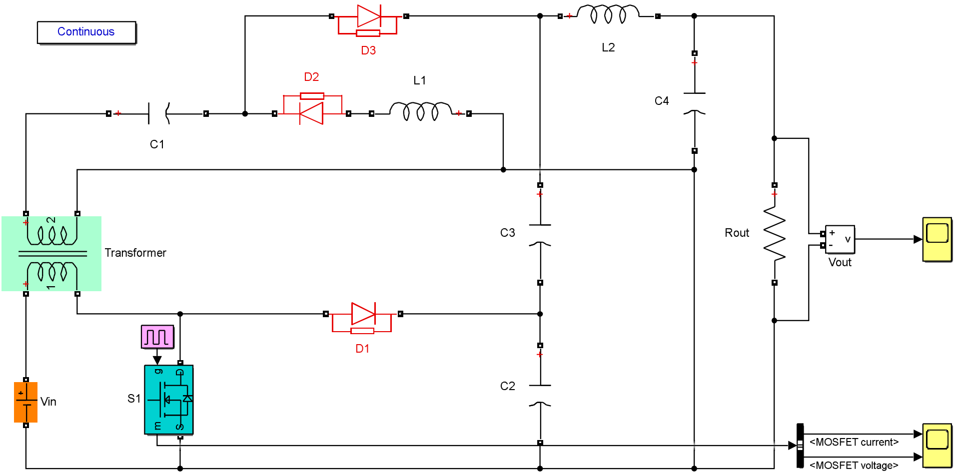

**Fig. 5.** The simulation model of the high gain DC-DC converter topology given in [33].

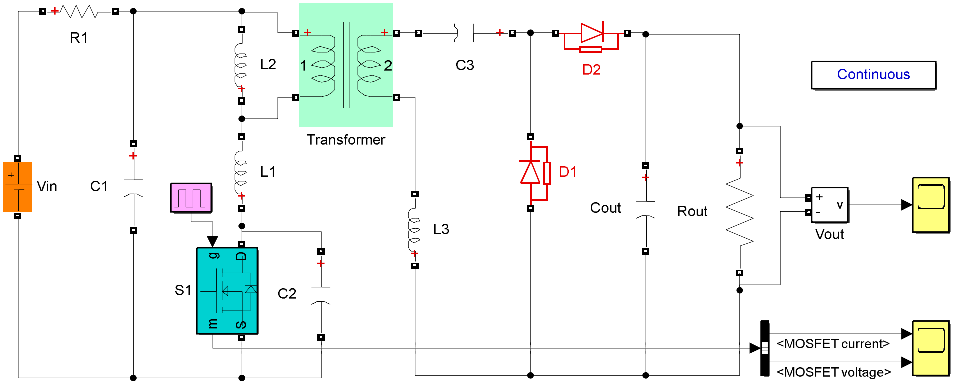

**Fig. 6.** The simulation model of the high gain DC-DC converter topology given in [37].

## 4. Simulation Results and Discussion

The simulation is conducted with the help of two specific analysis approaches, viz., analysis of transient response characteristics and analysis on switch rating requirement, as given in the following subsections.

### *4.1. Transient Response Analysis*

The responses of the abovementioned better topologies are plotted as shown in Fig. 7 to Fig. 11. The cumulative quantitative comparison metrics are evaluated and shown in Table 6 and Table 7. To assess the usefulness of these topologies, the values of input voltage and duty cycle are taken the same for all these five topologies. Further, various performance metrics, viz., delay time (time taken to reach from 0% to 50% of the final steady-state output), rise time (time taken to reach from 10% to 90% of the final steady-state output), peak overshoot (maximum deviation of the transient peak from the steady-state output), peak-time (time taken to reach from 0% to first peak of the response), and settling time (time taken to settle at a steady-state value) are computed for the responses obtained by these topologies. These performance metrics indicate the quality of the transient response and a response producing the lowest values of all these metrics is considered as the best response. The output voltages and the gain produced for these topologies are given in Table 6.

