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Enhancing voltage gain and switching efficiency in a non-isolated buck-boost converter through integrated switching inductor configuration

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ABSTRACT

This research presents a novel investigation into advancing the operational efficiency and performance of non-isolated buck-boost converters utilized in photovoltaic (PV) systems as charging controllers. The focus of this study lies in the development and integration of a specialized switching inductor configuration, aiming to augment the converter's voltage gain while concurrently mitigating stress imposed on the converter switch. The converter's efficacy is of paramount importance, particularly during stepping-up operations where the duty cycle reduction, a consequence of the integrated switched inductor, contributes to reduced stress. The proposed converter architecture is characterized by its simplicity, necessitating only minimal components for implementation. These include a single capacitor, a pair of diodes, a duo of inductors, and a trifecta of switches. Operating nominally at 12 volts, the converter dynamically adjusts the voltage level in response to varying duty cycles: elevating it beyond the 35% threshold and inversely attenuating it below this parameter. A salient outcome of this endeavor is the curtailment of the dependency on an additional diode (D), resulting in streamlined circuitry. The conceptualized switching inductor model was rigorously assessed using the MATLAB/SIMULINK simulation environment, affording a comprehensive evaluation of its efficacy and robustness. This study thus underscores the viability and potential for significant enhancements in non-isolated buck-boost converter systems through inventive switching inductor integration.

1. Introduction

Owing to the depletion of conventional gas reservoirs, the imperative of developing renewable energy sources has become paramount in fulfilling the escalating electricity requisites (Mayer, 2022; Kabeyi and Olanrewaju, 2022). Consequently, the significance of renewable sources such as solar and wind in aligning with sustainability targets has triggered an extensive array of research initiatives. Nonetheless, the inherent variability characterizing the output voltage of most renewable sources introduces the potential for supply disruptions. Notably, photovoltaic cells frequently yield fluctuating output voltages that oscillate beyond the designated range, compelling the deployment of a charging controller to harmonize the voltage output.

In the context of photovoltaic systems, the recourse to direct current (DC) to DC buck-boost converters has garnered prominence. These converters are pivotal in maintaining the requisite output voltage integrity as duty cycles are manipulated. It is worth noting that these DC-DC buck-boost converters manifest in two principal configurations: isolated and non-isolated, each possessing distinctive attributes and merits (Li and Wolfs, 2008). When a power transformer is added to a DC-to-DC boost converter, an isolated type is created, and the output voltage rises at a low-duty cycle. Because of the switch voltage stress at a high-duty cycle, a non-isolated typical boost converter can't be used to raise the voltage, hence an isolated boost converter is used instead. The poor voltage gain of the typical non-isolated converter has been pointed out as a serious drawback. When the PV output voltage must be lowered, however, a buck converter is the best choice (Rosas-Caro et al., 2010; Al-Ateeq and Alateeq, 2020).

Using a buck-boost converter, the advantages of both kinds of converters may be consolidated into a single, efficient architecture. When the duty cycle is

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less than 50%, this DC-to-DC converter operates as a buck converter, and when it's more than 50%, it operates as a boost converter. To adjust how much of a boost or buck is applied, a switched inductor (SI) cell is employed.

Despite needing more than one inductor, the novel switched inductor buck-boost (SIBB) converter performs identically to the traditional DC-DC buck-boost converter. The SIBB (Rosas-Caro et al., 2010) is comprised of two inductors, three switches, a capacitor, two diodes, and an output load.

SIBB's high voltage conversion ratio when using a non-isolated DC-to-DC voltage is perhaps its most striking feature. Voltage stress is a key factor to consider because of the switch's significance. Rather than using an input inductor, researchers have developed switching inductor models to increase the conversion ratio by increasing the duty cycle (Chung et al., 2000; Musale and Deshmukh, 2016; Alateeq et al., 2017; Axelrod et al., 2008; Almalaq et al., 2018).

Much research focuses on increasing voltage gain, but few consider the stress this may place on the switches. In addition, some designs include a switch in the switched inductor model, increasing the complexity of the converter (Allani et al., 2019; Ranjana et al., 2014; Tibola et al., 2015; Butti and Biela, 2011).

