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Design & Implementation of Quadratic Boost Converter in Hybrid Renewable System

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Abstract
The integration of renewable energy sources such as solar photovoltaic (PV) and wind turbines into modern power systems is essential to meet growing electrical demands and to address sustainability challenges. However, the inherent variability and low output voltage of sources like PV modules necessitate efficient power conditioning solutions for stable and reliable operation.
This paper presents the design and implementation of a quadratic boost converter (QBC) within a hybrid renewable energy system, enabling high voltage gain and reduced voltage stress on circuit components at lower duty cycles. The proposed QBC topology efficiently boosts and regulates the output voltage from combined renewable inputs, achieving four times voltage gain compared to conventional boost converters.
The project proposes the design of a quadratic boost converter that provides high voltage gain and efficiency. This converter has been fed with dual input of two renewable sources in parallel that can provide a solution to the issue of reliability related with renewable resources. A comparative analysis has been done on the performance of quadratic boost converter with conventional boost converter which highlights the beneficial advantages of the quadratic boost converter.

1. Introduction

Renewable energies are those sources of energy that can be obtained naturally without depleting the planet's resources. Present researchers are developing different technologies to capture and utilize these energies in recent years, making these resources increasingly viable and economical. Renewable energies are a key solution to combating climate change and reducing dependence on fossil fuels [1]. By investing in these energy sources, jobs can be created, and sustainable economic development can be promoted. In summary, renewable energies are a key alternative to ensure a cleaner and safer future for future generations. Hybrid renewable energy systems are those that combine two or more renewable energy sources to generate electricity. These systems are especially useful in places where there is no access to the conventional electrical grid, or where the connection is limited or unstable [2]. The most popular hybrid system combines solar and wind energies. During the day, when the sun shines, solar panels generate electricity that is stored in batteries for later use. At night, when there is no sun, wind energy conversion systems harness the wind to generate additional electricity and charge the batteries [3]. Another example of a hybrid system combines solar and hydro energies. During the day, solar panels generate electricity that is used to pump water from a river or lake to a dam. At night, when there is no sun, the water stored in the dam is released through a hydro turbine to generate additional electricity [4]. Hybrid renewable energy systems can be more efficient and reliable than systems that use a single energy source [5]. Additionally, they allow for a better use of available resources and reduce the cost of generated energy. For these reasons, hybrid systems are becoming increasingly popular worldwide, especially in rural or remote areas [6].
These hybrid systems, however, require the design of high-gain converters which are compatible with these systems to raise the output voltage, maintaining the efficiency of the system. These converters need a compatible design which can integrate different input sources by aligning them to same voltage level.
Various dc-dc converters can be selected which can integrate more than one renewable source in parallel. This paper provides an analytical comparison between conventional boost converter with modified and cascaded boost converter named as quadratic boost converter.

2. Literature Survey

In paper [1], the authors apply the Equilibrium Optimizer (EO) metaheuristic to find the cost-optimal sizing and configuration of a PV + wind + diesel + battery hybrid microgrid for the isolated city of Dakhla, Morocco, and they show EO finds a low-cost, high-renewables solution with fast convergence and better results than several recent optimizers on the same problem. This is important because isolated or remote locations often need a backup source, and a hybrid structure gives more reliability than using only solar or only wind and Dakhla is a good case study because it has strong renewable energy potential, especially for solar and wind. The paper uses this location to show that a hybrid system can reduce dependence on diesel fuel while still keeping power available when renewable sources are weak.

In paper [2], designing HRES is not just about adding solar panels or batteries; it requires a full strategy for sizing, optimization, and control so the system is economical and reliable. The review also suggests that this research area is still developing and there is room for better algorithms and smarter control methods.

In paper [3], wind-solar hybrid renewable energy systems are a strong way to produce cleaner and more reliable electricity, because wind and solar complement each other over time. Solar usually peaks in the daytime, while wind may be stronger at night or during different seasons, so combining them can reduce the intermittency problem that each source has alone.

In paper [4], hybrid PV-solar and wind systems were already promising back then, but they still needed better design, operation, and control methods to become practical and reliable. In simple words, the paper says: combine solar and wind because they complement each other, but the system must be carefully planned so it can deliver steady power efficiently.

In paper [5], the paper explains different storage/backup options for HRESs, such as batteries and other backup approaches, and why they matter for keeping power available when renewable generation drops. It also discusses different system architectures, meaning the way the sources, storage, and load are connected and coordinated.

In paper [6], combining wind, solar, diesel, and batteries can give reliable electricity at lower cost and with lower emissions than relying on diesel alone. The diesel generator is not the main source in their idea; it is a backup for times when renewable generation and battery storage are not enough. The paper uses real local solar radiation and wind-speed data for the Iranian village, then evaluates the system's feasibility from a techno-economic point of view. That means the authors are checking both:

whether the system can technically meet the load, and

whether it is economically sensible over the project life.

