Transformerless High Gain Boost and Buck-Boost DC-DC Converters Based on Extendable Switched Capacitor (SC) Cell for Stand-Alone Photovoltaic System

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| **ARTICLE INFO** | **ABSTRACT** |
| *ARTICLE HISTORY:* | This paper presents transformerless high gain boost and buck-boost DC-DC converters (B-BBCs) with extendable switched capacitor cells (SCs), suitable for applications operating at high voltage, above 300 V. Boosting low voltage to a high-enough level, with low duty ratio, is beyond the practical capability of the conventional boost converter. In addition, high duty ratio needed for operation of the boost converter, results in higher component stress that suppresses the overall efficiency of the converter. Therefore, by a convenient integration of SCs with conventional B-BBCs, increased voltage gain is attained with fewer losses. Such converters can be employed for Photovoltaic (PV) systems. The operational principles and modes of operation are analyzed to justify the utility of converters for stand-alone PV systems. Moreover, the proposed modular structure allows to increase SC cells in order to obtain reduced voltage stress on switching components with a higher voltage gain. Simulation and experimental results based on 100 W laboratory prototype extol the theoretical analysis. |
| *KEYWORDS:*  Extendable switched capacitor (SC) cells.  High voltage gain.  Wide input voltage variation.  Lower voltage stress. |

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| **Nomenclature**: | |
| **SC** | Switch Capacitor |
| **SI** | Switched Inductor |
| **B-BBC** | Boost and Buck-Boost Converters |
| **PV** | Photovoltaic |
| **HVT** | High Voltage Transformer |
| **VSB** | Volt–Second Balance |
| **CCM** | Continuous Current Mode |
| **STC** | Standard Test Conditions |
|  | Input Voltage |
| **iL** | Inductor Current |
|  | Duty Cycle |
|  | Sample Time |
|  | Voltage on Capacitor during Forward Bias Condition |
|  | Voltage on Capacitor during Reverse Bias Condition |
| **Q** | Closed Switch |
| **Vo** | Output Voltage |
| **Ro** | Load Resistance |
| **Ron** | Switch Resistance |
| **RD** | Diode Resistance |
| **VD** | Diode Threshold Voltage |
| **RL** | Non-ideal inherited resistive elements corresponding to series inductor |
| **M** | Voltage Gain |
|  | Efficiency |
|  | Output Capacitor |
|  | Change in Inductor current |
|  | Change in Output voltage |
| **Po** | Output Power |
| **PC(tot)** | Losses from capacitors |
| **Vo** | Output Voltage |
| **Io** | Output Current |
| **PD** | Diode power losses |
| **PD(tot)** | Total diode power losses |
| **PMOSFET** | The maximum losses from the switch |
| **PL** | Inductor losses |
| **fs** | Switching Frequency |

1. **Introduction**

Over the past few decades, photovoltaic (PV) systems have been gaining popularity among researchers as an alternative to fossil fuel based power generation systems [[1-6](#_ENREF_1)]. For stand-alone PV system, a voltage source inverter converts the DC power generated by the PV panel into ac power. Since a single PV panel offers less voltage, typically 25-45 VDC [[5](#_ENREF_5), [7-11](#_ENREF_7)], the panels are usually cascaded in series to achieve the minimum voltage requirement. For microinverter stand-alone applications, however, the inverter is connected to a single PV panel, so increasing DC voltage by series connection is not possible. For such application, DC-DC high boost converter needs to be utilized to boost up the voltage [[12-19](#_ENREF_12)].