Three approaches, incremental and conductance (IC), perturb and observe (PandO), and a fuzzy logic controller (FLC) based on IC (Li and Wolfs, 2008), are used to achieve maximum power point tracking (MPPT) in PV energy systems. However, among the three kinds of DC-to-DC converters used and regulated, the buck-boost converter is by far the most common. By reducing the necessary duty cycle, this approach helps effectively the design of the buck-boost converter. The suggested buck-boost converter offers similar optimization potential to MPPT approaches such as those described in Behih and Attoui (2021), Priyadarshi et al. (2022), and Singh and Agrawal (2021).

This study introduces a non-isolated switched inductor for reducing the stress brought on by the switching voltage. The process was carried out on a MATLAB/SIMULINK simulator, and the outcomes were compared to those of a regular buck-boost converter. The suggested approach produces a greater voltage gain at a shorter duty cycle than the conventional buck-boost converter, leading to less switch stress.

2. The proposed design

The non-isolated circuit of the proposed SIBB converter is comprised of two diodes, two inductors, one capacitor, and three MOSFET transistor switches (S_1, S_2, and S_3). In this configuration, the output capacitor is connected in parallel with the output load (Fig. 1). This article makes use of a switching inductor model that is conceptually similar to the one proposed by Al-Ateeq and Alateeq (2020).

3. Modes of operation

The single switch and CCM-assisted design of the converter allow for two possible setups (Fig. 2a and Fig. 2b). The on and off states of the switch define two distinct operational modes, referred to as Mode 1 and Mode 2, respectively.

- Mode 1: In Mode 1, $L_1$and L_2 are parallel-connected to the input source V_{in} via S_1, S_2, and S_3 (Fig. 2). D_2 is in an inverse biased condition since C is expected to be charged.
- Mode 2: Here, S_1, S_2 and S_3 are off with D_1, and D_2 active. A discharge into C through D_1 is triggered by activating D_2, which then connects L_1, and L_2 in series. As soon as C reaches its maximum capacity, the second mode ends due to the reverse bias on D_2 (Fig. 2).

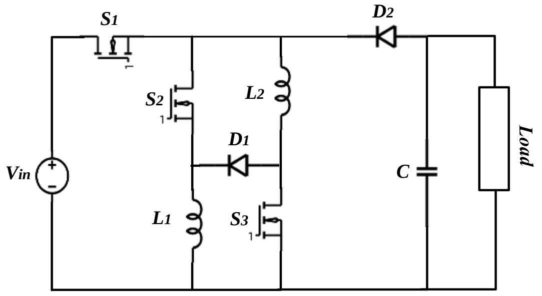
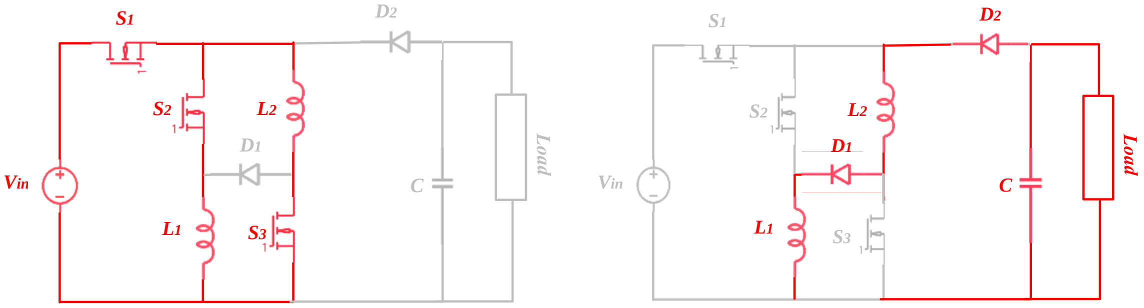


Fig. 1: Schematic diagram for the proposed buck-boost converter used for a PV system and based on a switched inductor cell



a. Mode 1

b. Mode 2

Fig. 2: Mode 1 and Mode 2 of the proposed SIBB converter

4. Analysis of the proposed model

When compared to a standard buck-boost converter, an SIBB is essentially identical (Rosas-Caro et al., 2010).

With the exception that it employs a series of switched inductor cells rather than a single inductor. It is assumed that inductors L1 and L2 are both perfect and identical. Since L_1 and L_2 are parallel linked in Mode 1, the V_{in} will act equally on each of them.

$$V_{in} = V_{L1} = V_{L2} \tag{1}$$

$$I_c = \frac{-V_{out}}{R_L} \tag{2}$$

where, V_{out} and R_L are the load voltage and resistor.

