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Study on High Step-up DC-DC Converter with High Gain Cell for PV Applications

[1*] **Dr. SRINIBASH SWAIN**, [2] **Mr. PRADOSH RANJAN PARIDA,**
[1*] *Professor, Dept. Of Electrical Engineering, NIT BBSR,*
Asst. Professor DEPT. of Electrical Engineering, NIT BBSR,
[1*] srinibashswain@thenalanda.com, , pradoshranjan@thenalanda.com

Abstract

Switching power converters for photovoltaic (PV) applications with high gain are rapidly expanding. To obtain higher voltage gain, low switch stress, low ripple, and cost-effective converters, researchers are creating several topologies. In this work, several High Gain (HG) cells are studied, and the performance of the cells when combined with quadratic boost converters is investigated. We compared the voltage gain, voltage stress and switch utilisation factor, and efficiency of each type of HG cell. The NL5 simulator is used for simulation. In a positive output HG cell, an effective HG cell is identified..

Keywords: DC-DC converter; Topology; High Gain(HG) cell; voltage gain; voltage stress.

1. Introduction

The total installed grid connected solar power capacity in India is about 8 GW as of 2016. Indian government has planned to invest $100 billion to expand the solar plants to 100 GW by 2022. To achieve high efficiency in this Renewable energy system (RES), the energy conversion system should improved by implementing novel and efficient topologies. The high voltage dc-dc converter is presented in the year 1997 with voltage multiplier, and it is advantageous in weight and size compared to conventional switched mode regulator [1]. M. S. Makowski addressed the question relating to the number of circuit elements required to achieve the particular voltage gain [18].

Nomenclature

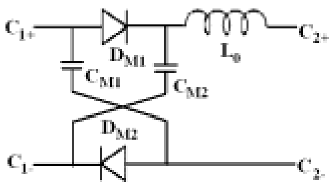
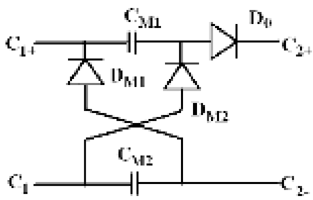
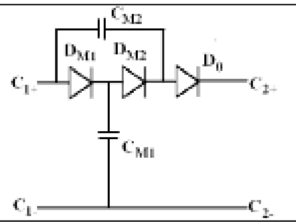
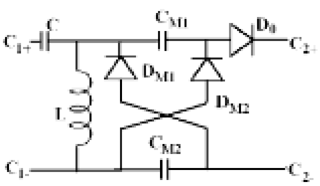
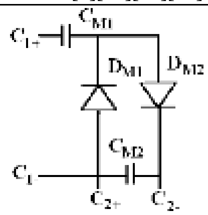
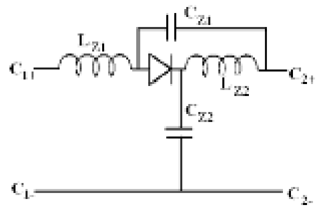
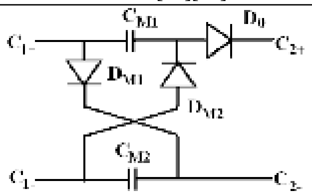
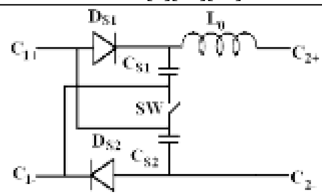
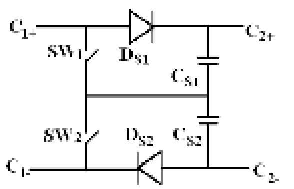
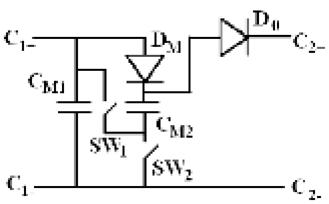
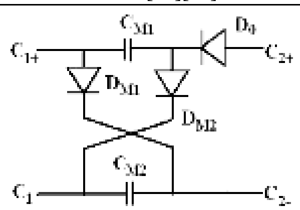
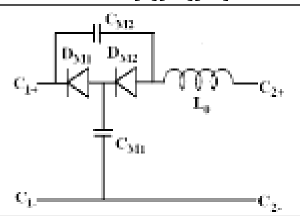
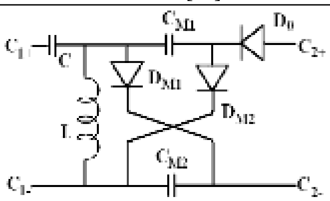
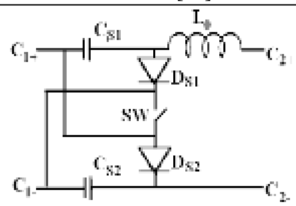
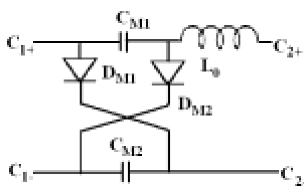
HG	High Gain
PQBHGC	Positive output Quadratic Boost Converter with High Gain Cell
D	Duty cycle
Vo	Output voltage
Vg	Input voltage
V_L	Inductor voltage
V_C	Capacitor voltage
V_{CM}	Multiplier capacitor voltage