In paper [7], it explains the fundamentals of hybrid AC/DC microgrids, their components, and how AC and DC parts can be combined in one system. It also focuses on the operational side: how to dispatch generation, manage storage, and keep the microgrid stable and economical under uncertainty in renewable resources and load. This review is useful because it helps researchers understand both the structure of hybrid AC/DC microgrids and the best ways to operate them under realistic conditions. It also shows that future work needs smarter optimization and control methods to make these systems more reliable, flexible, and cost-effective.

In paper [8], hybrid solar-wind renewable systems are a strong solution, but their success depends on solving technical, economic, and policy challenges together. This paper is a review, so it does not present one new design; instead, it explains why combining solar and wind is valuable, what problems still exist, and what policies can speed up adoption. This review is useful because it connects engineering with economics and policy, not just hardware design. It suggests that the future of hybrid renewable energy depends on coordinated progress in technology, grid integration, and regulation.

In paper [9], analysis of three different DC/DC converter topologies i.e. a conventional, a quadratic, and a double cascaded boost converter for a Solar PV system, has been presented. A conventional boost converter may not fulfill the purpose, so cascaded boost converters are employed to overcome this limitation. Cascaded boost converters provide high voltage conversion ratio along with higher efficiency values, in comparison to conventional boost converters.

In paper [10], stated that the application of the high-gain boost DC-DC converter is gaining more attention due to an increasingly wide range of applications for sustainable green energy solutions, as well as other high-voltage applications. A dual voltage boost cell has been developed by incorporating two capacitors in series with two inductors of a conventional quadratic boost converter, and a capacitor was integrated with a second voltage boost cell. The designed converter increases the voltage gain as well as reduces the voltage stress across the switch.

In paper [11], a high voltage gain modified quadratic boost dc-dc has been proposed, which increases the voltage gain as well as reduces the voltage stress across the switch but when duty cycle increases to 60%, the input current increases, making it less efficient.

In paper [12], the paper says that traditional PWM converters have limited conversion range, so they become inefficient or impractical when the input and output voltages vary widely. To solve this, the authors use a systematic synthesis approach to create new single-transistor converter families with quadratic conversion ratios.

In paper [13], the paper introduces a new switching converter concept that achieves large conversion ratios in a cleaner way than standard topologies. In simple words, it argues that transformer less circuits can still handle big voltage changes if the converter structure is chosen intelligently.

In paper [14], the authors want to show that a non-isolated converter can still achieve very high step-up voltage by integrating a boost converter with a SEPIC stage. Their main idea is to overcome the limitation of a standard boost converter, which needs an extremely high duty cycle to get a large voltage gain and then suffers from higher stress and lower efficiency. This approach is important for systems like renewable energy sources, fuel cells, and battery-powered applications where the input voltage is low but the output bus must be much higher. The integrated topology also helps reduce switch stress compared with forcing a normal boost converter to operate at an extreme duty ratio.

In paper [15], the authors want to systematically classify and compare step-up DC–DC converters in terms of how they boost voltage, how much stress they place on switches and diodes, how many components they use, and where each topology is best applied. In simple words, the paper says that if you need a high voltage from a low DC source, there are many converter families available, and each one has different tradeoffs in gain, efficiency, cost, and complexity.

In paper [16], the authors want to show that a quadratic boost converter can be improved to get higher voltage gain while reducing stress on the switch and diode. In simple words, the paper says that the ordinary quadratic boost converter is useful, but its gain is not enough for some high step-up applications, so the authors enhance it using a coupled inductor and passive clamping.it proposes a converter that gives higher voltage gain than a basic quadratic boost and also keeps the semiconductor voltage stress low. That matters because lower stress allows the use of lower-rated devices, which usually means better efficiency, lower cost, and improved reliability.

In paper [17], the authors want to show that a simple non-isolated boost converter can be extended into a higher-gain topology without needing a transformer. The main message is that the proposed structure gives higher voltage gain than conventional boost converters while keeping the circuit relatively simple and practical. This is important for low-voltage sources like solar panels, batteries, and fuel cells, where the output voltage often needs to be raised a lot. A conventional boost converter would need a very high duty ratio in such cases, which increases stress and reduces efficiency.

3. Quadratic Boost Converter (QBC)

A quadratic boost converter as shown in Figure 1 is a type of DC-DC converter that provides a higher voltage gain than a conventional boost converter by combining two boost converters with a single switch. It is particularly useful in applications requiring high step-up voltage, such as renewable energy systems (e.g., photovoltaic panels and fuel cells).