Such stand-alone PV systems have been presented in [[20-23](#_ENREF_20)]. Where, [[20](#_ENREF_20)] utilizes a high step up DC-DC converter with passive snubbed to reduce the hard switching and attain higher voltage. Here, the added passive snubber circuit decreases the efficiency of the overall PV system, [[21](#_ENREF_21)] utilizes a bidirectional DC-DC converter for the stand-alone DC Nano grid application, where the bidirectional converter being suitable for the application, yet cannot offer a higher voltage above 350 V. Similarly, [[22](#_ENREF_22)] utilizes a push-pull DC-DC converter, yet it remains insufficient for applications operating at a higher voltage (>350V). Similarly, [[23](#_ENREF_23)] utilizes a three-level boost converter for the wind energy conversion system, being suitable for the application, yet the converter is not designed to offer higher output-voltage. In order to realize an optimum performance of such stand-alone applications at higher voltage, modifications are required for converter topology. For such modifications, theoretically, the voltage gain of conventional B-BBCs can be infinitely extended. However, there is a practical limit to voltage gain due to parasitic elements of the power switches, capacitors and the inductors, as well as the reverse-recovery issue of diodes. These factors are responsible for lowering the overall efficiency of the converter. Adding to the list of disadvantages, voltage stresses on the switching power electronic components is equal to the output voltage, which will require power devices with high voltage rating if voltage gain is kept high.

A variety of isolated and non-isolated high-gain DC-DC converters have been proposed. First, isolated type converters incorporate a high voltage transformer (HVT) to achieve a higher voltage gain. However, HVT introduces non-idealities due to its large winding ratio, which can magnify voltage and current spikes, and increases the conduction losses [[24-26](#_ENREF_24)]. Instead of using HVT, coupled-inductor technique can also be used to achieve high voltage gain, by tweaking the turn ratios. However, the leakage inductance can cause unnecessary power loss in the switches, and requires additional clamp circuits for compensation[[27](#_ENREF_27)].

Apart from HVT and inductor based converters, some non-isolated converters achieve high gains based on switched capacitor (SC) technique, which can be found under categories such as voltage-lift [[28](#_ENREF_28), [29](#_ENREF_29)], three-switch high voltage [[30-32](#_ENREF_30)] and voltage multiplier [[33](#_ENREF_33)]. In [[34](#_ENREF_34)], a family of SC-based high voltage gain converters was proposed where the authors demonstrated the principles of achieving boost and buck-boost operation by configuring the position of the SC cells. However, the topologies are not extendable and are only restricted to two stages of SC cell, with limited voltage gain. In [[35](#_ENREF_35)], the authors attempted to improve the work in [[34](#_ENREF_34)] by introducing switched inductor (SI) cells, such that the voltage boosting stages can be extended for higher voltage gain.

The SC based converters for stand-alone PV system application can utilize Maximum Power Point Tracking (MPPT) techniques. An analog and digital classification of such techniques has been presented in [[36](#_ENREF_36)]. In particular, MPPT techniques as the conventional and modified techniques presented in [[10](#_ENREF_10)], optimization techniques as Ant Colony Optimization [[37](#_ENREF_37)], and BAT search algorithm can also be applied with an SC-based converter for MPPT tracking.

This paper demonstrates that by modifying the SC cells, a simple extendable SC-based converter can be obtained based on the topology in [[34](#_ENREF_34)] without using inductors. Analysis on the boost and buck-boost modes of operation is presented, and the impact on efficiency and gain, as the number of SC stage increases, are discussed. The studied topology is able to attain an increased voltage gain without operating at an extreme high duty cycle to avoid large current ripple. Moreover, reduced voltage stress at the switch can be attained and the converter efficiency can be enhanced.

The objectives of this research article are as follows:

1. Explain the operation of the proposed high gain Boost and Buck-Boost converters based on extendable Switch Capacitor cells.
2. Highlight the modes of operation for the proposed converters to justify converter utility for stand-alone PV systems.
3. Comparatively analyse the voltage gain and efficiency of the proposed converters against the conventional converters.
4. Guide for future work on B-BBC with extendable SC cells.

The contents of this paper are presented as follows: Section II explains topology of the proposed high gain B-BBCs based on extendable SC cells. The modes of operations are discussed in Section III, and voltage gain and efficiency analysis are given in Section IV. Subsequently, the simulation and experimental results are shown in Section V to validate prior theoretical discussion before the concluding remarks are made in Section VI.

1. **Proposed High Gain B-BBCs**

The main purpose of integrating SC technique with the conventional B-BBCs is to reduce switch ON time while maintaining the same output voltage. As a result, current ripple at the input as well as across the power devices are reduced, therefore reducing the conduction losses. Furthermore, the problem of reverse-recovery experienced at output rectifier due to short pulse current during extreme duty ratio can also be reduced.

