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RESEARCH ARTICLE

INVESTIGATION OF HIGH GAIN SWITCHED CAPACITOR DC-DC CONVERTER FOR PV APPLICATIONS

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ABSTRACT

Photovoltaics (PV) is the fast growing segment among the renewable source of energy owing to the depletion of fossil fuels. But the output of PV module is low. In order to obtain a sufficiently high voltage, a step up dc-dc converter is required. The conventional boost converter experiences switching losses and switching stresses during turn- on and turn-off periods. This paper focuses on the investigation of switched capacitor boost dc-dc converter. The switched capacitor module is selected as it provides high gain, low cost and low fabrication space. Simulation studies are carried out using MATLAB/SIMULINK. A PV panel is used as input to the converter. In order to extract maximum power from the panel, an MPPT algorithm is also used. The resultant module is analyzed and the performance parameters are determined. The simulation results are verified by developing a prototype of the proposed SC

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INTRODUCTION

Solar energy provides much cheap, clean and abundantly available source of generating electric power. The only hindrance is its high installation cost and low conversion efficiency. Therefore, to increase the efficiency and power output of the system, it is necessary to couple PV array with the boost converter of high voltage gain (Leyva *et al*., 2013). The conventional DC-DC converters are normally used for the voltage step-up. But for high voltage gain the duty cycle nearly approaches unity, which may have high impact on conduction loss, switching loss and thus results in low efficiency. To counteract the above mentioned problem, a switched-capacitor DC-DC converter is proposed in this paper. The switched capacitor converter can obtain a high voltage gain. The configuration consists of many capacitors connected in parallel during the charging phase and in series during the discharging phase which results in high voltage gain (Chen *et al*., 2013).
In the literature, a novel method to integrate the boost converter with switched capacitor is proposed which provides an excellent output voltage regulation (Gang Wu *et al*., 2014).

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A few simple switching structures, formed by both two capacitors and two-three diodes (C-switching), or two inductors and two-three diodes (L-switching) are proposed by Axel rod (Axelrod *et al*., 2008). These structures can be of two types: C- and L- switching structures. These blocks are inserted in classical converters: buck, boost, buck-boost, Cuk, Zeta, Sepic. In the paper titled, "Modeling and Simulation of PV array with Boost converter' a converter circuit that delivers constant and stepped up dc voltage to the load irrespective of the variation in temperature and solar insolation levels is investigated. This paper clearly demonstrates the open loop characteristics of PV array and couples PV array with the boost converter displaying the open loop characteristics of varying input current and voltage for variation in loads. The main aim of the paper is to investigate the non-isolated high step up switched capacitor DC-DC converter topology for photovoltaic system and elaborates on the design of the proposed converter. Moreover, the paper focuses on the modeling of PV system and briefly illustrates the theory behind the need to interface the high step up DC-DC converter with PV system. The concept of Maximum power point tracking (MPPT) mechanism is explained and the focus is laid, in particular, on Perturb & Observe (P&O) MPPT algorithm. The simulation studies of the proposed converter are executed in MATLAB.

Performance parameters such as voltage gain, output voltage ripple, input current ripple and voltage stress are calculated for the proposed topology and the results are compared with the conventional boost and integrated switched inductor/switched capacitor boost converter. A laboratory model of the non-isolated switched capacitor boost converter is developed and the simulation results are verified.

Proposed non isolated high step-up switched capacitor dc-dc converter

The switched-capacitor (SC) converter can obtain a high voltage gain, but the input current is pulsating, and the load and line regulation is poor. Meanwhile, the voltage gain is predetermined by the circuit structure (Hsieh *et al*., 2013). By incorporating the switched-capacitor structure into the switching-mode dc-dc converters, the voltage gain can be dramatically increased with appropriate duty cycle while the voltage regulation is achieved and the pulsating input current can be reduced.

The voltage gain of the SC converter is high, but the output voltage is not regulated. The output regulation of the non-isolated switching-mode dc-dc converter is excellent but the voltage gain cannot be too high for achieving a high efficiency. Thus this topology is a combination method of the SC converter and the switching-mode dc-dc converter. The basic approach is introducing multiple capacitors into the switching-mode dc-dc converters. When the switch is off, the energy released from the inductor is used to charge the capacitors in parallel. When the switch is on, the capacitors are connected in series to supply the load (Li *et al*., 2011). Thus, the voltage gain is increased and the duty cycle is decreased, leading to small ripple current and turn-off current of the switch, and a high efficiency can be expected. Meanwhile, the voltages of the capacitors are well regulated, and thus achieving a tightly regulated output voltage. The circuit diagram of the proposed converter is shown in Fig.1.

