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An Integrated Boost-Sepic Higher Static Gain DC-DC Converter for Photovoltaic (PV) Based Micro-Grid Application

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ABSTRACT
A new circuit topology is designed for a DC-DC converter. The proposed converter employs a single power switch which integrates a conventional boost with a single-ended primary inductor converter (SEPIC) for photovoltaic (PV) panels. A prototype is developed and implemented for 105 V DC output from 9 V DC input. The performance of the proposed topology was validated using theoretical and practical verification. The results indicated a higher voltage gain of 11.67, low duty-cycle of 0.82 and reduced voltage stress across the components of about 54 V. The circuit can be used for PV panels and other renewable energy resources that require a DC-DC voltage step-up conversion ratio.
Keywords: DC-DC step-up Converter, Photovoltaic (PV) panel, Voltage gain, Duty-cycle and Voltage stress.

INTRODUCTION
Carbon-neutral society can be achieved by switching from fossil fuels to renewable energy power resources (Isah *et al.*, 2019). This energy transformation is capable of enhancing the economy, bring resilience to disasters and help the rural communities to access electricity with less compromisation to their environments (Isah*et al.,* 2020). Solar power is one of the naturally available, clean and cheap energy resources that require the use of photovoltaic (PV) panels for electricity generation (Gopi and Sreejith, 2018; Engin and Çak, 2016).
PV panels harness the sun in the form of electromechanical energy and convert it into electrical energy through the use of solar cells (Oulad-abbou *et al*., 2019; Ahmad et al., 2019; Jiang *et al*., 2016). Weather conditions and areas for installations are some of the significant factors affecting the performances of PV panels (Kuo *et al*., 2015). PV system of electricity generation can either be for grid connection or micro-grid connection (Kuo *et al*., 2015; Öztürk *et al*., 2018).Usually, the grid connection requires utility substations. For that reason, a lot of PV panels are required to construct solar farmland, which in turn occupy an extensive area meant for agricultural practices and other purposes, whereas micro-grid or sometimes called off-grid system is for domestic and industrial purposes which can be installed on the rooftops and can easily be affected by the shadow of trees and tall buildings. PV panels are naturally known to generate a low voltage in nature, which is not sufficient for energy storage or inverter applications (Kumar *et al*., 2017). This means there is an increasing demand for energy every day, and voltage per PV generating unit is proportionally low (Engin and Çak, 2016). Hence, there is a need for adaptation of power converter technology.

A power converter can be used to step-up low dc voltage generated by the PV panel into a desired output dc voltage value. There are two types of the power converter, they are; DC-DC and DC-AC (H-ossain and Rahim, 2018). The former can be placed at the back of the individual PV panel or anywhere in between the panel and storage device to act as an impedance unit to the PV panel. The latter could serve as an inverter connected between the storage device and grid lines. The DC-DC converters are subdivided into isolated and non-isolated (Amir *et al*., 2018).The isolated converters require the use of a transformer, examples are; fly-back, push-pull among many others (Fathabadi, 2016). Fly-back is the most widely used and its topology is well exploited in the literature due to its simplicity and higher power efficiency (Fernão *et al*., 2017; Imam*et al*., 2019). Also, it has a mode of operation with other non-isolated buck-boost converters, but its disadvantage is higher voltage gain depend on the duty-cycle and turn ratio of the transformer(Gopi and Sreejith, 2018). Non-isolated converters don't require transformer and higher voltage gain depend on duty-cycle only. Examples of transformer-less non-isolated DC-DC converters are; Boost Converters, Interleaved, Switch Capacitor with Switch Inductor among many others.

There are many types of boost converters with some of their topologies already exploited in the literature and were realized by either utilizing switch capacitor, integrating two or three converters or incorporating them with voltage multiplier cells (Ajami *et al*., 2015; Kumar *et al*., 2017; Saravanan and Babu, 2017; Rizky *et al*., 2018). Comparatively, low voltage gain, higher duty-cycle and higher switching stress across the semiconductor devices have been the problems of every presented converter (Fernão *et al*., 2017;Saravanan and Babu, 2017; Sabzali *et al*., 2014).The conventional boost converters can achieve a higher voltage gain at the expense of a higher duty-cycle which can cause complexity within the semiconductor components (Gopi and Sreejith, 2018; Engin and Çak, 2016). The single-ended primary inductor converter (SEPIC) can achieve a moderately low duty-cycle with low voltage stress across its components but the voltage gain is believed to always be low (Oulad-abbou *et al*., 2019; Ahmad et al., 2019).The switch capacitor with switch inductor converters can achieve a higher gain with a low duty-cycle but the stress across the semiconductor is believe to be too much (Tewari and Sreedevi, 2018; Axelrod *et al*., 2003). Cuk is too expensive and besides, it has higher stress across the active components (Taghvaee *et al*., 2013). This means that, it is hard to design a converter with high voltage gain, low duty-cycle and less stress across the semiconductor components, it had to suffer at least one of the three mentioned factors (Navamani *et al*., 2016).