Fig. 1 shows the 2-stage SC-cell based transformerless DC-DC converters introduced by [[34](#_ENREF_34)]. Note that the operation of the



Fig. 1: 2-Stage SC-cell based transformerless DC-DC converters; (a) boost, (b) buck-boost.

converter, either in boost mode or buck-boost mode, depends on whether the SC-cell (highlighted in Fig. 1) is located across the switch or the inductor. While the topology was able to give higher voltage gain than conventional boost and buck-boost converter, the SC-cells are not directly extendable for higher voltage boost.



(a)



(b)

Fig. 2. Proposed extendable SC-cells; (a) Boost SC-cell, (b) Buck-boost SC-cell.

Fig. 2 shows the proposed extendable SC-cells in boost and buck-boost modes, where extended SC-cells are added to the 2-stage SC-cell in Fig. 1. As seen in Fig. 2, each extended SC-cell consists of two diode-capacitor pairs similar to a voltage doubler circuit: one in forward bias manner (CFb and DFb), another in reversed-bias manner (CRb and DRb). However, as will be shown later, the operation of the SC-cells differs from that of the conventional voltage doubler such that the reverse-biased branch is not actively involved in the voltage extension. By increasing the number of extended SC-cells, the boosting ratio can be increased.

Considering the volt–second balance (VSB) on the inductor:

(1)  
 (2)

Each forward boost *CFb* capacitor connected to the SC network adds up a voltage equal to (3) whereas each forward buck-boost *CFbb* capacitor adds up a voltage equal to (4)

(3)

(4)

1. **Steady State Operation of the Proposed B-BBCs**

For the 2-stage SC-cell B-BBCs, a set of two forward capacitors *CFb1* and *CFb2* can be isolated by two forward diodes *DFb1* and *DFb2* and an output voltage twice higher than the conventional can be harvested by connecting the SC-cell between source and the load as shown in Fig. 2.



Fig. 3. Steady state operation waveform for 2-stage SC-cell based B-BBCs.

**3.1.****Operating modes based on 2-stage SC-cells**

There are two operating modes for B-BBCs based on 2-stage SC-cells in continuous current mode (CCM). The steady state operation waveform for the converters is given in Fig. 3, where *VGE* is the gate voltage of the switch *Q*, the current of the inductor is *iL*and the forward capacitor voltages for *C1* and *C2* are shown by *VCFb1* and *VCFb2* curves, respectively.

***Mode 1 [t0–t1]:*** the switch *Q* is closed and the inductor *L* is charged by the input voltage source *VG*. By this configuration, capacitors *C2* and *C1* form a loop in series to supply the load through the closed switch *Q* as presented in Fig. 4a. Thus, the voltage across the series combination of *C2* and *C1* decreases to half.

***Mode 2 [t1–TS]:*** the switch opens and *L* charges forward capacitors *C2* and *C1* via *D1* and *D2* respectively in parallel as shown in Fig. 4b.



(a) (b)

Fig. 4: Current flow of 2-stage SC-cell based boost DC-DC converter, when switch; (a) ON, (b) OFF.



(a) (b)

Fig. 5: Current flow of 2-stage SC-cell based buck-boost DC-DC converter, when switch; (a) ON, (b) OFF.

Similar operations for the 2-stage SC based buck-boost version of the converter, with the respective current path as shown in Fig. 5. The operation of 2-stage SC-cell B-BBCs have been discussed by authors in [[35](#_ENREF_35)], where the authors pointed out that the topology cannot be extended to increase the gains.

In order to allow extendable gain, modified SCs are added to the 2-stage SC-cell as shown in Fig. 6. To form *N*-stage SC-cell, forward capacitors *CFb3…CFb(N)* cannot be connected directly with capacitors *CFb1* and *CFb2*. As seen from Fig. 6, reverse diodes *DRb1…DRb(N)* and reverse capacitors *CRb1…CRb(N)*are connected between each forward extension of SC-cell network. Therefore, the steady state operation of *N*-stage SC-cell based B-BBCs is different from the 2-stage SC-cell based B-BBCs.



(a)



(b)

Fig. 6: Proposed *N*-Stage SC-cell based transformerless DC-DC converters; (a) boost, (b) buck-boost.