For the last decade, many types of research are going on the high gain dc-dc converters. It can be realized by adding High Gain (HG) cell before the output of the converter. Three state switching cells combined with voltage multiplier cell to increase the output voltage. However, the converter is bulky due the presence of auto transformer [3][17]. Zero voltage switching and zero current switching are proposed for the high step-up dc-dc converter with voltage multiplier cell [16]. Leakage inductance in the active clamp coupled inductor based dc-dc converter affects the voltage gain of the converter. This drawback is overcome by combining coupled inductor and voltage multiplier cell which reduces the high pulse current in the voltage doubler cell [8].Modified interleaved boost converter is integrated with voltage multiplier module with dual coupled inductor to balance the primary currents [5].

The most predominately used HG cell are given in Table 1. Table 1 provides different connection of Diode-Capacitor (D-C) cell and Diode-Capacitor-Inductor (D-C-L) cell. Initially used voltage multiplier circuits are Villard, Heinrich Greinacher, Dickson and Cockcroft-Walton circuits to achieve high output voltage. The HGC-2 cell is combined with voltage lift circuit to obtain low voltage stress on the switches [14]. The HGC-3 cell is Dickson multiplier cell and, it is used to derive significant voltage dc-dc converter in [15][23]. In [12] Dickson cell is used along with switched coupled inductor to increase the voltage gain. Diode reverse recovery losses are alleviated in the converter proposed with interleaved three winding coupled inductor with voltage multiplier cell [7]. The HGC-3 cell is integrated with conventional boost converter, and its performance is thoroughly studied in [10]. Ultra step-up dc-dc converter is derived with the HGC-3 cell in [4]. In [10] multiphase dc-dc converter is combined with HGC-7 cell to reduce input current ripple and for proper current sharing in the components of the converters. It is also in the interleaved boost converter with alternating phase shift control scheme [13]. Chung-Ming Young et al, proposed transformerless high step-up dc-dc converter with Cockcroft-Walton (HGC-5) cell for small input dc system [2]. HGC-9 is proposed as the bidirectional dc-dc converter in [6]. HGC-1 and HGC-15 are proposed in [11] for increasing PV cell voltage. HGC-2, 4,11,12,13 are proposed as inverting and non-inverting cell to derive a family of single switch high step-up dc-dc converter [19]. HGC-8 and HGC-14 are presented as four terminals PWM switch to achieve reduced voltage stress in [20]. HGC-10 is a Marx generator and a dc-dc converter is presented on this principle to generate the higher voltage in [27]. HGC-6 is quasi z-source network, -and it is used to derive Step-up dc-dc converters by cascading quasi z-source cell [28].