There are lots of works presented by many researchers to solve the aforementioned problems. Some topologies utilize voltage multiplier cell Saravanan and Babu, (2017), switch capacitor Ajami *et al*., (2015) while others utilize two or three converters being integrated (Pires., 2016; Kumar *et al*., 2017).The double boost integrated with a single-ended primary inductor (SEPIC) converter proposed in Sabzali *et al*., (2014) has a higher voltage gain with a relatively good duty-cycle, but the stress across the components was believed to be too much for the converter. The DC-DC converter reported in Pires *et al*., (2016)by joining boost with self-lift Cuk has a moderate duty-cycle value with relatively low voltage gain. A boost-boost combination in Ching-ming *et al*., (2017) has a reasonable duty-cycle value. However, the voltage gain value is low. A triple combination consisting of Boost-SEPIC integrated with Cuk reported in Kumar *et al*. (2017) has a good value of voltage gain with a low duty-cycle. However, the voltage stress across the components deemed too high.

This paper presents a single switch DC-DC step-up converter built by adding some components of single-ended primary inductor converter (SEPIC) to the conventional boost converter (boost-SEPIC) for PV and other renewable applications. The proposed topology utilizes one power switch with increased voltage gain and low voltage stress within the semiconductor components. This topology will take 9 V DC voltage as input and generate 105 V DC as output.

MATERIALS AND METHODS

Materials

The new converter was built with two inductors (L_1& L_2), two diodes (D_1& D_O), three capacitors (C_1, C_2& C_O), one power switch (S_W),a load resistor (R_L), Dx9 socket and pulse generator. Components are considered ideal because they were selected from the datasheet. The components were purchased at MICA electronics Ltd, Kano. Nigeria.

Methodology

The proposed circuit in Figure 1 was constructed by integrating a conventional boost with a SEPIC converter. In modification to the method adopted by Kumar *et al.*, (2017), the Cuk converter there has now been removed to make the new topology cheap and the negative terminal of C_2 has now been placed between the L_2 and D_o which extend the voltage gain of the present study. This method also altered the one presented in Saravanan and Babu, (2017) hereby substituting the voltage doubler used there with a conventional boost converter. After the realization of the circuit, Multism version 11.0.1 was used to run the simulation of the proposed topology. After that, a Trainer (TPS 3371) was employed to validate the output of the proposed converter in the laboratory.

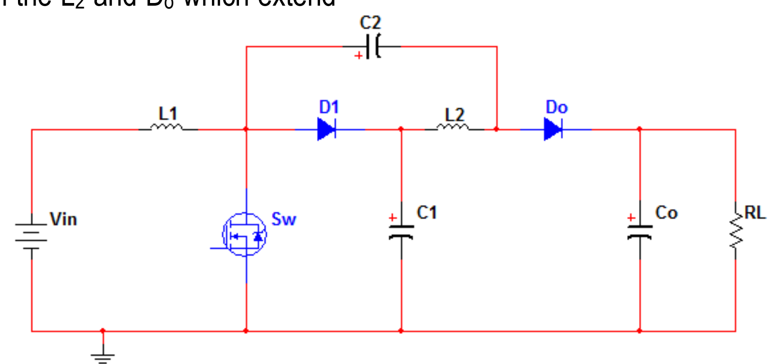

Figure: 1: Proposed topology.