Fig. 7. Steady state operation waveform for the proposed extendable SC-cell based B-BBCs.

**3.2.****Operating modes based on N-stage SC-cells**

There are three operating modes for both the B-BBCs based on extendable *N*-stage SC-cell in continuous current mode (CCM). The boost B-BBCs is considered on the steady state operation as given in Fig. 7. *VGE* is the gate voltage of the switch *Q*, the current of the inductor is *iL*and the forward capacitor voltages for *C1* and *C2* are shown by *VCFb1* and *VCFb2* curves, respectively. Moreover, extendable forward and reverse capacitors are shown by *CFb3…CFb(N)* and *CRb1…CRb(N)*, respectively.

***Mode 1 [t0–t1]*:** the switch *Q* is closed and the inductor *L* is charged by the input voltage source *VG*. By this configuration, forward capacitors *CFb1*, *CFb2*, *CFb3…CFb(N)* form a loop in series to supply the load through *Q* as presented in Fig. 8a. Thus, the voltage across the series combination of forward capacitors *CFb1, CFb2, CFb3…CFb(N)* decreases by *Vo/Nb*.

***Mode 2 [t1–t2]:*** voltage of forward capacitor *CF3* increases while voltage of reverse capacitor *CR1*decreases. This mode of operation continues until capacitors *CF3*and *CR1*become equal *VCRb1 = VCFb3*.

***Mode 3 [t2–TS]:*** the switch is open. Due to the fact *VCRb1 > VCFb3*, *DFb3* continues to conduct and *DFb2* remains OFF. Inductor *L* charges forward capacitor *CFb1* via forward diode *DFb1*. Moreover, inductor *L* charges forward capacitors *CFb2* and *CFb3* via forward diode *DFb3* while reverse capacitor *CRb1* discharges. The paths of current flow are shown in Fig. 8c.



(a)



(b)



(c)

Fig. 8: Current flow for extendable SC-cell based boost DC-DC converter, when switch; (a) ON (Mode 1), (b) OFF (Mode 2), (c) OFF (Mode 3).



(a)



(b)



(c)

Fig. 9: Current flow for extendable SC-cell based buck-boost DC-DC converter, when switch; (a) ON (Mode 1), (b) OFF (Mode 2), (c) OFF (Mode 3).

Similar operations can be found for the *N*-stage SC based buck-boost version of the converter, with the respective current path as shown in Fig. 9. Therefore, boost and buck-boost SC-cell based DC-DC converters output voltage; *VbO* and *VbbO* is given in (5) and (6) respectively.

(5)

(6)

Since no SC-stages are connected to the basic B-BBCs, the voltage gain *M* can be given for boost and buck-boost version as in (7) and (8) respectively.

(7)

(8)

Moreover, equation for voltage gain *M* is determined by (9) and (10) for two stage B-BBCs shown in Fig. 2.

(9)

(10)

In addition, the voltage gain *M* of *N*-stage boost and buck-boost SC-cells can be given as in (11) and (12).

(11)

(12)

1. **Voltage Gain and Efficiency Analysis**

**4.1.****Voltage gain and efficiency analysis of basic B-BBCs**

It is necessary to take into account the presence of the parasitic elements as seen in Fig. 10. Theoretically, this can be attained by utilizing VSB and current charge balance (CCB) principles in the continuous conduction mode [[38](#_ENREF_38)].

**4.1.1.****Basic boost DC-DC converter**

As observed in Fig. 10, VSB and CCB of the basic boost converter are given in (13) and (14) respectively:

(13)  
 (14)

Where, *Vo* is the output voltage, *VG* is input voltage, *Ro* is load resistance and *D* is duty cycle. Non-ideal inherited resistive elements corresponding to the series inductor is *RL*, switch resistance is *Ron*, diode resistance is *RD* and diode threshold voltage *VD*have also been considered, as shown in Fig. 10.