In Mode 2, switches S_1, S_2, and S_3 are all turned off, and inductor pairs L_1 and L_2 are linked in series to provide an output voltage equal to the sum of the voltages across the two inductors.

$$V_{out} = V_{L1} + V_{L2}. \tag{3}$$

Due to their equality, L_1 and L_2 will be charged at the same rate; nevertheless, in this mode, the V_{out} will be opposite to the sum of the voltages on L_1 and L_2.

$$-V_{out} = V_{L1} + V_{L2} \tag{4}$$

$$2V_L = V_{L1} + V_{L2} \tag{5}$$

rewrite Eq. 4 into Eq. 5 to get Eq. 6,

$$V_{out} = -2V_L \tag{6}$$

$$V_L = \frac{-V_{out}}{2}. \tag{7}$$

Applying the second balance of the inductor voltage to Eqs. 1 and 7 yields the voltage gain of the proposed model.

$$DV_{in} = (1-D)\left(\frac{-V_{out}}{2}\right). \tag{8}$$

Converter gain in the usual form is equivalent to Eq. 8 after simplification.

$$\frac{V_{out}}{V_{in}} = \frac{-2D}{1-D}. \tag{9}$$

Table 1 presents the converters' gain of the two compared designs, the proposed one and Al-Ateeq and Alateeq (2020). To calculate I_L which represents the total currents of $I_{L1}, and\ I_{L2}$,

$$P_{out} = P_{in}. \tag{10}$$

Eq. 10 can be understood as Eq. 11,

$$I_{out}V_{out} = I_{in}V_{in} \tag{11}$$

where, I_{in} is the input current of the buck-boost converter:

$$I_L = \left(-\frac{V_{out}\,2D}{R_L(1-D)}\right) \tag{12}$$

Table 1: Conversion ratio of three different BBC types at ideal components assumption

Buck-boost model by Al-Ateeq and Alateeq (2020)	$\frac{V_{out}}{V_{in}} = \frac{-D}{1-D}$
The proposed buck-boost	$\frac{V_{out}}{V_{in}} = \frac{-2D}{1-D}$

5. Results and discussion

The fundamentals of the proposed converter were explored in MATLAB SIMULINK. Every part of the design came from the electronics toolbox in Sims Cape, and the ode23t solver configuration was utilized. The suggested SIBB converter was compared to a standard buck-boost converter model presented in Chung et al. (2000). The two models were compared by measuring their minimum and maximum duty cycles in boosting and bucking mode, as well as their voltage gains and the stress placed on their switches. Instead of a traditional inductor, the proposed model makes use of a switched inductor model; in Al-Ateeq and Alateeq (2020), a single inductor is used in the buck-boost's architecture. Using a power supply of 10 volts, a 50 kHz switching frequency (f_{sw}) and a 75%-10% duty cycle were chosen where all design parameters were provided in Table 2.

Table 2: Design parameters calculated by Allani et al. (2019)

Input Voltage (V)	10V
Inductors ($L_1 = L_2$)	1 mH
Capacitors	220 µF
Load	200 Ω
Duty Cycle	25% to 75%

Two inductors were utilized in the SIBB model's functioning, with a parallel connection established between them during conduction and a series connection established during discharge (Figs. 3 and 4). Pulse waveforms of the gate drive signal V_g are reflected in the waveforms of the currents I_{IL1} and I_{IL2} flowing through L_1 and L_2, respectively, as shown in Fig. 4. Since I_{L1} and V_g share the same phase, it makes sense to link L_1, and L_2 in parallel and series during charging and discharging modes. Voltage gain versus duty cycle for each converter is shown for ease of comparison in Fig 5. Both types had a voltage gain that scaled linearly with increasing duty cycles. On the other hand, the suggested model was shown to be superior to the conventional method in terms of duty cycle needs. Moreover, compared to the other converter under evaluation, the suggested converter seems to be better capable of reducing switch voltage stress. The proposed converter successfully reduced switch voltage stress while increasing voltage gain. V_{out} at 60% duty cycle is shown in Fig. 6 for the two compared converters. Figs. 4-6 demonstrates that the suggested converter was able to provide the same amount of power with just 50% of the usual duty cycle. By decreasing the duty cycle, the switch's switching losses might be kept to a minimum desirable value.