This paper is organized as follows: Section 1 gives the introduction about the high gain dc-dc converter with voltage multiplier cell. Section 2 provides the general representation of dc-dc converter with HG cell. Section 3 provides the steady state analysis of PQBHGC. Section 4 gives the comparison of different HG cell. Section 5 concludes the work.

Table 1: Various Voltage multiplier cell in literature

HIGH GAIN (HG) CELL		
		
HGC-1[4][9][11][22]	HGC-2[4][14][19][24]	HGC-3[10][4][21][12][15]
		
HGC-4 [19][24]	HGC-5[2][12][15]	HGC-6[28]
		
HGC-7[10][13][25]	HGC-8[20][25]	HGC-9 [6][25][26]
		
HGC-10[27]	HGC-11 [19]	HGC-12[19]
		
HGC-13[19]	HGC-14[20]	HGC-15[11]

2. Analysis of DC-DC converter with HG cell:

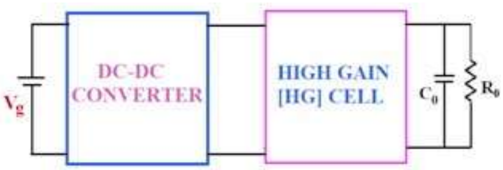


Fig 1: (a) DC-DC converter with HG cell

Fig 1(a) shows the integration of high gain cell to any basic dc-dc converter. The quadratic boost converter is taken for analysis with all the cells regarding voltage gain, voltage stress and other performance related parameters of dc-dc converter. Most of the high gain cell is made up of diode and capacitor. HGC-1-3 and 5-7 is voltage multiplier cell. “M” numbers of cells can be added to the converter to increase the voltage gain. HGC-4, 8, 9 increases the voltage conversion ratio of the converter and only single cell integration is applicable. HGC-1 to HGC-10 gives positive output voltage. HGC-11 to HGC-15 provides the negative output voltage. The theoretical voltage gain of HGC-10 is M, where M is the number of the capacitor in HG cell [27].

3. Steady state analysis of Positive output Quadratic Boost converter with HG cell [PQBHG]:

To study about the positive output Quadratic boost converters in detail, few topologies are taken for analysis and their steady state analysis is carried out to determine their voltage gain with high gain cell. Fig 2 gives the Quadratic boost converter with HGC- 1cell in fig 2(a), HGC-3 in fig 2(b), HGC-4 in fig 2(c) and HGC-8 in fig 2(d).