(a) (b)

Fig. 10: Equivalent circuits considering parasitic resistive elements for basic boost DC-DC converter.

where static gain and efficiency of basic boost DC-DC converter are expressed by (15) and (16) respectively:

(15)

(16)

**4.1.2.****Basic buck-boost DC-DC converter**

As presented in Fig. 11, VSB and CCB of basic boost converter are given as in (17) and (18) respectively:

(17)  
 (18)

where *Vo* is voltage at the output, *VG* is input voltage, *Ro* is load resistance and *D* is duty cycle. Non-ideal inherent resistive elements corresponding to the series inductor *RL*, switch resistance *Ron*, diode resistance *RD* and diode threshold voltage *VD*have also been considered.



(a) (b)

Fig. 11: Equivalent circuits considering parasitic resistive elements for basic buck-boost DC-DC converter.

Here, static gain of basic buck-boost DC-DC converter is presented by (19):

(19)

Efficiency is presented by (20):

(20)

**4.2.****Voltage gain and efficiency analysis of N-stage SC-cell based B-BBCs**

*N*-stage B-BBCs is shown in Fig. 6. For the same duty cycle given to conventional B-BBCs, the SC-cells allow boost converter to attain an increased voltage at the output. *N*-Stage SC-cells have been employed for high voltage conversion. Equivalent circuit models during each switching mode has been presented in Fig. 12. Here, parasitic resistive elements have also been considered as depicted in Fig. 12. During the ON state, voltage is provided to load through series connected capacitors *CFb1, CFb2…, nCFb*, where voltage drop on each capacitor will be equal; *VCFb1*=*VCFb2*=*VnCFb*. With the capacitor connected in series, voltage drops across each capacitor is *VO*/2+*Nb*, whereas the output voltage *VO* supplied to the load is equal to *VO*=*VCFb1*+*VCFb2*…+*VnCFb*. Observing Fig. 12, voltage drop across *RON*,*RDFb1*and*RDFb2*cancel out each other’s effect due to opposite polarities. During the OFF time as illustrated in Fig. 12b, voltage is supplied to the load through output capacitor *CO*. In addition, forward capacitors *CFb1* and *CFb2*are charged in a parallel fashion, through the inductor *RL*.

**4.2.1. N-stage SC-cell based boost DC-DC converter**

VSB and CCB of the *N*-stage SC boost based DC-DC converter are given by (21) and (22) respectively:

(21)  
 (22)



(a)



(b)



(c)

Fig. 12: Equivalent circuits considering parasitic resistive elements for *N*-stage SC-cell based boost DC-DC converter, switch; (a) ON (Mode 1), (b) OFF (Mode 2), and (c) OFF (Mode 3).

Here, the static gain and efficiency of *N*-stage SC-cell based boost DC-DC converter are given by (23) and (24), respectively.

(23)

(24)

**4.2.2. N-stage SC-cell based buck-boost DC-DC converters**

Fig. 13 presents the ON and OFF switching cycles for *N*-stage SC-cell based buck-boost DC-DC converter. The VSB and CCB have been utilized for determining the voltage across the inductor and current through the capacitor. As given by (24) and (25) respectively:

(25)  
 (26)



(a)



(b)



(c)

Fig. 13: Equivalent circuits considering parasitic resistive elements for *N*-stage SC-cell based buck-boost DC-DC converter, switch; (a) ON (Mode 1), (b) OFF (Mode 2), and (c) OFF (Mode 3).

Here, (27) and (28) gives static gain and efficiency.

(27)

(28)

1. **Parameters Test**

In order to visualize the effect of parasitic elements on extendable SC-cell based B-BBCs, the variations of voltage gain and efficiency against duty cycle are plotted using MATLAB. Table I presents the main parameters considered for simulation and experimental results. For more realistic results, the values of the parasitic elements are selected based on actual components.

TABLE I

Parameters Values

|  |  |
| --- | --- |
| Parameter | Values |
| *VIN* | 25-45 |
| *VOUT* | 380 |
| *fs*(kHz) | 100 |
| *WOUT* | 100 |
| *Ro* | 1250 Ω |

**5.1. Semiconductor components**

MOSFET IXTH 40N30 (with *RDS(ON)*being 0.085 Ω) and diode 30CPF12PbF (*VD* =1.41 V) are used as the power electronic components.