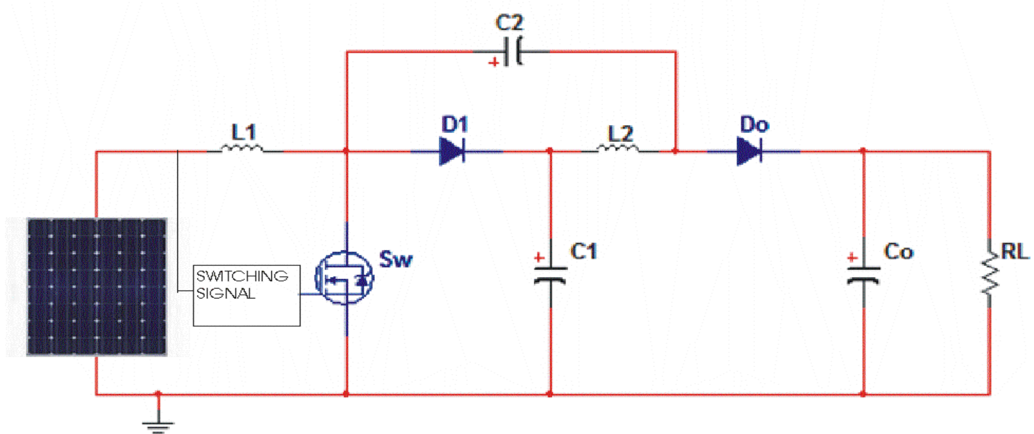

Figure 2: Proposed topology with the PV panel.

Operation Principle of the Proposed Topology under Continuous Conduction Mode:

Stage 1:

When switch $s_w$is turned ON, inductors L_1& L_2 stores energy and their current will increase linearly. Diode D_1 will charge capacitor C_1 while diode D_o will be reverse bias. Capacitor C_2 will receive energy from the switch and capacitor C_o will discharge to the output.

Stage 2:

When switch s_w is turned OFF, inductors L_1& L_2will discharge energy and their current will decrease linearly. Diode D_1 will be reverse bias and diode D_o will deliver energy to the capacitor C_o.

THEORETICAL ANALYSIS

The theoretical analysis of a conventional boost converter can be written as viz:

$V_i \partial T = (V_o - V_i)(1-\partial)T$ (Rashid., 2001) (1)

$V_i \partial T = \left(V_{C_O} - V_i\right)(T - \partial T)$ (2)

The theoretical analysis of the present study can be computed using Figure 1,

$V_{in} = V_{L1}$ (3)

$V_{sw} = V_{C1} = V_{C2} = V_{L2}$ (4)

Where: V_{in} = input voltage; V_{L1} =voltage across L1; V_{sw} =voltage across the switch; V_{C1} =voltage across C1; V_{C2} =voltage across C2, V_{L2} =voltage across L2;

The average current passing through inductor L1can be computed as viz;

$\Delta I_1 = \frac{V_{in}\partial}{f\,L_1}$ (Saravanan and Babu, 2017) (5)

The current passing through inductor L2 can be computed as;

$\Delta I_2 = \frac{V_{C1}(1-\partial)}{f\,L_2}$ (6)

Though, $C_O$represents the capacitor for the SEPIC converter but the voltage it contains is a sum of the boost and SEPIC combined. That is;

$V_{CO} = V_{C1} + V_{C2}$ (7)

From equation (3), it means that$V_{C1}$is the output voltage of the boost converter and V_{C2} is the output voltage of the SEPIC converter. The sameequation (3) can be rewritten as:

$V_{BS} = V_B + V_S$ (8)

Where $V_{BS} = V_{CO}$.And V_{BS}means output voltage of the boost and SEPIC converters combined.

Normally, the input/output relationship of the boost converter can be written as:

$V_B = \left(\frac{1}{1-\partial}\right)V_{in}$ as reported in (Kumar *et al*., 2017) (9)

∂ represents duty-cycle.

Thus, equation (7) can be written in terms of the voltage gain of the SEPIC converter as:

$g_S = \frac{V_S}{V_{in}} = \left(\frac{\partial}{1-\partial}\right)$ (12)

$g_B \; and \; g_s$ mean voltage gain of the boost and SEPIC converters

Therefore, combining equation (6) & (8) will give the voltage gain of the new converter as;

$g_{BS} = g_B + g_S$ (13)

That is; $g_{BS} = \frac{V_{BS}}{V_{in}} = \frac{1+\partial}{1-\partial}$ (14)

From equation (10),the duty-cycle of the new converter can be evaluated as:

$\partial = \frac{V_{BS-}V_{in}}{V_{BS+}V_{in}}$ (15)