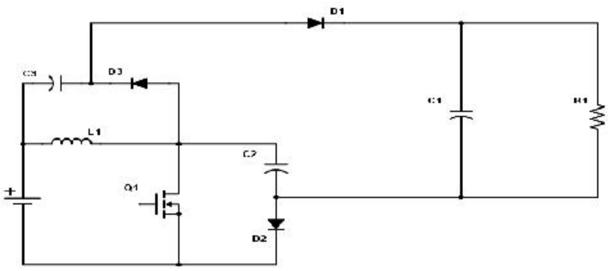

Fig.1. Switched capacitor DC-DC converter

MODES OF OPERATION

When the inductor current is continuous, there exist two operating modes for high step up converter with the single inductor energy storage cell based on SCs derived from boost converter.

MODE 1

The switch Q_1 is in on condition as shown in Fig.2. The input voltage source charges the inductor. The diodes D_3 and D_2 are reversed biased. The capacitor C_2 is in series with the source and C_3 to supply the load with help of switch.

Thus the capacitors discharge in series along with the voltage source producing the large voltage gain

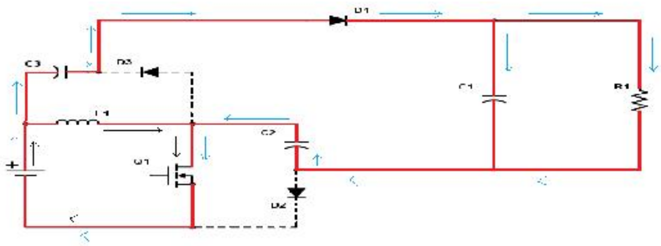

Fig.2. Mode 1 operation of SC DC-DC converter

MODE 2

The switch Q_1 is turned off as shown in Fig.3. The diodes D_3 and D_2 conduct. The inductor charges the capacitors C_2 and C_3 in parallel. The load is powered by the source.

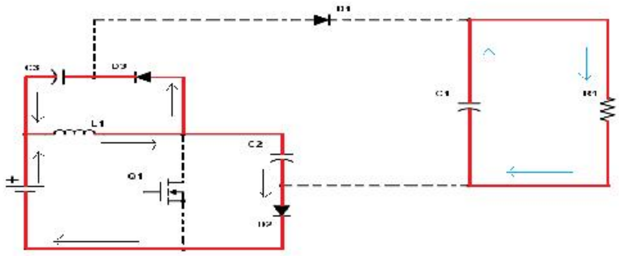

Fig. 3. Mode 2 operation SC DC-DC converter

DESIGN CALCULATION

The design equations of the proposed converter are discussed below:

Voltage gain of the converter

$$M = \frac{V_0}{V_S} = \frac{1}{1-\delta} + \frac{\delta}{1-\delta} + 1 = \frac{2}{1-\delta} \quad (1)$$

Where Vo- Output voltage, Vs –Input voltage,

Output Voltage

$$V_0 = \frac{2V_S}{1-\delta} \quad (2)$$

The ripple in input current ΔI, is 30% to 50% of I_L

ΔI=5A.

And also,

$$\Delta I = \frac{V_S \delta T}{L} \quad (3)$$

For C_2 and C_3

$$\Delta V_{c2} = \frac{I_O T_S}{C_2} \quad (4)$$

$$\Delta V_{c_3} = \frac{I_O T}{C_3} \quad (5)$$

Filter capacitance C_1

$$C_1 = \frac{P_0}{2\pi f_{line} \Delta V_0 V_0} (6)$$

From the above equations, the simulation parameters are calculated.

SIMULATION RESULTS

With the help of the design equations (1)-(6), the following parameters are calculated and used in the SIMULINK model.

Table 1. Simulation parameters of SC high gain converter

Parameters	Value
Input voltage, V_{in}	12V
Inductor, L_1	33.6µH
Capacitor, C_f	9.95mF
Capacitor, C_3	178.571 µF
Capacitor, C_2	125 µF

The SIMULINK model of SC high gain Converter is shown in the Fig.4.

From the table, it can be inferred that the high gain switched capacitor converter has high voltage gain and reduced output voltage ripple compared to other topology. Hence, it is suited for PV applications.

