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Mathematical Modelling and Analysis of Solar PV Based Modified Quadratic Boost Converter for Extraction of Maximum Power

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Abstract: A dc-dc boost converter is essential for Solar PV system to step up the low voltage to required voltage and for maximum power point tracking from Solar PV panel/array. Boost converters are generally operated with high duty ratio to achieve the higher output voltage. This high duty ratio limits the switching frequency because of high reverse recovery time, also it results poor efficiency and electromagnetic interference. The solar PV based modified quadratic boost converter is proposed in this paper. It offers high output voltage in low duty ratio and thus eliminates the above mentioned drawbacks. Also the voltage stress is less at the same irradiance level compare to solar PV based conventional boost converter. The proposed system is simulated using MATLAB/Simulink. The Perturb & Observe (P & O) algorithm is adopted to ensure the maximum power from the PV panel. A 250W prototype is developed in the laboratory. The simulation and the hardware results validate the performance of the solar PV based modified quadratic boost converter.

Keywords: Solar PV, Boost Converter, Boost Ratio, MPPT technique, Efficiency.

1 Introduction

Global warming, deficit of natural resources and power shortage are the most common problems in the world. The renewable energy based power generation systems such as wind, solar, biomass, biogas, geothermal & etc gives the solution towards the above mentioned problems. Amongst the many non-conventional energy sources country like India depends more on wind & solar energy. This is due to the availability of huge wind and solar potential in almost all geographical locations. The special attention is given to develop solar power based electricity generation nowadays due to the availability of 300 sunny days over a year. The solar panels offers less voltage and fluctuating power throughout the day depends on the environmental conditions [1]-[5]. The less voltage needs to be boosted to required voltage based on the applications and the maximum power to be extracted from the PV panel continuously. A DC/DC converter can be employed for the purpose. High voltage gain, less voltage stress, high efficiency and continuous input current [10]-[11] are the expected parameters in DC-DC converter. The high voltage gain and efficiency is possible only with high duty ratio. But the span of high duty ratio leads to reverse recovery problem in the power switches of the converter and thus limits the switching frequency [12]-[17]. There are many boost converters with different topologies has introduced to overcome the above said issues [6]-[10],[18]-[20]. The new topology is derived by modifying the quadratic boost converter called Modified Quadratic Boost Converter (MQBC) to perform better than other converters [18]. However the topology is not used for any renewable energy based applications. In this work the advantages of this converter is used for solar PV applications. The solar PV based modified quadratic boost converter is simulated using MATLAB/Simulink. The Perturb & Observe (P & O) algorithm is adopted to track the maximum power from the solar PV panel [21]-[23]. The proposed system is compared with the existing boost converter. The prototype of a 250W converter is made. The simulation and the hardware results are given to validate the performance of the solar PV based modified quadratic boost converter. The block diagram of the system is shown in Fig.1.

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The solar PV panel used as an input source for modified

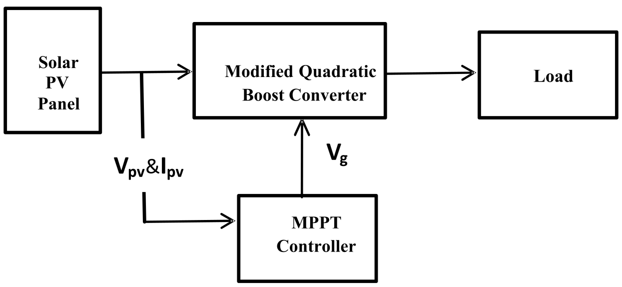


Fig. 1: Block Diagram of Solar PV based Modified Quadratic Boost Converter

quadratic boost converter. The instantaneous voltage and current are continuously measured and given to the controller where the MPPT algorithm is implemented. The gate pulse generated by the controller is given to the power switches gate terminal through the driver board so as to extract the maximum power available from the PV panel.

2 Modeling of Solar Photo Voltaic Panel

The solar PV panel converts light energy into electricity. It comprises of many cells. The equivalent circuit of the practical photo voltaic cell is shown in Fig.2.