From equation (10) again, the voltage across the output capacitor can be written as:

$V_{BS} = \left(\frac{1+\partial}{1-\partial}\right)V_{in}$ (16)

RESULTS

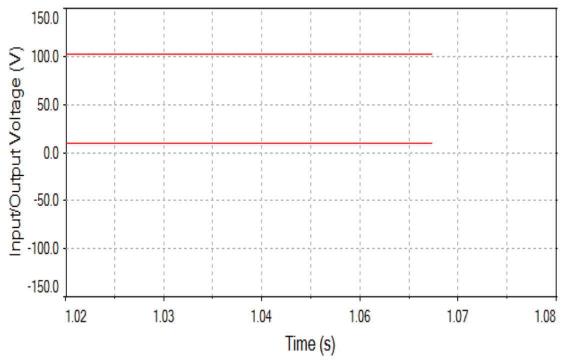

Figure 3: Input and output voltage signals.

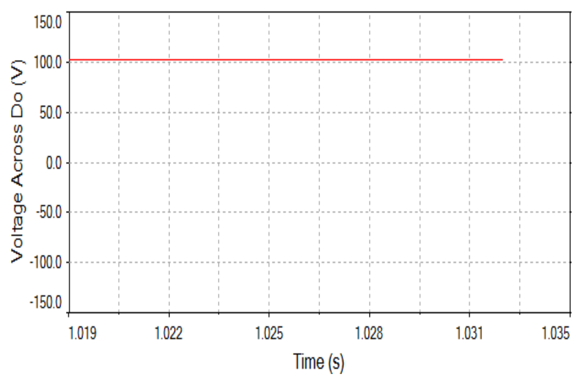

Figure 4: Voltage across the output diode.