Interface of High gain SC converter with PV

The proposed high gain SC DC-DC converter is interfaced with PV (Pandiarajan and Ranganath Muthu, 2011) and the specifications are shown in Table: 3. The SIMULINK model of PV is shown in Fig.9. The output voltage waveform of the interface of the PV with proposed converter is shown in the Fig.13.P&O MPPT is employed to extract maximum power from PV (Tarek Selmi *et al.*, 2014; William *et al.*, 2014; Hairul Nissah Zainudin and Saad Mekhilef, 2010). The output voltage obtained is 68V.

Development of Laboratory Prototype of High gain SC DC-DC Converter

The prototype of the proposed converter is built by designing the gating circuit and the power circuit. Gate pulse is generated for the COOLMOS switch using Arduino board and the power converter circuit consists of boost inductors, resonant

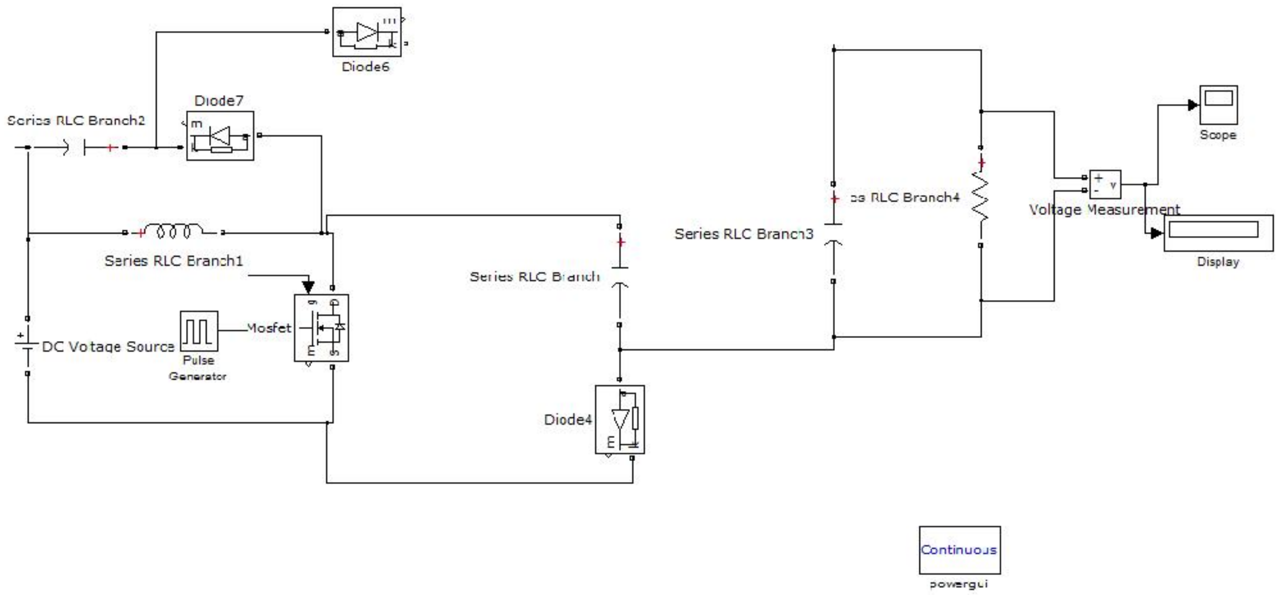

Fig.4. Simulation circuit of SC high gain converter

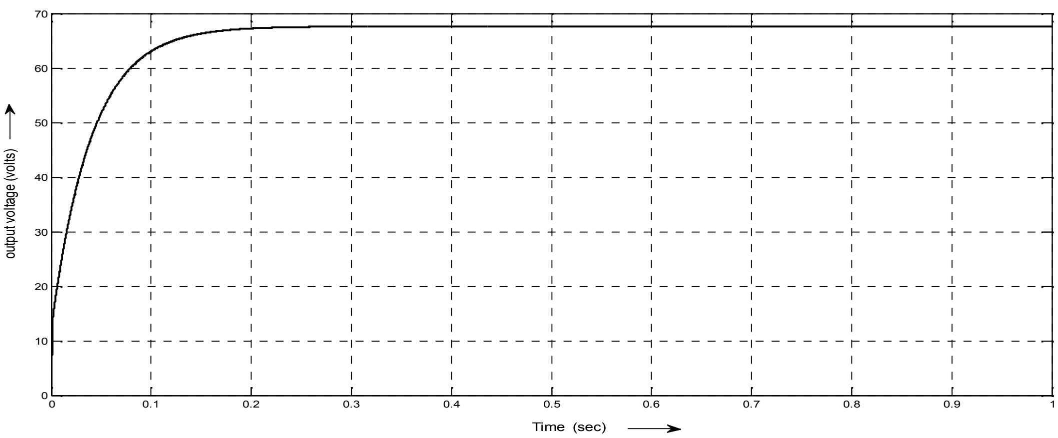

Fig.5. Output Voltage of SC high gain converter

The output voltage obtained is 80V as shown in Fig.5 for an input of 12V.