As per the order of superiority given in Table 6, it is observed that [29] is achieving more gain and [37] is achieving less gain compared to other topologies. As per the superior order in Table 7, [37] is chosen to be best compared to other topologies in transient response characteristics. From the obtained responses, it is observed that the response of [11] has the peak overshoot at 170.9, whereas, the response of [28], [29], [33], [37] don't have any peak overshoot. This is one of the key factors which ensures the safety of loads.

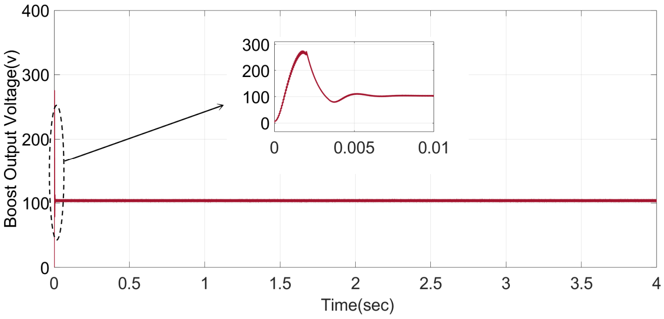

**Fig. 7.** Simulation response of the converter topology [11].

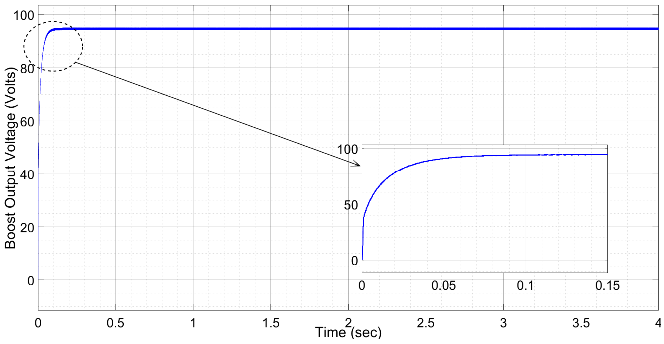

**Fig. 8.** Simulation response of the converter topology [28].

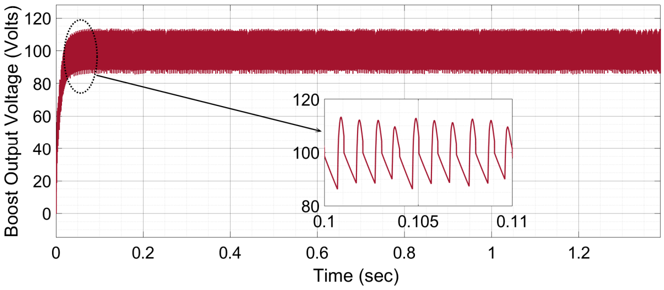

**Fig. 9.** Simulation response of the converter topology [29].

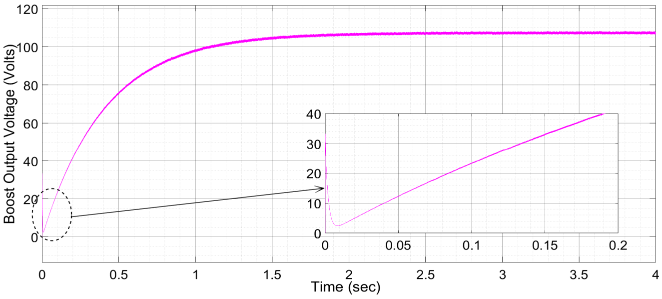

**Fig. 10.** Simulation response of the converter topology [33].

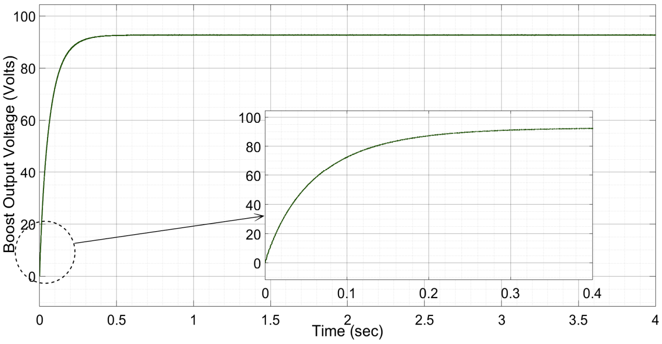

**Fig. 11.** Simulation response of the converter topology [37].

**Table 6.** Comparison Through Output Gain Achieved

| Reference | Duty Cycle (%) | Input Voltage (V) | Gain Achieved | Output Voltage (V) |
|---|---|---|---|---|
| [11] | 60 | 10 | 10.15 | 101.5 |
| [28] | 60 | 10 | 9.47 | 94.7 |
| [29] | 60 | 10 | 11.34 | 113.4 |
| [33] | 60 | 10 | 10.56 | 105.6 |
| [37] | 60 | 10 | 9.26 | 92.6 |