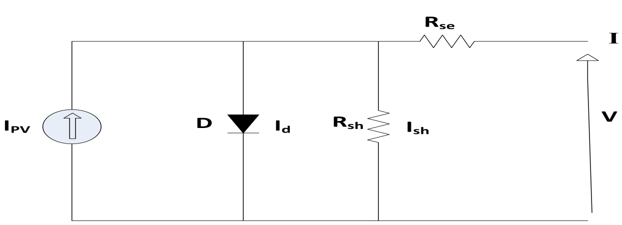


Fig. 2: Equivalent Circuit of a Practical Photovoltaic Cell

The basic equation of the I-V characteristic of the ideal photo voltaic cell is

$$I = I_{pv} - I_0 \left[exp\left(\frac{qV}{akT}\right)\right] - 1 \qquad (1)$$

where,
I_{pv} - Current generated by the incident light
(Directly proportional to the Sun irradiation)
I_d - Shockley diode equation
I_0- Reverse saturation or leakage current of the diode
q - Electron charge $[1.60217646 \times 10^{-19} C]$
k - Boltzmann constant $[1.3806503 \times 10^{-23} J/K]$
$T[K]$ - is the temperature of the $p-n$ junction diode.

The inclusion of the additional parameters to the basic equation of the ideal photo voltaic cell gives the $I-V$ characteristic expression of a practical photo voltaic panel.

$$I = I_{pv} - I_0 \left[exp\left(\frac{V + R_{se}I}{V_t\ a}\right) - 1\right] - \frac{V + R_{se}I}{R_{sh}} \qquad (2)$$

Where, Thermal voltage of the array, $V_t = \frac{N_s kT}{q}$, N_s- Cells connected in series.

Here, the solar PV panel is modeled by using MATLAB/Simulink for commercially available solar panel i.e solar semiconductor (Model; SSI-M6-250) make 250W. The specification of the SSI-M6-250 PV panel is given in table 1.

Table 1: Specification of PV Panel (Solar Semiconductor Model: SSI-M6-250)

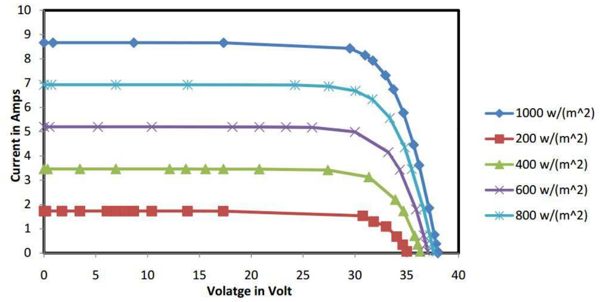
S.No	Specifications	Ratings
1.	Peak Power (Pmax,W)	250
2.	Binning (Wp)	-2,+3
3.	Measurement Tolerance (%)	± 3
4.	Max Power Voltage (Vmp)	30.69
5.	Max Power current (Imp)	8.15
6.	Open Circuit Voltage (Voc)	37.98
7.	Short Circuit Current (Isc)	8.67
8.	Module Efficiency (%)	15.61

2.1 I-V and P-V Curve of PV Panel

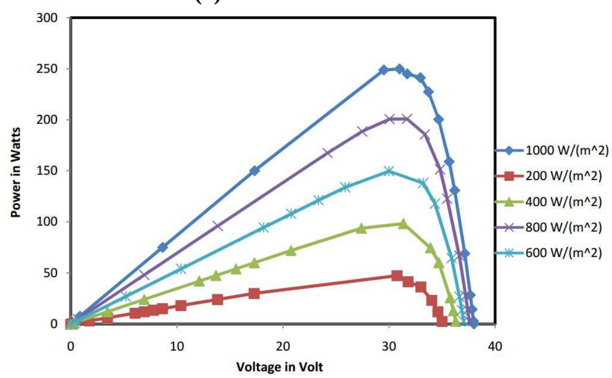
The current- voltage (I-V) characteristics and power-voltage (P-V) characteristics curve of the modeled PV Panel for different irradiance in W/m^2 is shown in Fig.3(a) and 3(b) respectively.
In the characteristics curve of PV panel resemble the parameters specified in table 1 voltage at maximum power (V_{mp}), current at maximum power (I_{mp}), open circuit voltage (V_{oc}) and short circuit current (I_{sc}).
The V-I and P-V characteristics of the modeled PV panel exhibits the characteristics of the commercial available solar panel i.e., solar semiconductor (Model: SSI-M6-250 PV panel).

3 Implementation of MPPT Technique

As found in literature Perturb and Observe (P & O) algorithm offers the better extraction capability of maximum power point from the solar panel. The MPPT controller is modeled using MATLAB/Simulink and the



(a) I-V Characteristics



(b) P-V Characteristics

Fig. 3: V-I & P-V Characteristics of SSI-M6-250

MPPT controller which uses the Perturb & Observe algorithm is track the maximum power from the solar panel by producing the gate pulse with different duty ratio. The PV panels voltage and current are given continuously as inputs to the controller. The MPPT controller continuously varying the width of the gate pulse while irradiance and temperature changing.

4 Analysis of Solar PV based Modified Quadratic Boost Converter

The proposed solar PV based modified quadratic boost converter is shown in Fig. 4.