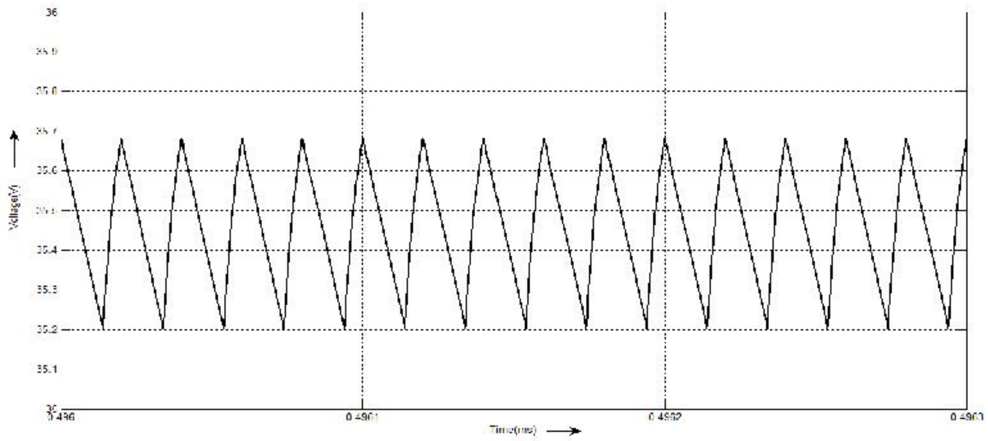

Fig.6. Output Voltage ripple of SC high gain converter

The output voltage ripple obtained is 0.6V as depicted in Fig.6.

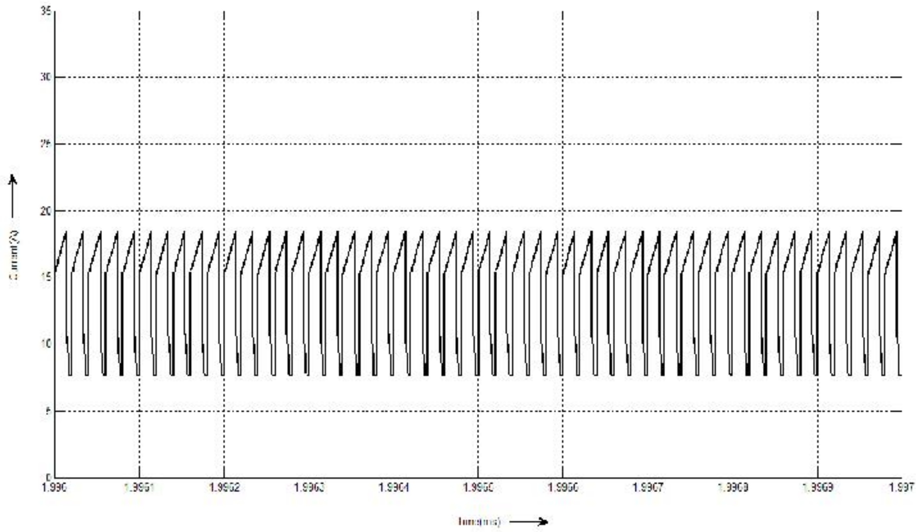

Fig.7. Input Current ripple of SC high gain converter

The input current ripple obtained is 5A as illustrated in Fig.7.