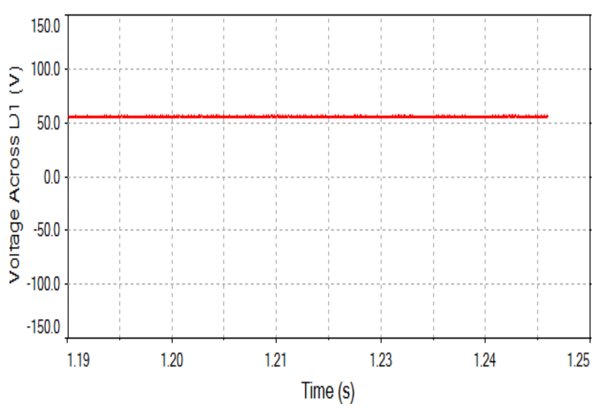

Figure 5: Voltage across diode D_1

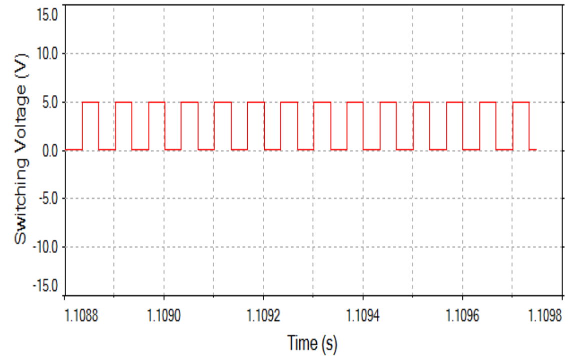

Figure 6: Switching voltage

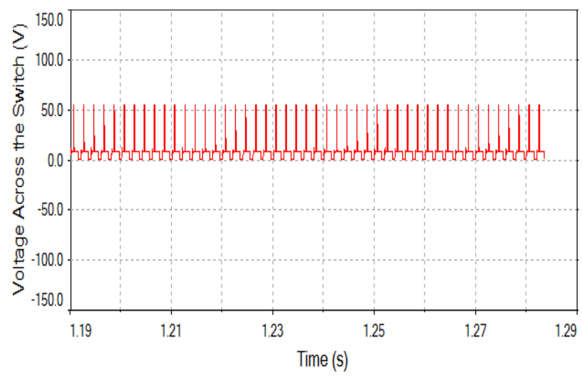

Figure 7: Voltage across the power switch

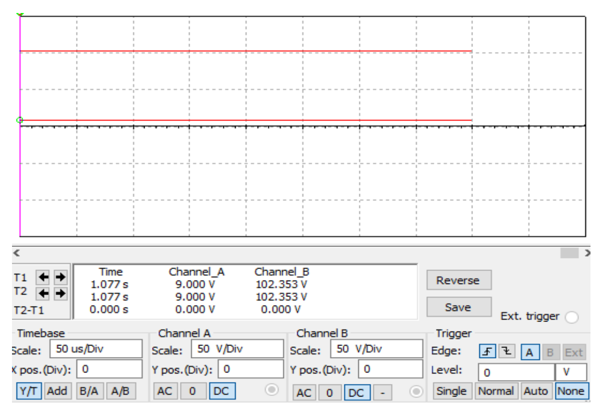

Figure 8: Input and output voltage obtained from oscilloscope using Dx9 socket.

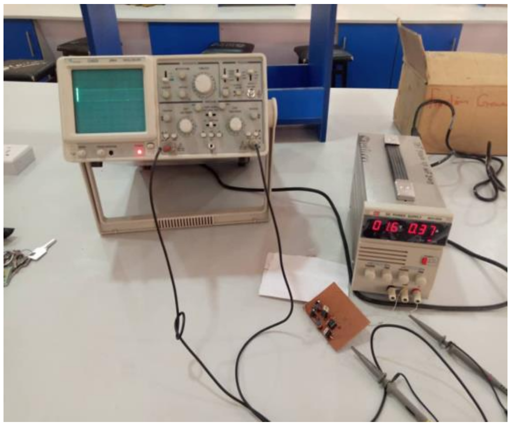

Figure 9: Experimental setup

Table 1: List of components and their values selected from Datasheet

COMPONENTS	VALUE
L_1	205μH
L_2	1 mH
C_1	5μF
C_2	10μF
C_O	200 μF
$D_1 = D_O$	MUR 115
Power Switch	IRFZ48 NS

Table 2: List of parameters and their values obtained from simulation

PARAMETER	VALUE
Input Voltage	9 V
Output Voltage	105 V
Voltage Gain	11.67
Duty-cycle	0.82
Switching frequency	30.3 KHz

Table 3: List of parameters and their values obtained from experiment/theoretical equations

PARAMETER	VALUE
Input Voltage	9 V
Output Voltage	102 V
Voltage Gain	11.33
Duty-cycle	0.83
Switching frequency	30.3 KHz

DISCUSSION

Simulation

Figure 3 represents the input/output signals obtained with a duty-cycle of 0.82 and it can be seen from the said figure that, 105 V DC output was realized from 9 V DC input. This means a voltage gain of $g = 11.67$ is confirmed, which is better than the values reported in (Saravanan and Babu, 2017; Pires *et al*., 2016; Kumar *et al*., 2017). For a free voltage stress converter, half of the output voltage value is expected to cross the active components. From Figures 5 & 7 it can be seen that $54\ V$ DC voltage passed through diode D_1 &active power switch Sw which is slightly above the expected values. This is proof that the voltage stress across the active components of the new converter has been minimized compared to the values reported in (Saravanan and Babu, 2017; Pires *et al*., 2016). Table 1 represents the list of components with their values while the values obtained from simulation are in Table 2. Figure 4 is the voltage across the output diode and Figure 6 represents the switching signal.

Experimental/Theoretical

To validate the simulated results, components in Figure (1) were placed on the trainer's (TPS 3371) PC board in the laboratory. Dx9 USB cable was connected between the trainer's socket and computer USB spot and signal in Figure 8 was generated from the screen. It can be seen from Figure (1) that 102 V DC output voltage was obtained from 9 V DC input value and hence, a voltage gain of 11.33 is confirmed. But according to equation (14), the voltage gain value is 10.11 with a duty-cycle of 0.83 which is obtained from equation (15). These values of voltage gain and duty cycle improve the ones reported in Sabzali *et al*. (2014; Pires *et al*. (2016); Saravanan and Babu, (2017) and Kumar *et al*. (2017). The experimental set up is depicted in Figure 9 and values obtained after the experiment are in Table 3.

CONCLUSION

A boost-SEPIC step-up DC-DC converter has been proposed in this paper. The results obtained shows that pairing boost and SEPIC converters together provide an extended voltage gain withthe reduced value of duty-cycle and the stress within the semiconductor components has been reduced to a minimum. This characteristic has makes the new converter ideal for application in PV panels and other renewable energy resources as shown in Figure 2.

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