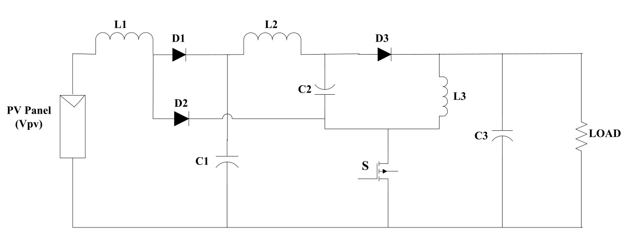


Fig. 4: Circuit Diagram for Solar PV based Modified Quadratic Boost Converter

The steady-state analysis of converter is carried out as following.

Mode 1: When switch is ON:

The equivalent circuit of the converter is shown in Fig.5 when the MOSFET switch is ON. In this period, switch S & diode D2 is ON and diodes D1 & D3 are OFF.

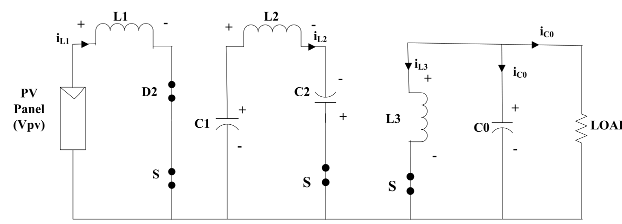


Fig. 5: Equivalent circuit of converter during Switch ON

Mode 2: When switch is OFF:

The equivalent circuit of the converter is shown in Fig.6 when switch is OFF. In this period, diodes D1 & D3 are ON and switch S & diode D2 is OFF and the inductor current decreases. Voltage across capacitor C_1 can be

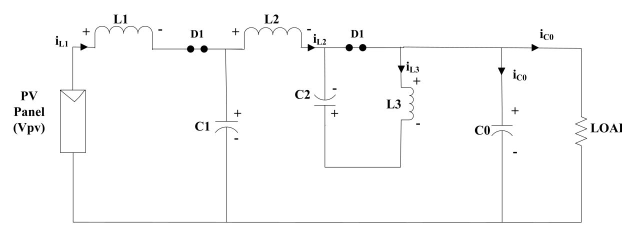


Fig. 6: Equivalent circuit of converter during switch OFF

determined by applying volt-second balance principle on inductor L_1 and is given by

$$V_{C1} = \frac{V_{PV}}{(1-D)} \tag{3}$$

Voltage across capacitor C_2 can be determined from volt-second balance for L_2 and is given by

$$V_{C2} = \frac{DV_{C1}}{(1-2D)} \tag{4}$$

Similarly, voltage across capacitor C_0 can be given as

$$V_0 = \frac{(1-D)V_{C1}}{(1-2D)} \tag{5}$$

The relationship between the input and output voltage of the converter is determined from (3) to (5)

$$\text{Ideal output voltage, } V_0 = \frac{V_{pv}}{(1-2D)} \tag{6}$$

The ideal voltage boost gain is,

$$M_{ideal} = \frac{V_0}{V_{pv}} = \frac{1}{(1-2D)} \tag{7}$$

Non-Ideal Output Voltage,

$$\begin{aligned} V_{ONI} = \frac{1}{1-2D}(V_{pv} - DV_{rL3} - 2DV_{rd3} - V_{rc1} \\ -(1-3D+2D^2)(V_{rC2}+V_{rd3}) - DV_{rd2} - DV_{F2} \\ -V_{rL1} - V_{rd1}(1-D) - V_{F1}(2-2D) \end{aligned} \tag{8}$$

5 Effects on Input Resistance of the Converter for different Duty Cycle

To make the converter suitable for solar PV application it is essential to derive the relationship amongst the input resistance of the converter, load resistance and duty ratio. The relationship is derived as follows,

The output voltage of the converter,

$$V_0 = \frac{V_{in}}{1-2\delta} \tag{9}$$

$$I_{in} = \frac{I_0}{1-2\delta} \tag{10}$$

$$\frac{V_{in}}{I_{in}} = \frac{V_0}{I_0}(1-2\delta)^2 \tag{11}$$

Reflected resistance at input side,

$$R_{in} = R_L(1-2\delta)^2 \tag{12}$$

From (12), the input resistance of the converter can vary by changing the duty ratio. Fig.7 shows the change in R_{in} corresponding to duty cycle range from 0 to 1.