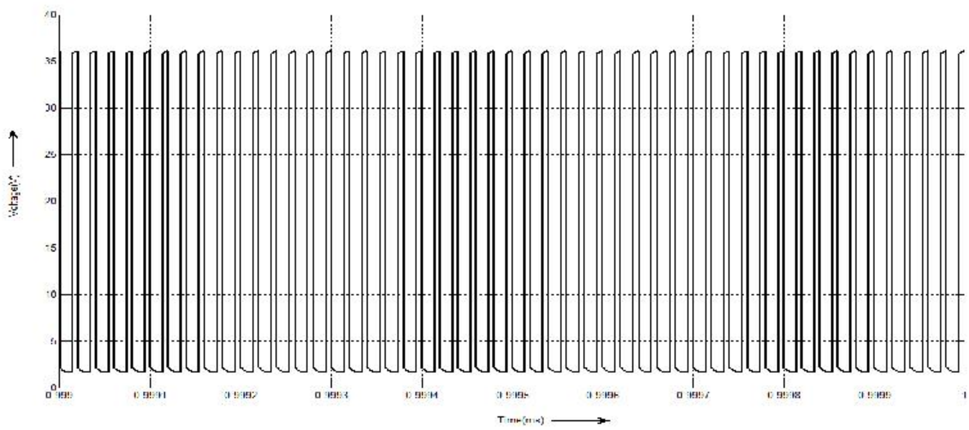

Fig.8. Stress Voltage of the switch SC high gain converter

The stress voltage of the switch is 35.38V which is shown in Fig.8.

Table 2. Comparison of parameters of Boost with Switched capacitor

Parameters	High gain Switched Capacitor topology	Conventional Boost with SC/ Switched Inductor
Voltage Gain	6.66	5.66
Output Voltage	80V	68V
Voltage ripple	0.58V	0.68V
Current ripple	5A	5A
Voltage stress across the switch	35.38V	32.03V

Table 3. PV Panel Specification

Parameters	Value
Open circuit Voltage	21.5V
Short circuit current	1.15A
Maximum Power	20W
Voltage at max power	17V
Current at max power	1.1A

The SIMULINK model of PV is shown in Fig.9.