**5.2. Boost Inductor**

The criteria for the inductance selection are to limit the inductor ripple current to 20-40% of the output current. For 100 W system, maximum output current is *iOUT(MAX)*. If we limit the ripple current to 20 % for the input voltage 25 *VDC* the ripple current calculated is *ΔiL* is 0.912 A using (29):

(29)

Input voltage is varied from 25-45 *VDC*. Maximum input voltage is selected as the decrease in duty cycle increases the current ripple. By substituting, ripple current *ΔiL*=0.912 A, switching frequency *Ts*=1/*fs*=10µs into (30) we get inductor value equals to *L*=434 µH.

(30)

**5.3. Output Capacitor**

Following equation was used to select the value of the output capacitor to achieve the preferred output voltage ripple:

(31)

For 100 W system, maximum output current is given by *iOUT(*MAX) and the output voltage ripple *ΔVOUT* is desiredequal to 1%. Therefore, electrolytic capacitor was employed as the output capacitor *CO*withcapacitance 220 μF and ESR equivalent to 0.3 Ω and 450 V voltage rating as the desired output voltage was 380 V.

**5.4. SC-cell Capacitors**

As the switch is closed, the forward capacitors *CFb1*, *CFb2* and *CFb3* are connected in series with the source to supply the load. Moreover, *iOUT(MAX)*isthe average current that all the forward capacitors output to the load while the switch is closed. If 1% voltage ripple *ΔVo* is desired at the output voltage, forward capacitors value is 1µF based on (32):

(32)

1. **Results and Discussion**

## **Simulation Results**

Fig. 14 shows the plots of efficiency (left axis) and voltage gains (right axis) against *D* offered to the considered switch. In addition, voltage gain and efficiency curves are plotted in Fig.14a using MATLAB based on equations (15)-(16) and (23)-(24) for conventional boost and the proposed boost converters (with 2, 3, 4, and 5-stages) respectively. On the other hand, the voltage gain and efficiency curves have been presented with graphical plots, Fig. 14b for the conventional buck-boost and the proposed buck-boost converters (with 2, 3, 4, and 5-stages) based on equations (19)-(20) and (27)-(28) respectively. The parasitic resistive elements considered are *RL*=0.6Ω, *RO*=1250Ω, *RON*=0.085Ω, *RD*=0Ω, and *VD*=1.41V. These values selection is based on the datasheets of the actual components used in the lab prototype, to ensure good correlation between simulation and experiment. All the results were acquired considering the Standard Test Conditions (STC), where the irradiance and temperature were considered to be constant for the PV system.

In general, the voltage gain for all converters increases with the increase in *D*, with a sharp fall as *D* approaches 1 due to the parasitic elements. In contrast, as *D* increases, the efficiency also increases slowly, peaking around 0.8 before falling sharply, again, as the duty cycle approaches 1. It is anticipated that the switch should not operate with extreme duty cycles, so “favorable operation region” should be with duty cycles in the range of (0.5-0.8).

As expected, the voltage gain increases with the increase in the SC stages. However, it is clear from Fig. 14, efficiency of the converter degrades with the increase in SC stages due to the increase in the number of components.

Taking into consideration the values of parasitic elements, the maximum voltage gain is limited to about 14.5 for basic boost, 29 after adding 2-stage SC cell. It can be concluded that the efficiency of basic boost converter is best, when compared with the efficiency of the *N*-stage SC converters due to the lower component count. The efficiency of 3-stage SC based boost converter is reasonably favorable if operated at a duty cycle between 0.5-0.8. However if the objective is to obtain the same voltage gain, the 3-stage SC based boost converter gives the same gain at a lower duty ratio, resulting in compensation of the efficiency with conventional boost converter. Even though the cost of a 3-stage SC boost based converter is more than that of conventional boost converter, it allows enhancement of voltage gain that would otherwise not be practically viable with the basic boost. Considering this point, the trade-off between higher voltage gain and efficiency remains reasonable. In addition, considering the lower voltage stress and reasonable reverse recovery time for active components, the trade-off between cost and high gain remains affordable for number of applications.