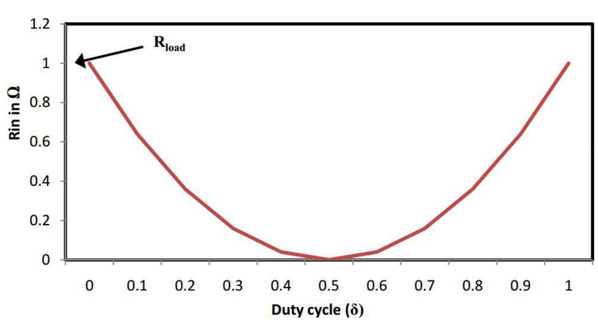


Fig. 7: Relation between duty cycle and input impedance of the converter

R_{in} is varies from R_L to 0 and 0 to R_L for duty ratio 0 to 0.5 and 0.5 to 1 respectively. Whereas, in boost converter R_{in} varies from R_L to 0 for the duty ratio 0 to 1 correspondingly. Since the modified quadratic boost converter offers high efficiency and high boost gain for the duty ratio even below 50%, it doesnt allow to operate more than 50%. Therefore variation in R_{in} is obtained from R_L to 0 between 0 to 0.5 duty ratio ranges.

The solar PV panel is connected as a source to a modified quadratic boost converter. Therefore PV panel output resistance (R_{pv}) will be the input resistance of the converter (R_{in}).

Any point at the I-V characteristics curve,

$$R_{in} = R_{pv} = \frac{V_{pv}}{I_{pv}} = R_L(1-2\delta)^2 \tag{13}$$

To extract the maximum power from the PV panel, R_{in}or R_{pv} should be lies in the knee point of the I-V characteristics curve. At the knee point the voltage and current of the PV panel is V_{mp} and I_{mp}.

At the knee point,

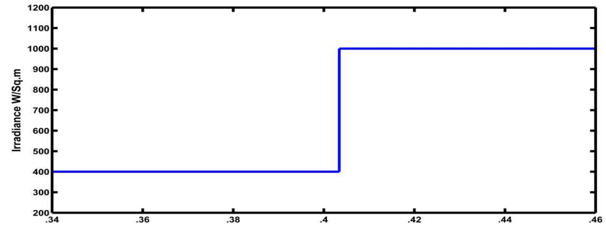
$$R_{in} = R_{mp} = \frac{V_{mp}}{I_{mp}} \tag{14}$$

The R_{in} or R_{pv} can be located at the knee point by controlling the duty ratio of the gate pulse of the converter. This can be done through the MPPT controller. In the solar PV based modified quadratic boost converter the reflected input resistance (R_{pv}) is always be lesser than load resistance (R_L). Therefore, the maximum attainable R_{in} is R_L and it is essential to maintain the condition $R_L \geq R_{mp}$ for the maximum power point tracking.

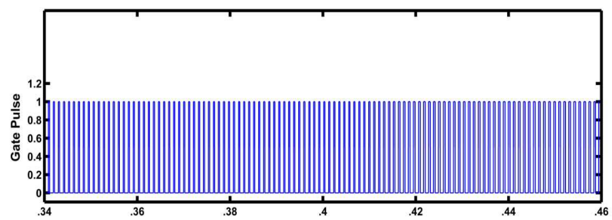
6 Simulation of Solar PV based Modified Quadratic Boost Converter

The Solar PV panel is connected with the modified quadratic boost converter and the P&O algorithm is used as the MPPT technique. The performance of the MPPT controller is analysed by verifies the parameters like duty ratio of the gate pulse generated by the MPPT controller, panel voltage, current and power. Similarly the performance of the converter is analysed through load voltage, current and power. Fig.8(a)-(h) shows simulation results of the gate pulse, panel voltage, current, power, load voltage, current and power for two different irradiance level ie., 400 W/m^2 and 1000 W/m^2. For better understanding of the variations in various parameters the simulation time taken from 0.34 sec to 0.46 sec. The irradiance level 400 W/m^2 is maintained till 0.4 sec subsequently it is changed to 1000 W/m^2.

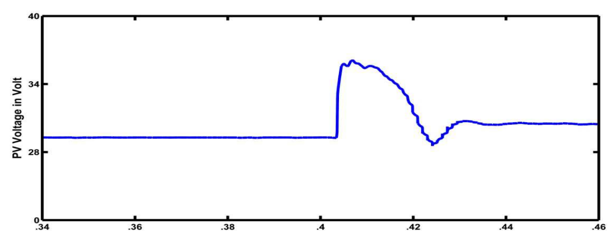
Duty ratio of the gate pulse is varied from 0.15 to 0.35 when irradiance changes from 400 W/m^2 to 1000 W/m^2 respectively. Similarly panel voltage, current and power changes from 30.5 Volt to 32.2 Volt, 1.4 amps to 7.7 amps, 42.7 to 247.9 watts respectively. Table 2 shows the simulation results of PV panel parameters for different