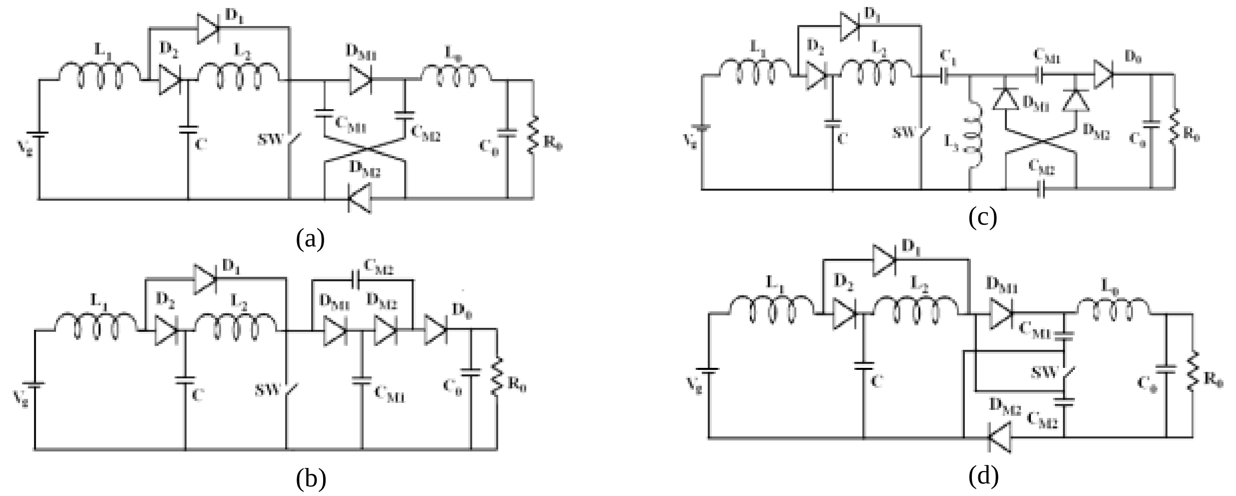


Fig 2: Positive output Quadratic Boost Converter with High Gain Cell (a) PQBHGC-1 (b) PQBHGC-3 (c) PQBHGC-4 (d) PQBHGC-8

PQBHGC-1 & PQBHGC-8 Topology

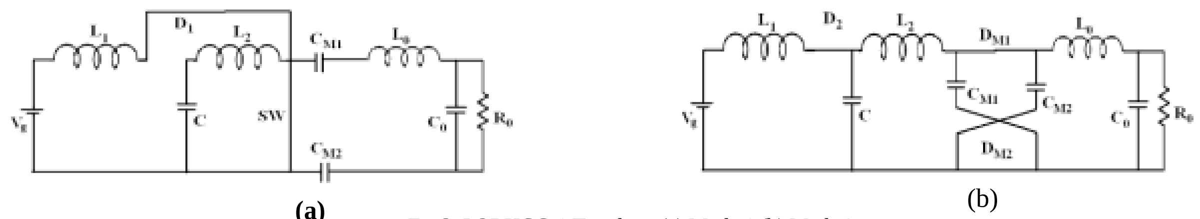


Fig 3: PQBHGC-1 Topology (a) Mode 1 (b) Mode 2

Modes of operation of Positive output quadratic boost converter with HGC-1 and 4 is given fig 3(a) and (b). Single HG cell is considered for PQHGC-1 to simplify the analysis. For PQHGC-8 only single HG cell is applicable. Steady state analysis is carried out by determining the current through the inductor and voltage across the capacitor during the on and off modes.

Voltage across the inductor in mode 1 and 2 is written as

$$V_{L1} = V_g \quad ; \quad V_{L1} = V_g - V_C \quad (1); \qquad V_{L2} = V_C \quad ; \qquad V_{L2} = V_C - V_{CM} \quad (2)$$

$$V_{LO} = 2V_{CM} - V_O \;;\quad V_{LO} = V_{CM} - V_O \qquad (3)$$

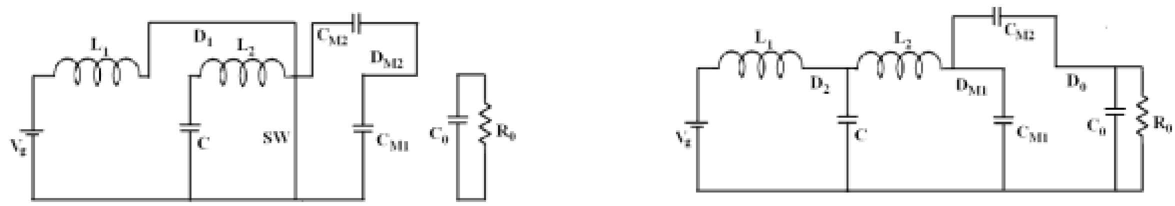
Applying volt second balance on Eqn 1, 2, and 3

$$V_C = \frac{V_g}{[1-D]}; V_{CM1} = V_{CM2} = \frac{V_g}{[1-D]^2} \quad (4)$$

The voltage conversion ratio is

$$\frac{V_O}{V_g} = \frac{1+D}{[1-D]^2} \quad (5)$$

PQBHGC-3 Topology:



(a) (b)

Fig 4: PQBHGC-3 Topology (a) Mode 1 (b) Mode 2

Positive output quadratic boost converter derived with HG cell- 3 is a Dickson multiplier cell. For simplicity, only one cell is considered for steady state analysis and its modes of operation is given in fig 4 (a) and (b).