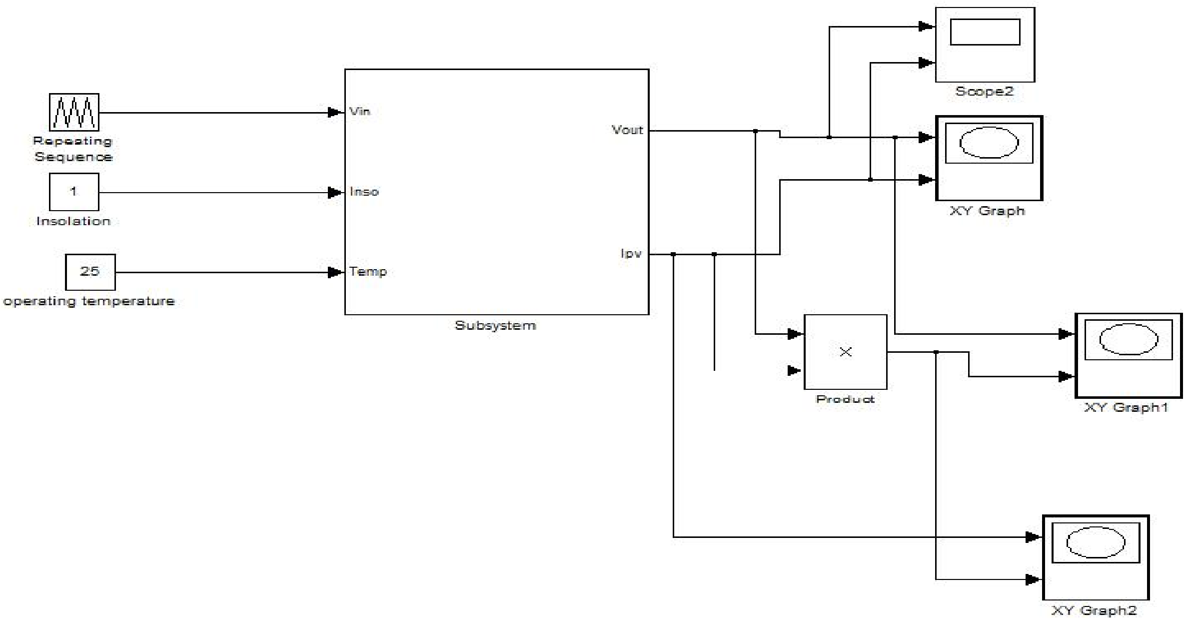

Fig.9. SIMULINK model of PV

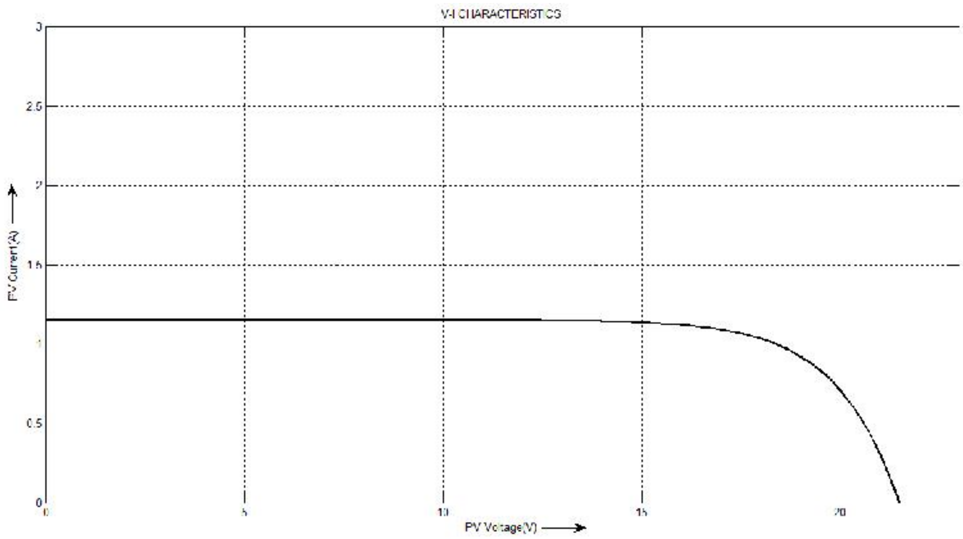

Fig.10. Simulation waveform of V-I characteristics of PV

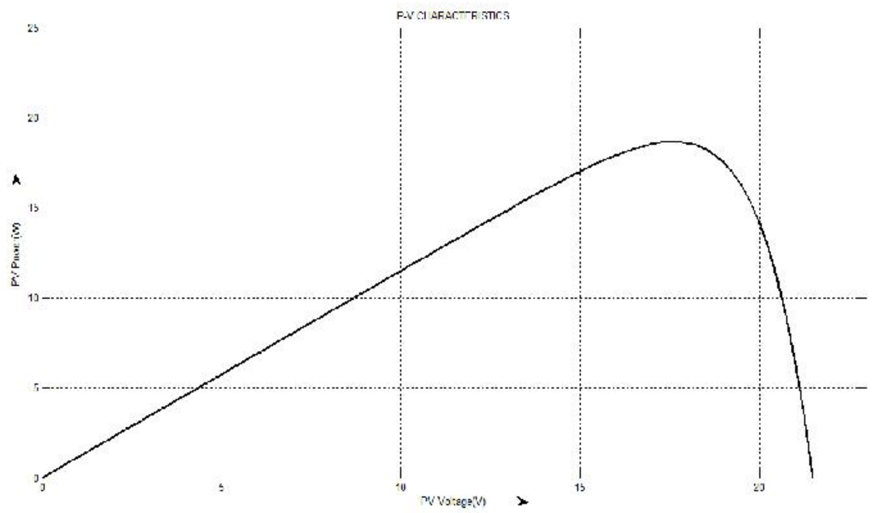

Fig.11. Simulation waveform of P-V characteristics of PV

Figs.10 -11 show the V-I and P-V characteristics of PV.