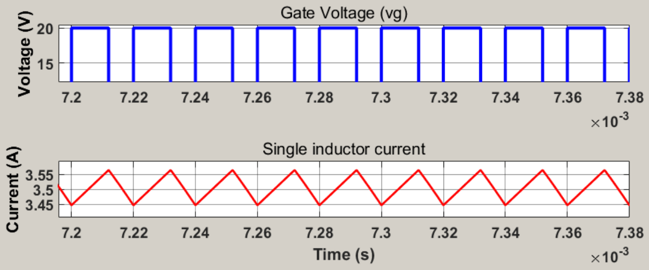


Fig. 3: The charging and discharging states of the inductor matched with Vg

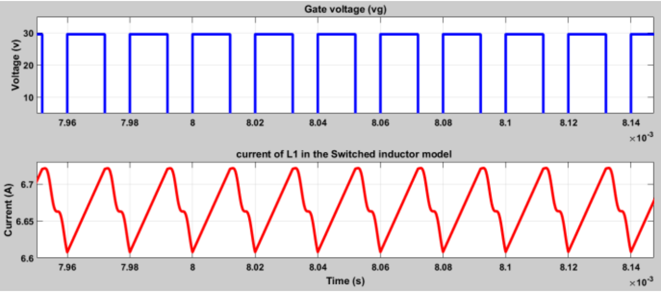


Fig. 4: The charging and discharging states of the one inductor in the SI matched with Vg

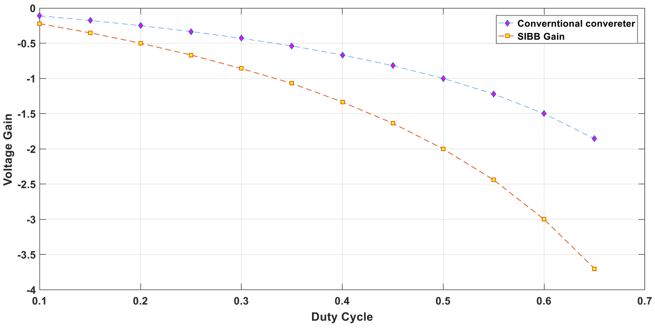


Fig. 5: The voltage gain versus duty cycle of the two compared converters

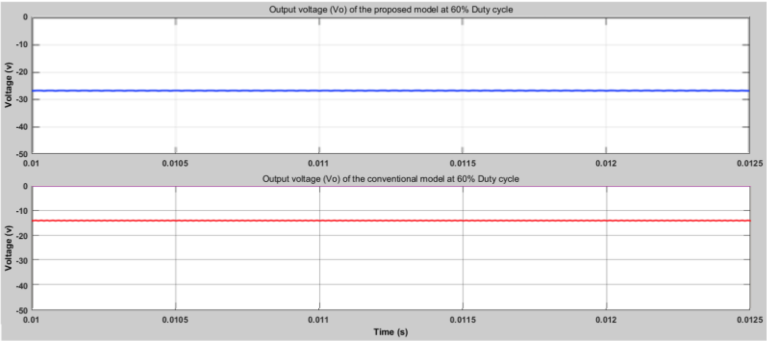


Fig. 6: The output voltage at a 60% duty cycle of the two compared converters

5.1. Remarks

1. Similar to the work suggested (Rosas-Caro et al., 2010), this work uses a switched inductor model instead of a single inductor to increase the converter voltage gain.
2. Referring to the main application of the buck-boost converter in controlling the PV system, the proposed model is faster than the conventional model.
3. The work (Rosas-Caro et al., 2010) used one inductor to implement the conventional buck-boost converter; however, this work used two inductors.
4. The two inductors in this work are connected to the source through a switch that allows these two inductors to behave as additional input sources.
5. From a practical point of view, the switching states of the three switches achieve higher gain at a lower duty cycle.

6. Conclusion

In order to investigate the fundamentals of the design, such as V_{out}, I_{out}, and D, we used MATLAB/SIMULINK. Both increased voltage gain and less switch voltage stress were the result of the proposed SIBB. Due to the fact that the non-isolated converter consists of only a single switch, which is an essential component, this design was effective in assisting in the reduction of the switch voltage stress that is normally experienced. The suggested switched inductor converter has demonstrated not only a reduction in stress but also an improvement in voltage gain, which ultimately results in an increase in V_{out}. Both the simulated and the theoretical results have exhibited certain inconsistencies, and these inconsistencies are connected to the parasitic components that are present in all inductors, capacitors, and semiconductor elements. The proposed model was evaluated in comparison to the conventional buck-boost model. A 10-V supply operating at 50 kHz f_{sw} and a 60% duty cycle were used to power the proposed model. V_{out} has been successfully achieved with lower D when compared to the conventional model.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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