Voltage across the inductor in mode 1 and 2 is written as

$$V_{L1} = V_g \quad ; \quad V_{L1} = V_g - V_C \quad (6)$$

$$V_{L2} = V_C \quad ; \quad V_{L2} = V_C - V_{CM} \quad (7)$$

$$V_{CM1} = V_{CM2}; \quad V_O = V_{CM1} + V_{CM2} \quad (8)$$

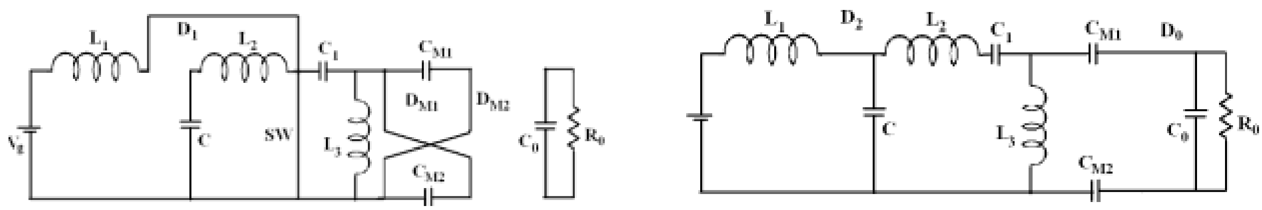
Applying volt second balance on Eqn 1 and 2

$$V_C = \frac{V_g}{[1-D]}; V_{CM1} = V_{CM2} = \frac{V_g}{[1-D]^2} \quad (9)$$

The voltage conversion ratio is

$$\frac{V_O}{V_g} = \frac{2}{[1-D]^2} \quad (10)$$

PQBHGC-4 Topology



(a) (b)

Fig 5: PQBHGC-4 Topology (a) Mode 1 (b) Mode 2

Voltage across the inductor in mode 1 and 2 is written as

$$V_{L1} = V_g \quad ; \quad V_{L1} = V_g - V_C \quad (11)$$

$$V_{L2} = V_C \quad ; \quad V_{L2} = V_C - V_{CM} \quad (12)$$

$$V_{L3} = V_{CM} \; ; \; V_{L3} = 2V_{CM} - V_O \quad (13)$$

Applying volt second balance on Eqn 1 and 2

$$V_C = \frac{V_g}{[1-D]}; V_{CM1} = V_{CM2} = \frac{V_g}{[1-D]^2} \quad (14)$$

The voltage conversion ratio is

$$\frac{V_O}{V_g} = \frac{2-D}{[1-D]^2} \quad (15)$$

4. Comparison of Positive output Quadratic Boost converter with HG cell [PQBHG]:

The comparison of Positive output Quadratic Boost converter with HG cell [PQBHG] is carried out with following specifications: Po = 40 W, Vg = 12 V, fs = 60 kHz, D = 0.5. The information inferred from the Table 2 and 3 are given as follows:

- HGC- 1, 3 and 5 are multiplier cell, and their general voltage gain expression is given in Table 2. The gain of the converter with HGC-4, 8 and 9 cannot be increased with increase in HG cell. The voltage gain of few positive output HG cells are calculated and plotted versus duty cycle and given in Fig 6(a). HGC- 3, 5 and 9 gain is high compared to other HG cell. HGC-5 requires double the HG cell to provide the same voltage gain compared to other topologies. HGC-9 calls for an extra switch to achieve this voltage gain.
- The expression for voltage stress across the active switch is found to be similar to all the HG cell, and it depends on the input voltage and duty cycle. Switch pressure is less for HGC-3 compared to HGC-1 for different duty cycle. Maximum switch voltage versus different output voltage is given in fig 6(d).
- Switch Utilization Factor (SUF) of PQBHGC-3 is 82% of PQBHGC-1 for 96 V and 80% for 266 V. The cost of the active switch and passive switch of PQBHGC-3 is less compared to PQBHGC-1.
- 4.The rating of two inductors in positive output quadratic boost converter with the HGC-3 cell is just 88 and 75 % of the PQBHGC-1. The energy volume of the inductor of PQBHGC-3 is less compared to PQBHGC-1. Table 3 provides the comparative study of passive component rating of PQBHGC-3 and PQBHGC-1. Graphical comparison of energy volume of the inductor is given in fig 7. Therefore, the cost, rating, and volume of PQBHGC-3 are less compared to PQBHGC-1 for different voltage rating and duty cycle. Compared to several HG cell, HGC-3 is efficient compared to other HG cell.