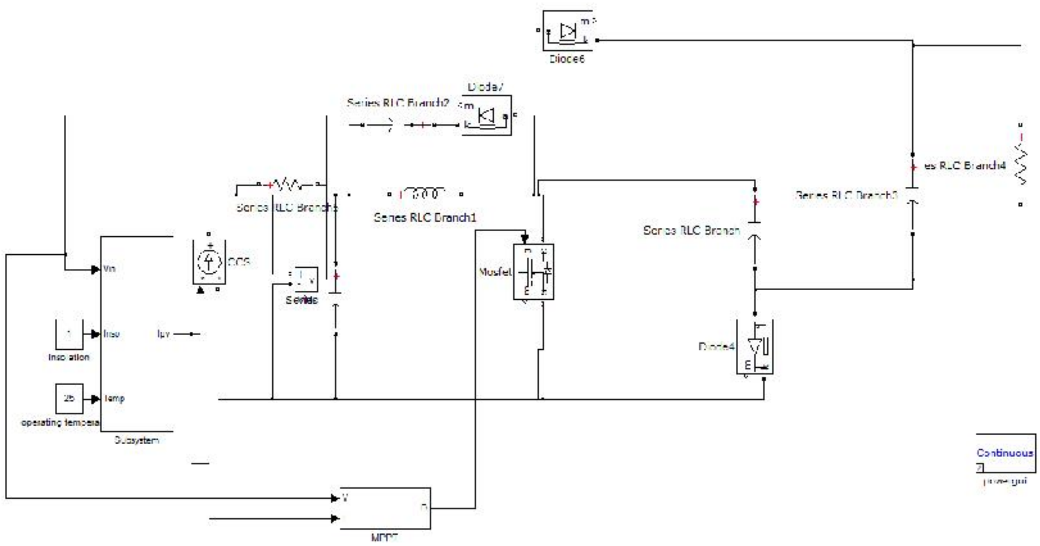

Fig.12. Simulation circuit of SC high gain converter with PV & P&O MPPT

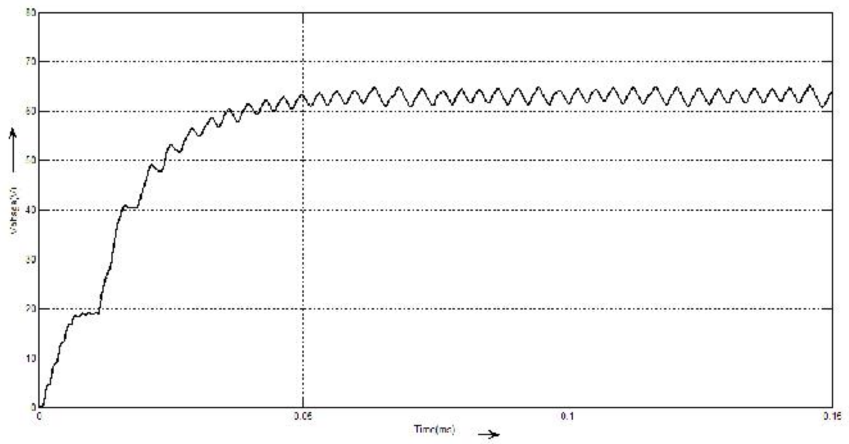

Fig.13. Output voltage waveform of SC high gain converter with PV

The output voltage obtained is 68V.

The gate pulse of the interface of the PV with proposed converter is shown in Fig.14.