## **Experiment Results**

To authenticate the theoretical analysis, mathematical modeling and the simulation results, experiment tests were conducted on a lab-scale prototype. Boost converter extension of SCs to *N*-stages has been taken as preliminary example. It offers high voltage gain with a simple circuit configuration. Fig. 6a presents the circuit considered. For evaluating the impact of the proposed extendable SC techniques, a comparison between conventional boost converter and proposed 3-stage SC boost based converter is held. Prototype is fabricated in the laboratory with a full load of 100 W. Both converters are tested with the same specifications listed in Table I. Experiment waveforms shown in Fig. 15 compare the voltage stress on switch *VCE*, the input inductor current *iL* and the voltage stress on output diode *VDO*. Fixed output voltage *Vo* of 380 *VDC* is extracted from input voltage, varied from 25, 35 and 45 *VDC* at full load, by controlling the ON time *D* offered to switch *Q* as presented in Fig. 15.

The waveforms shown in Fig. 15 show experiment results for basic boost converter and proposed 3-stage SC boost based converter respectively. All the results were acquired considering the Standard Test Conditions (STC), where the irradiance and temperature were considered to be constant for the PV system.

When the input voltage was 25 *VDC*, switch ON time for basic boost converter was 92%, whereas switch ON time of the proposed 3-stage SC boost based converter was 79%. Moreover, when the input voltage was 35 *VDC* the ON time of the basic boost converter was 91%, whereas the ON time of the proposed 3-stage SC boost based converter was 73%. Lastly, when the input voltage was 45 *VDC* the ON time of the basic boost converter was 89%, whereas the ON time of the proposed 3-stage SC boost based converter was 65%. It is obvious in Fig. 15; the ON time for the proposed 3-stage SC boost based converter is less than conventional boost converter. Comparatively, lower inductor ripple current is achieved. The efficiencies of the proposed converter with different input voltages (25, 35, and 45 V) but constant output voltage (380V) are shown in Fig. 17. The results show that the proposed converter has lower efficiency at lower input because of higher conducting loss accompanied by higher input current, due to higher ON time of the switch. The highest system efficiency for 45 *VDC* input voltage appeared 94.86% at *Po*=100 W load as given by (33). The total losses of power, *PD(100W)*, is given by (32). The maximum losses was from the switch; *PMOSFET* = 2.96 W. Losses from diodes equals to *PD(tot)*= 2.1 W. Losses from inductor was *PL* = 0.83 W and losses from capacitors was *PC(tot)* = 0.6 W.

(33)

(34)

 

(a) (b)

Fig. 14: Simulation results to compare voltage gain (M) and efficiency (η) for; (a) basic boost and 2-3-4-5-stage SC based boost DC-DC converter, (b) basic buck-boost and 2-3-4-5-stage SC based buck-boost DC-DC converter.



(a) 

(b) 

(c)

Fig. 15. (left) basic boost, (right) 3-stage SC based boost DC-DC converter. Experiment results to compare input ripple current (iL) switch voltage stress (VCE) and output diode voltage stress (VDO) for (a) input voltage 25 VDC, (b) input voltage 35 VDC, (c) input voltage 45 VDC



Fig. 16. Efficiency comparison between basic boost DC-DC converter and 3-stage SC based boost DC-DC converter (35 *VDC* input voltage).



Fig. 17. Efficiency for 3-stage SC based boost DC-DC converter.

1. **Conclusion**

This paper presents study of high gain B-BBCs based on extendable SC cells. The SC based converters attain a creditable position for stand-alone PV systems operating at a higher voltage level, above 300 V, in comparison to the conventional B-BBCs. The operation principles and modes of operation are analyzed to validate the converters employability with the stand-alone PV system operating at STC. The structure allows to increase SC cells in order to obtain reduced voltage stress on switching components with a higher voltage gain. Using theoretical and simulation approaches, it is validated that voltage gain can be increased by extending the number of SC-stages, but at a cost of reduced efficiency. Compared to conventional boost and buck-boost converter, the benefit of the studied topology is twofold: Firstly, it allows the converter to achieve higher gain that is otherwise not possible in conventional converter. Furthermore, for the same output voltage, it allows the converter to operate at lower duty cycle, which gives significant efficiency improvements compared to conventional converters operating at extreme duty cycles (>90%).

Acknowledgement

The authors would like to thank the financial and technical assistance provided by the University of Malaya and UM Power Energy Dedicated Advanced Centre (UMPEDAC).

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