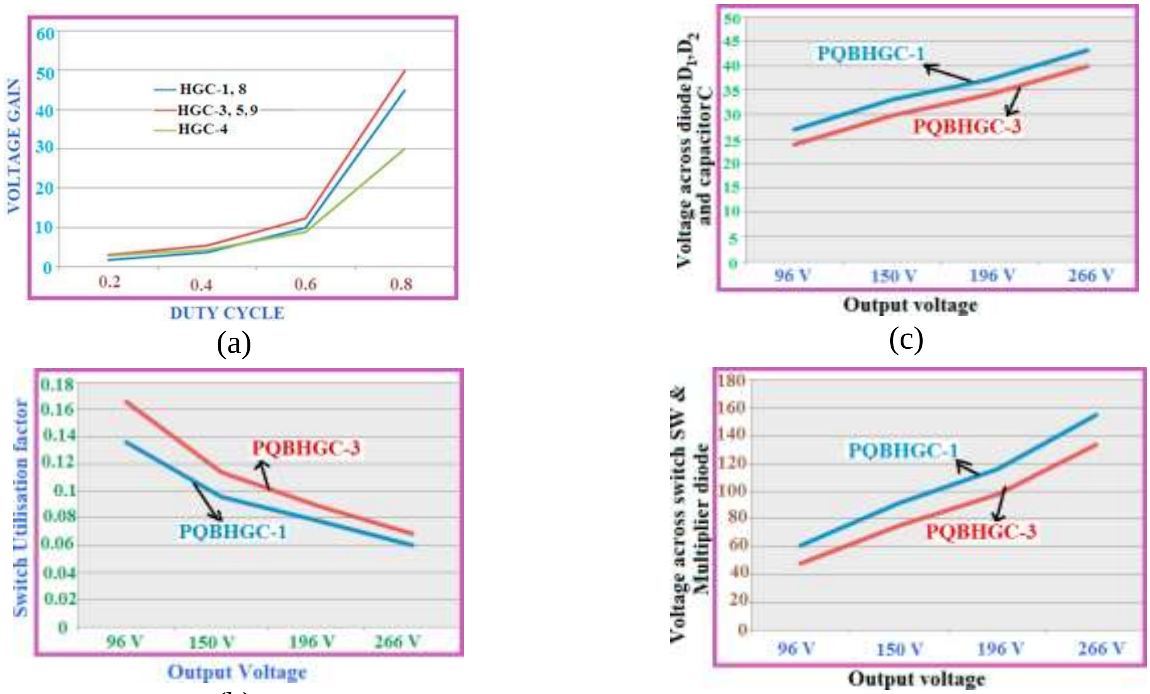
Table 2: Comparison of PQBHGC

Cell	Voltage gain-QB with HG cell	Voltage stress across the switch	Total components in HG cell: Diode	Capacitor	Inductor	Multiplier cell	General voltage gain expression
PQBHGC-1	$\frac{1+D}{[1-D]^2}$	$\frac{V_g}{[1-D]^2}$	2	2	1	√	$\frac{HG+D}{[1-D]^2}$
PQBHGC-3	$\frac{2}{[1-D]^2}$		3	2	-	√	$\frac{HG+1}{[1-D]^2}$
PQBHGC-4	$\frac{2-D}{[1-D]^2}$		3	3	1	X	X
PQBHGC-5	$\frac{2}{[1-D]^2}$ (2 HG cell)		5	4	-	√	$\frac{HG}{[1-D]^2}$
PQBHGC-8	$\frac{1+D}{[1-D]^2}$		2	2	1	X	X
PQBHGC-9	$\frac{2}{[1-D]^2}$		2(1 extra switch)	2	-	X	X

Table 3: Comparison of passive component rating

Topology	Inductor	Design equation of inductor	Output power = 40 W; Vg = 12 V; fs = 60 kHz — OUTPUT VOLATGE: 96 V	150 V	196V	266V
PQBHGC-1	L_1 (uH)	$L_1 = \frac{R_O(1-D)^4D}{2(1+D)^2f_s}$	17	19	20.4	21.4
	L_2 (uH)	$L_2 = \frac{R_O(1-D)^2D}{2(1+D)^2f_s}$	86	146	198	277
	L_O(mH)	$L_0 = \frac{R_0(1-D)D}{2(1+D)f_s}$	0.30	0.66	1.03	1.7

Energy volume (mJ)			0.425	0.466	0.49	0.51
PQBHGC-3	L_1 (uH)	$L_1 = \frac{R_O(1-D)^4 D}{2(HG+1)^2 f_s}$	15	18	19.5	20.8
	L_2 (uH)	$L_2 = \frac{R_O(1-D)^2 D}{2(HG+1)^2 f_s}$	60	112	159	232
Energy volume (mJ)			0.33	0.396	0.42	0.45



(a) (c)

(b) (d)

Fig 6: Performance analysis of PQBHGC (a) Voltage gain Vs Duty cycle. (b) SUF Vs Output voltage (c) Diode voltage Vs Output voltage. (d) Switch voltage Vs Output voltage.

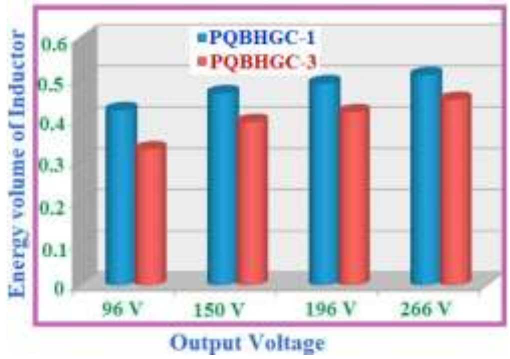
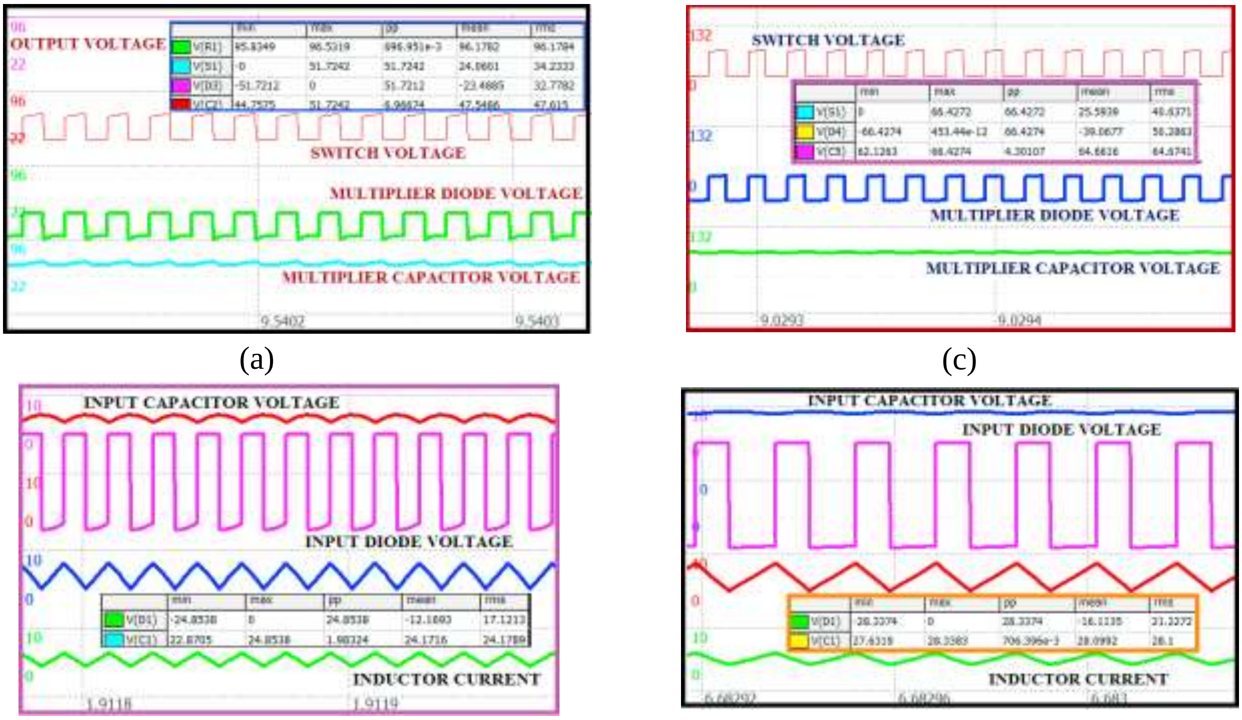