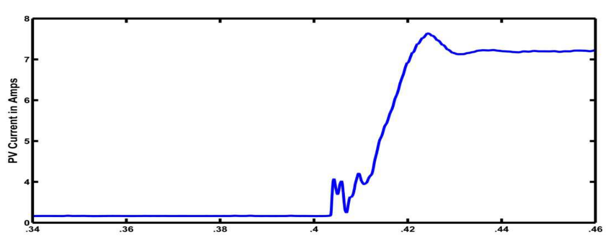
(a)



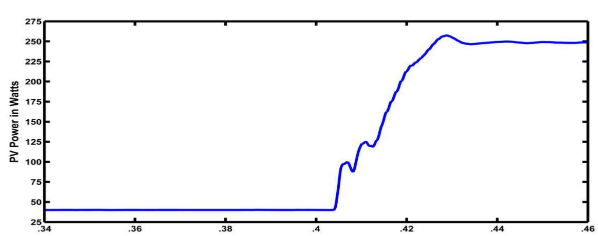
(b)



(c)

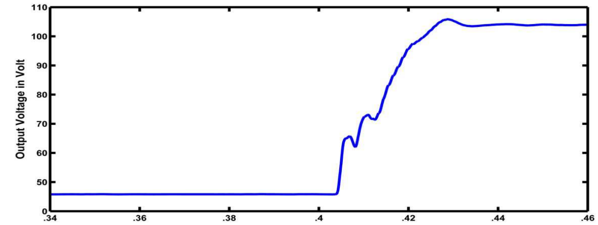


(d)

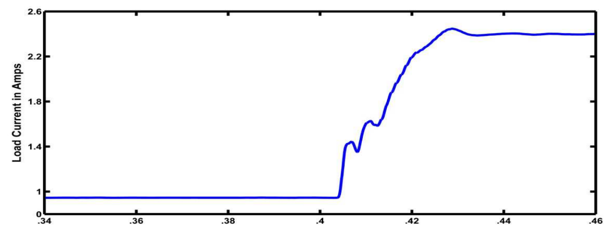


(e)

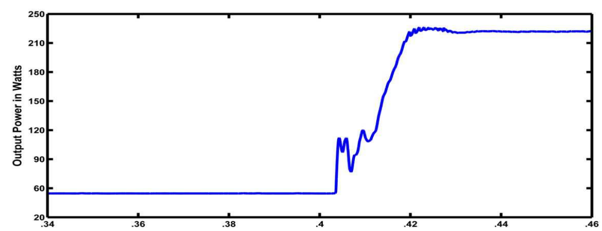
irradiance and table 3 shows the MPPT capability of the proposed system in terms of duty ratio of the gate pulse,



(f)



(g)



(h)

Fig. 8: (a)-(h) Irradiance (G), Gate Pulse of MPPT Controller, $V_{pv}, I_{pv}, P_{pv}, V_{load}, I_{load}$&$P_{load}$ for $G = 400W/m^2$&$1000W/m^2$

maximum power (P_{max}) extracted from the PV panel through MPPT controller and deviation in P_{max}.

Table 2: PV Panel Parameters for different Irradiance

Irradiance (G) in, W/m^2	V_{max} **in Volt**	I_{max} **in Amps**	P_{max} **in Watts**
200	29.9	1.53	45.74
400	30.0	3.13	93.9
600	30.3	4.9	148.4
800	30.5	6.3	192.1
1000	30.7	8.14	249.8

From table 3, when the irradiance increases, duty ratio increases to catch the maximum power from the solar panel. The duty ratio of the gate pulse offered by the MPPT controller is less than the required duty ratio value and therefore extracted maximum power by the MPPT controller is less than the available maximum power of the PV panel. The higher deviation in the maximum

Table 3: P_{max} and Duty Ratio (Converter with MPPT Controller)

Irradiance (G) in, W/m^2	Duty Ration (δ)	V_{max} in Volt	I_{max} in Amps	P_{max} in Watts	Deviation P_{max}
200	0.15	30.5	1.4	42.7	3
400	0.25	31.4	2.9	91.0	2.9
600	0.3	31.7	4.6	145.8	2.6
800	0.33	31.9	5.95	189.8	2.2
1000	0.35	32.2	7.7	247.9	1.9

power tracking is 3 Watt. The output parameters of the converter for various irradiance is given in table 4.