| Order of Superiority | | | [29] > [33] > [11] > [28] > [37] | |

**Table 7.** Comparison Through Transient Response Metrics

| Reference | Delay Time (msec) | Rise Time (msec) | Peak Overshoot (%) | Peak-Time (msec) | Settling Time (msec) |
|---|---|---|---|---|---|
| [11] | 0.4 | 1.85 | 170.9 | 2 | 10 |
| [28] | 7.5 | 0.029 | 0 | 0 | 350 |
| [29] | 1.95 | 20.3 | 0 | 0 | 150 |
| [33] | 0.265 | 0.065 | 0 | 0 | 2000 |
| [37] | 0.085 | 0.00025 | 0 | 0 | 600 |
| Superior | [37], [33] | [37], [28], [33] | [28], [37], [33] | [28], [37], [33] | [11], [29], [37] |

### *4.2. Analysis of Switch Rating Requirement*

The ratings of the switching devices affect the converter cost. The selection of inadequately rated switches leads to damage of the circuit by causing a short circuit or open circuit faults in the circuit operation. Hence, to further understand the voltage (V) and current (I) stresses on the switching units used in different topologies, their responses are plotted as shown in Fig. 12 to Fig. 16. The corresponding ratings observed across switches of various topologies are presented in Table 8. From this, it is observed that voltage stress on the MOSFET is very high in the case of [37], so, it is excluded from the comparison. As it is always expected a low voltage and current should be drawn by the MOSFET, the topology [28] is superior compared to the others.