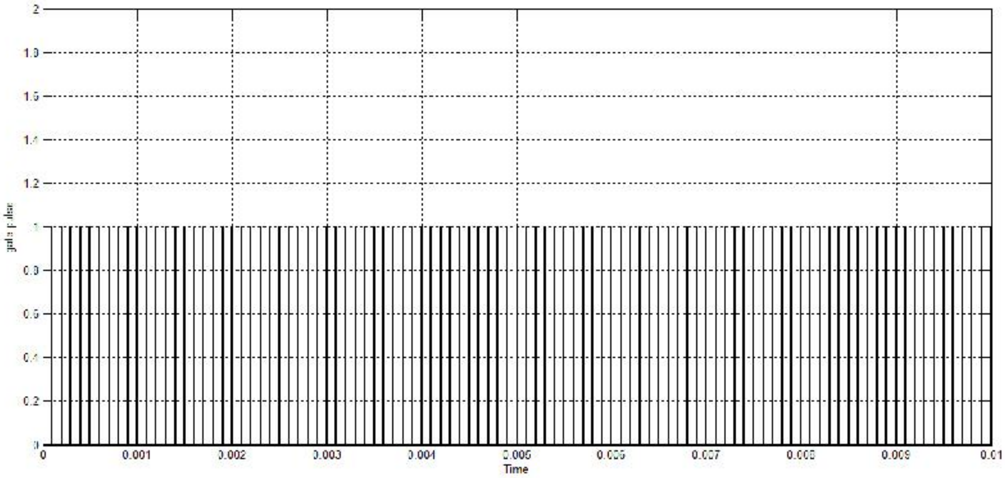

Fig.14. Gate pulse of SC high gain converter with PV

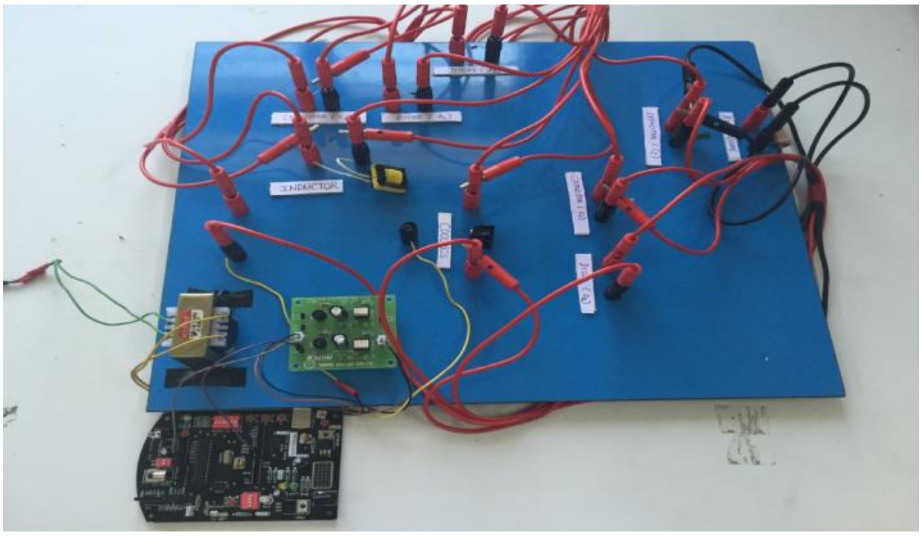

Fig.15. Prototype of the proposed SC

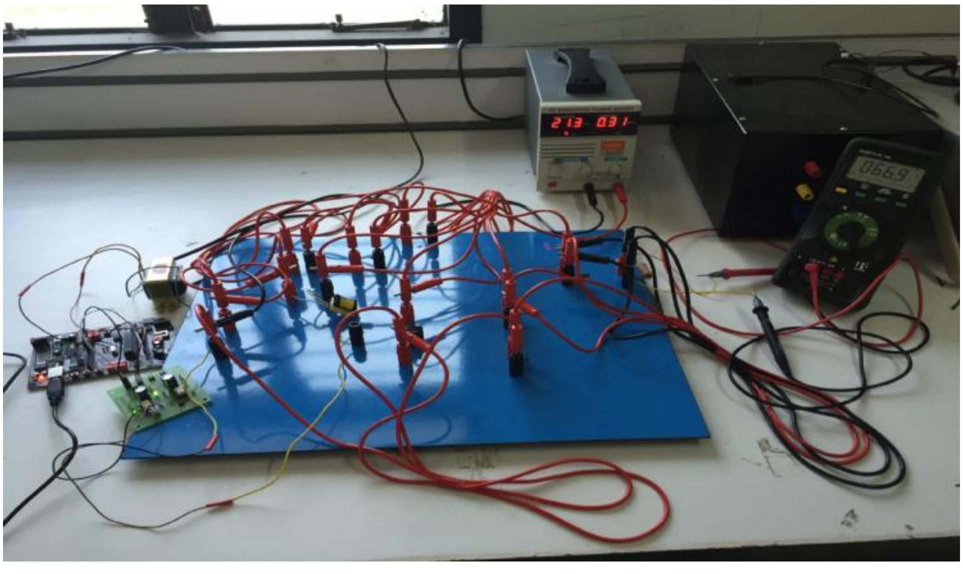

Fig.16. Input and output voltage of the converter

capacitor, cool mosfets, fast recovery diodes, output filter capacitor and output load as shown in Fig.15. The voltage from the input DC source is boosted by the non-isolated high step up switched capacitor DC-DC converter. The complete circuit with converter is shown in Fig.16. For an input of 21V, the output of the converter is 69V. The duty cycle of operation is 50% as sown in Fig.16.

Table 4. Ripple calculation

Simulation Result	Experimental Result
0.6V	0.768V

Table 4 shows that the output voltage ripple is about 0.768V and it is verified with the simulation results.

Conclusion

This paper provides an insight on the use of Switched Capacitor (SC) DC-DC converter for photovoltaic (PV) applications. The primary objective is to obtain high voltage gain from the given duty ratio. This is done by incorporating network of capacitors in the circuit. These capacitors are connected in parallel during the charging phase and in series during the discharging phase thereby resulting in high voltage gain. The SC based converters have many advantages which include, low cost, high voltage gain and it is suitable for the integrated circuit implementation. The SC based cell are introduced in the conventional converters and the voltage gain and several parameters were analyzed of which non-isolated high step up SC converter was found to give high voltage gain for the given duty cycle. This converter is taken to be the proposed converter and it is interfaced with the PV. Since PV installation has low conversion efficiency, we aim to couple boost converter with PV module in order to increase the efficiency and power output of the system. The converter is then interfaced with the low voltage PV module and a maximum power point tracking algorithm is carried to extract maximum incoming power from the PV source. Simulations have been carried out using MATLAB/SIMULINK software with Perturb & Observe MPPT algorithm to achieve high level of converter efficiency. Hardware prototype of the non-isolated high step up Switched Capacitor DC-DC converter was implemented. For the input voltage of 21V, the output voltage obtained is 69V for the duty ratio 50%.

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