Table 4: Output Parameters of the Converter for different Irradiance

Irradiance (G) in W/m^2	Duty Ratio (δ)	P_{pvmax} in Watts	Output Voltage (Vo) in Volts	Output Current (Io) in amps	Output Power (Po) in Watts	Efficiency (η)in %
200	0.15	42.7	40.7	0.95	38.66	90.5
400	0.25	91.0	59.5	1.39	82.70	90.8
500	0.3	145.8	75.8	1.76	133.40	91.4
800	0.33	189.8	87	2.02	175.74	92.5
1000	0.35	247.9	99.8	2.32	231.53	93.4

When irradiance changes from 400 W/m^2 to 1000 W/m^2 , Load voltage, current and power changes from 40.7 Volt to 99.8 Volt, 0.95 amps to 2.32 amps, 38.6 watts to 231.5 watts respectively. And the efficiency varies from 90.5 % to 93.4 %.

6.1 Voltage Gain

Voltage gain is the ratio between output voltage to the input voltage of the converter. The formula for the output voltage of the solar PV based modified quadratic boost converter is given below,

$$V_0 = \frac{V_{pv}}{(1-2\delta)} \tag{15}$$

Fig.9 shows the simulated values of the output voltage of the converter for different irradiance.

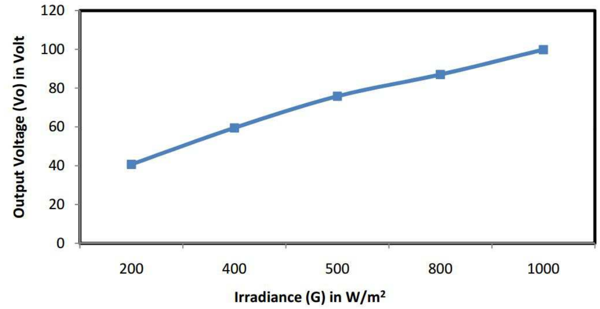


Fig. 9: Output voltage for different Irradiance

6.2 Voltage Stress of the Switch

The frequent turn on and turn off of the switch generates voltage stress. The voltage stress across the switch in the converter is directly proportional to the duty ratio. When the voltage stress increases, the losses in the converter are also increased drastically. The voltage stress across the switch is given by

Voltage Stress,

$$V_s = \frac{(1+\delta)V_{pv}}{(1-2\delta)} \tag{16}$$

Voltage stress across the switch for each duty ratio is shown in Fig.10.

In the proposed system, voltage stress is always high than the output voltage. It is (1+ δ) times higher than V_o.

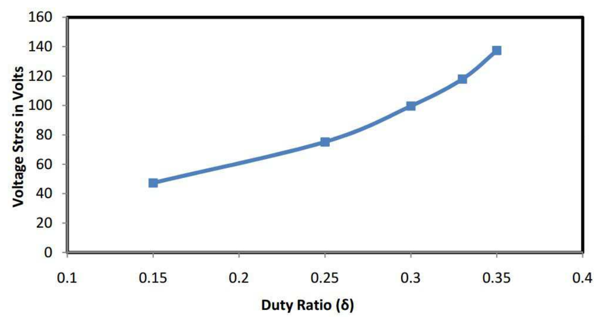


Fig. 10: Voltage Stress for different Duty Ratio

6.3 Efficiency

Efficiency is defined as the output power to the input power of the converter.

$$\eta = \frac{P_{out}}{\rho_{pv}} \tag{17}$$

Fig.11 shows the relationship between irradiance and efficiency of the converter.

From Fig.11 there is a variation in efficiency of the converter for different irradiance. When irradiance increases efficiency is slightly increased.

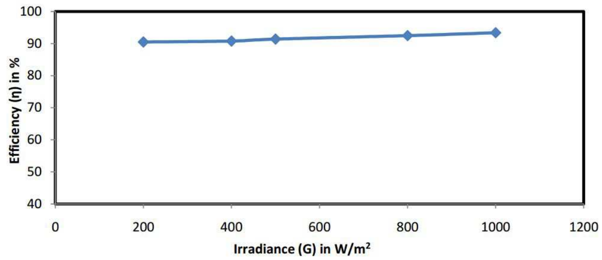
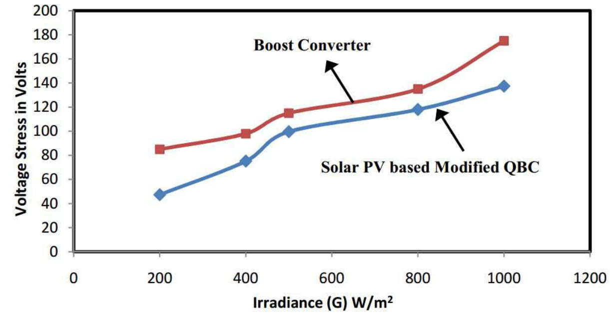
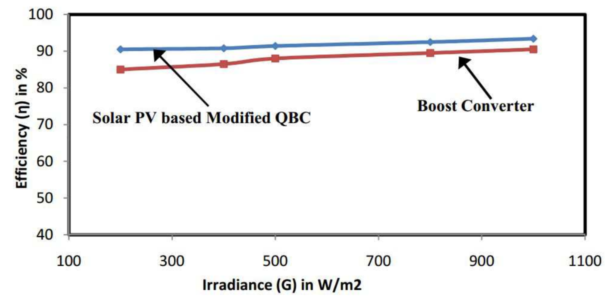