Fig 7: Energy volume of inductor Vs Output voltage

Simulation is carried out with the nl5 simulator, and the results are presented in fig 8. Fig 8(a) and (b) provides the simulation results of PQBHGC-3. Fig 8(c) and (d) provides the simulation results of PQBHGC-1. The following information is inferred from the results obtained, and it validates the mathematical calculation of the compared topology:

- PQBHGC-1 achieves the voltage gain 8 with the duty cycle of 0.566.

- With the same voltage and power rating, the stresses across the components in PQBHGC-1 are high compared to PQBHGC-3. Voltage stress across the switch, multiplier diode, and capacitor in PQBHGC-3 is 75% of the voltage obtained in PQBHGC-1 as given in fig 8(a) and (c).
- Maximum voltage across input diode and input capacitor voltage in PQBHGC-3 is 87% of the voltage obtained in PQBHGC-1 as given in fig 8(b) and (d).
- Input inductor current waveforms are presented in fig 8(b) and (d) and ripples are found to be less in PQBHGC-3.



(a) (c) (b) (d)

Fig 8: Simulation results (a), (b) Waveforms of PQBHGC-3. (c), (d) Waveforms of PQBHGC-1

5. Conclusion:

This paper conducts and presents a study on High Gain (HG) cells. The voltage stress across the active switch is lessened by the HG cell. As a result, the active switch can be used with low Rds(on), which lowers the switch's conduction loss. For PQBHGC-3, simulation data are shown to demonstrate its superiority over other cells. For multiple HG cells using the quadratic boost converter, an expression representing the voltage gain and voltage stress is constructed, and it is confirmed by simulation results. These equations are used to study and analyze the performance of HG cell. Complete and systematic study on positive and negative HG cell reveals that the PQBHGC-3 has following advantage:

1. Higher voltage conversion ratio and it can be further increased by increasing the HG cell.
2. Low voltage stress and switch utilization factor which reduces the cost of the active switch.
3. Less energy volume of the inductor which reduces the cost and size of the converter.

Thus the PQBHGC-3 topology is the best and efficient converter to implement in stand alone or grid connected PV applications.

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