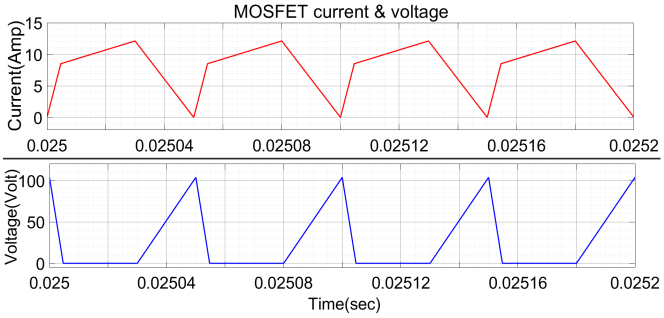

**Fig. 12.** Switching device V/I measured for topology [11].

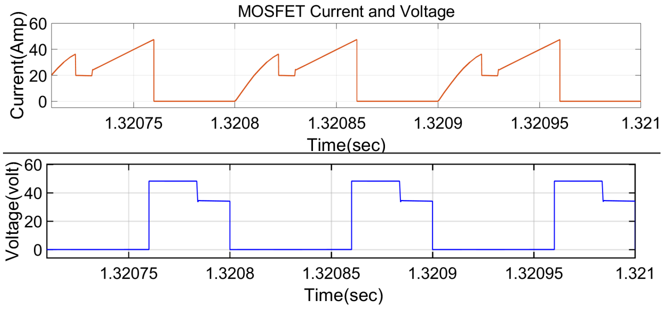

**Fig. 13.** Switching device V/I measured for topology [28].

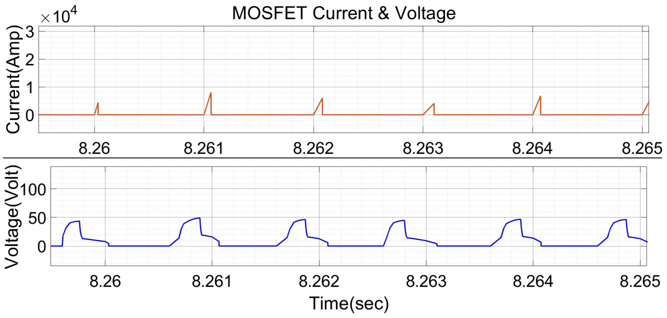

**Fig. 14.** Switching device V/I measured for topology [29].

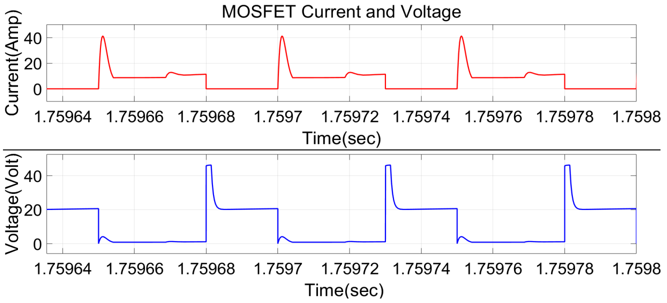

**Fig. 15.** Switching device V/I measured for topology [33].

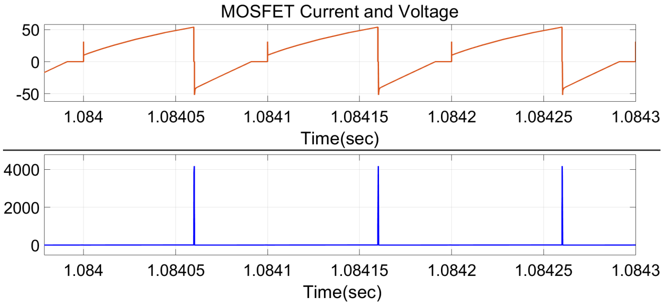

**Fig. 16.** Switching device V/I measured for topology [37].

**Table 8.** Comparison of V and I Ratings of Switches

| Reference | Switch - 1 | | Switch - 2 | |
|---|---|---|---|---|
| | Current (A) | Voltage (V) | Current (A) | Voltage (V) |
| [11] | 12.1 | 104 | 12.1 | 104 |
| [28] | 47.5 | 48 | 47.5 | 48 |
| [29] | 8000 | 49 | No 2nd switch | No 2nd switch |
| [33] | 41.7 | 46.7 | No 2nd switch | No 2nd switch |
| [37] | ±53.7 | 4178 | No 2nd switch | No 2nd switch |

## 5. Conclusions

Hence, to analyze the effectiveness of all the important state-of-the-art high-gain DC-DC converters, this paper presents a comprehensive qualitative and quantitative analysis. From the detailed qualitative analysis conducted, various better topologies concerning critical factors such as the number of components, voltage gain, voltage stress, ripple current, switching frequency, efficiency, and duty cycle used are identified. From this qualitative analysis, topologies presented in [11], [28], [29], [33], and [37] are found as better topologies compared to all other topologies. Further, to recommend the best topology, simulation studies are conducted. Various quantitative metrics are computed for the analysis, thereby, the following remarks can be derived.

- There are sudden peak overshoots present in topologies of [29] and [33], which is not safe for the load side. Hence, these topologies are not considered best.
- Among the remaining three i.e. [11], [28], and [37], the topology given in [28] has more gain and low voltage stress on the switching devices. So, it is producing effective results with high gain.
- Further, the topology of [28] is more effective with respect to the switching frequency requirement.

Hence, from these qualitative and quantitative analyses conducted on all-important advanced high-gain DC-DC converters, it is concluded that the topology presented in [28] is the best one for the renewable energy applications out of all other topologies. For this topology, the current and voltage stress on the switching device is observed as 47.5A and 48V respectively, and voltage gain is observed as 9.47 times of the input when using a switching frequency of 10kHz. This topology is made with 13 components and produces high-quality output waveform with very low transients when compared to other state-of-the-art topologies.

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