Fig. 11: Efficiency of Solar PV based Modified Quadratic Boost Converter



(c) Irradiance Vs Voltage Stress

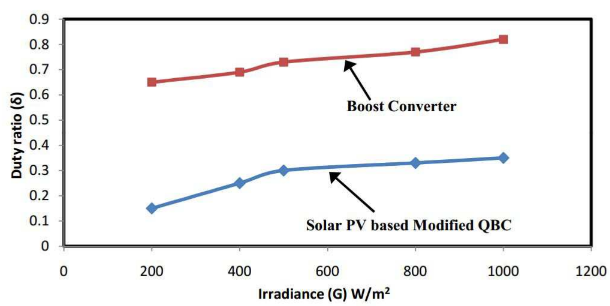


(d) Irradiance Vs Efficiency

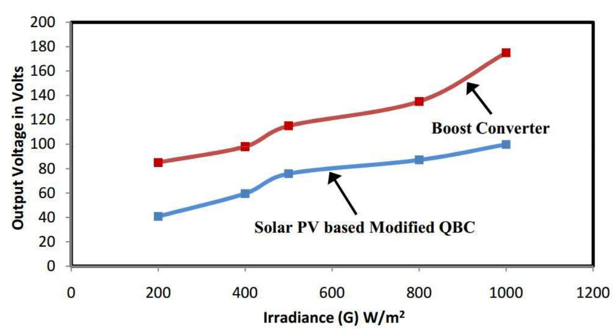
Fig. 12: Performance Analysis of solar PV based Modified Quadratic Boost Converter

7 Performance Analysis of the Solar PV based Modified Quadratic Boost Converter

The performance of the solar PV based modified quadratic boost converter is analysed by comparing it with the conventional boost converter in terms of operating duty ratio, output voltage, voltage stress and efficiency. Fig 12 (a)-(d) shows the performance comparison of the proposed system.



(a) Irradiation Vs Duty Ratio



(b) Output Voltage for different Irradiance

From Fig 12(a) duty ratio of the solar PV based modified quadratic boost converter less than the conventional boost converter to track the maximum power from the PV panel. In boost converter wide changes in duty ratio occur while irradiance changes. This increases the tracking time to catch the maximum power meantime there will be a power loss. Also the high duty ratio results in less efficiency. Fig 12 (b) shows the comparative output voltage of conventional and proposed system for different irradiance. Though the proposed system offers less output voltage than conventional converter, its low operating duty ratio offers less voltage stress and high efficiency. Fig.12 (c) and (d) shows less voltage stress and high efficiency of the proposed system. Therefore it is well suited for solar PV applications.

8 Hardware Implementation

The hardware set up of solar PV based modified quadratic boost converter is shown in Fig.13. It consists of solar PV panel (Solar Semiconductor Model: SSI-M6-250), MPPT controller, driver board and modified quadratic boost converter.

According to the value of PV panels voltage and current, gate pulse (δ) is generated from the MPPT controller and it is magnified through the driver board to switching the MOSFET. Driver board consists of driver IC IR2110 and opto-coupler IC TLP250 along with

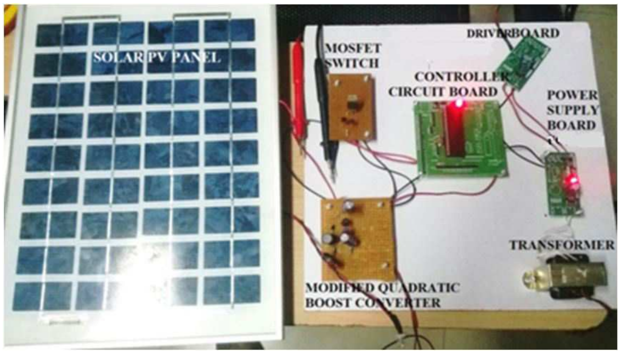
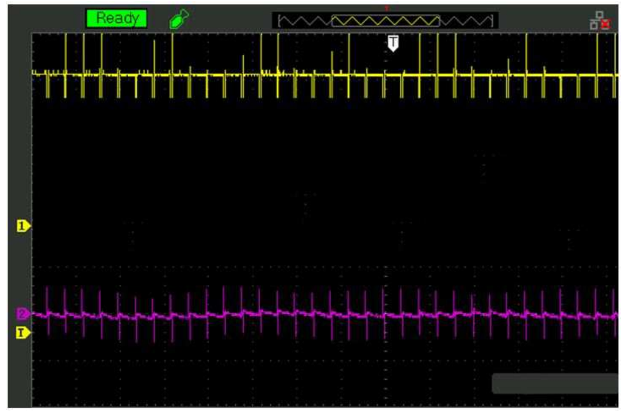
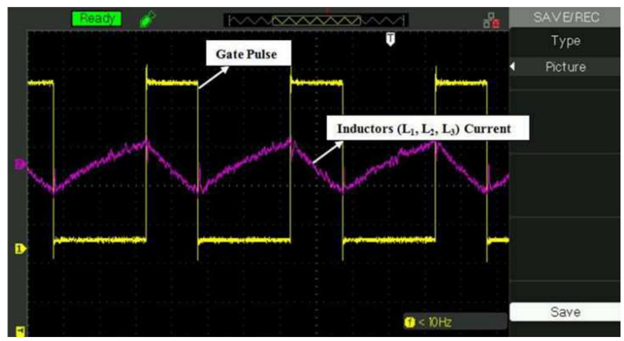


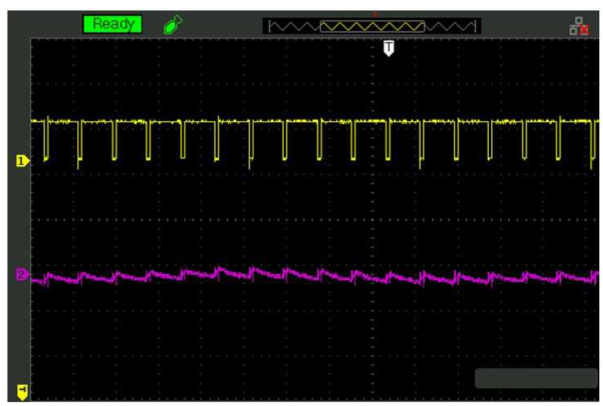
Fig. 13: Hardware Setup of Solar PV Based Modified Quadratic Boost Converter



(a) Solar PV Voltage and Current Waveform



(b) Gate Pulse and Current in Inductors $L_1, L_2 \& L_3$



(c) Output Voltage and Current

Fig. 14: Hardware results

passive elements. The specification of the experimental setup is given in table 5.

Table 5: Specification of the Experimental Setup

S.No	Components	Specification
1	PV Panel	SSI-M6-250
2	Inductors L_1, L_2, L_3	40.5μH, 76.8μH, 352μH
3	Capacitors C_1, C_2, C_0	52.7μF , 188.1μF, 39.9μF
4	Switching Frequency	10 kHz
5	Switch & Diode	IRF 540, MUR 860
6	Load Resistance	43 Ω

The hardware results are given in Fig.14(a)-(c). Fig.14(a) shows the waveform of the PV panel voltage and current at irradiance 1000 W/m^2. Fig.14 (b) shows the gate pulse of MOSFET switch and current waveform of inductors (L_1, L_2, L_3) for irradiance 1000 W/m^2. The output voltage and current waveform is shown in Fig.14(c).

Voltage, current and power of the PV panel is 33.2 V, 6.9 A and 229 W respectively. Duty ratio of the gate pulse is 0.36. Output voltage, current, power is 106 V, 1.9 A, 201.5 W respectively. The efficiency is calculated as 87.9%. The above hardware results validate the performance of solar PV based modified quadratic boost converter.

9 Conclusion

Higher output voltage is achieved in the existing boost converters by operating it with high duty ratio. This high duty ratio limits the switching frequency and results in poor efficiency. The solar PV based modified quadratic boost converter is proposed in this paper. The converter has desirable features like high step up voltage at low duty ratio, limitation of serious reverse recovery problem, high efficiency and less voltage stress at the same irradiance. The proposed system is simulated using MATLAB/Simulink tool. The comparisons of solar PV based conventional boost converter and solar PV based modified quadratic boost converter with various parameters are discussed. The P&O algorithm is used as a

MPPT technique to track the maximum power from the solar panel. The proposed converter has offered high output voltage at low duty ratio, less voltage stress and high efficiency. A prototype was built to verify the practicability of converter. Experimental results validate the theoretical analysis and simulation results.

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