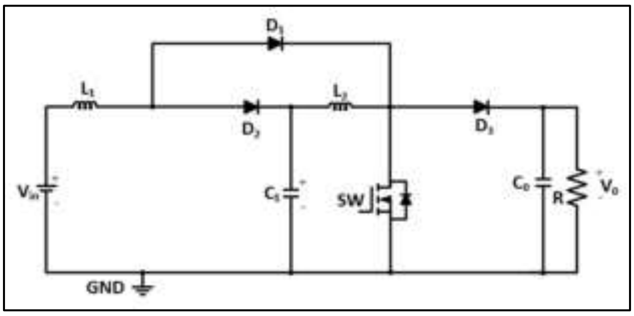

Figure 1: Quadratic Boost Converter

This project focuses on the design and development of a quadratic boost converter. A quadratic boost converter combines the principles of two conventional boost converters into a single topology using one switch, two inductors, two capacitors, and three diodes [7]. It can achieve a higher output voltage for the same duty cycle compared to a standard boost converter.

In the on-state, the switch (IGBT) is turned on, D1 and D2 are reverse-biased, whereas D3 is forward-biased. Vin and C1 supply currents to inductors L1 and L2, respectively. Thus, the inductor current increases in this model [1].

In the off state, the switch (IGBT) is turned off, D1 and D2 are forward biased, whereas D3 is reverse biased. Capacitors C1 and C2 get charged through diodes D1 and D2 from the energy stored in inductors L1 and L2, respectively. Thus, the inductor current decreases in this model [1].

4. Applications of Quadratic Boost Converter

Photovoltaic (PV) systems and micro-inverters where PV/string voltage must be stepped up for grid tie or inverter input.

Fuel-cell power conditioning and electric-vehicle front-ends that require high step-up with low switch stress.

Battery-to-bus converters in hybrid/renewable systems and low-voltage energy harvesting where a high DC bus is needed without an isolated transformer.

5. Key Advantages of Quadratic Boost Converter

High voltage gain in a single stage: QBCs reach much larger step-up ratios than a conventional boost without extreme duty cycles, improving dynamic range and control stability.

Lower voltage/current stress on semiconductor devices: Many QBC variants split voltage/current across diodes, capacitors, or coupled inductors so switches and passive parts see reduced peak stress compared with single-stage high-duty boost designs.
Smaller passive components: Because the effective gain is higher, inductance and capacitance values required for the same ripple/spec can often be smaller (or more practical) than in very high-duty conventional boosts.
Better efficiency and thermal performance when combined with soft-switching or interleaving: Modern QBC topologies include synchronous switches, coupled inductors, or ZVS/ZCS schemes that reduce switching losses and permit higher switching frequency.
Reduced EMI and improved reliability: Lower switch stress and softer switching transitions help lower EMI and extend device lifetime in many implementations.
Quadratic boost converter maintains higher efficiency and reduces the thermal/electrical stress on switching components.
Quadratic boost converter provides a high voltage gain compared with boost converter.
Simple circuit design compared with a cascaded boost converter

6. Comparison of Boost Converter and Quadratic Boost Converter

Boost converter and quadratic boost converters were simulated in MATLAB platform with similar values of design parameters as shown in Figure 2 and 3.
Results in terms of efficiency and voltage gain were obtained by varying the input voltage and duty cycle so that an analysis can be done by comparing their outputs.

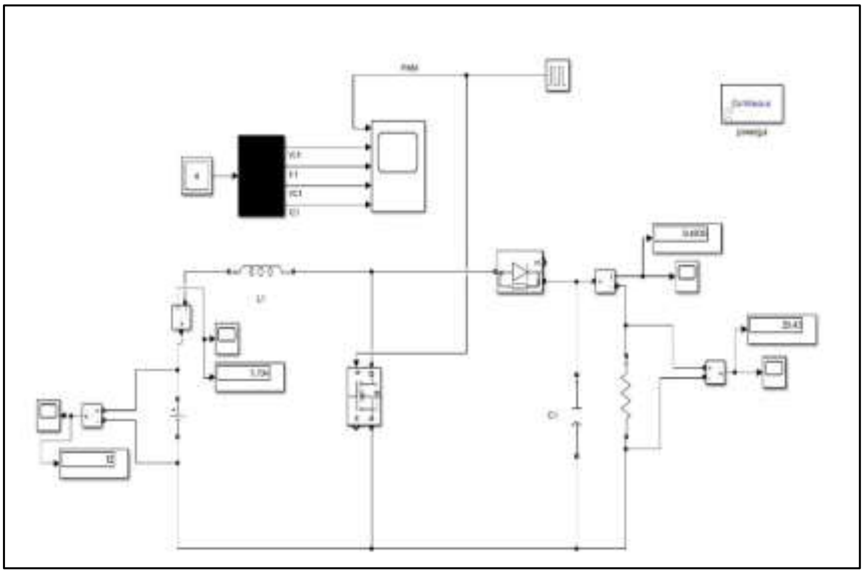

Figure 2: Simulated Boost Converter

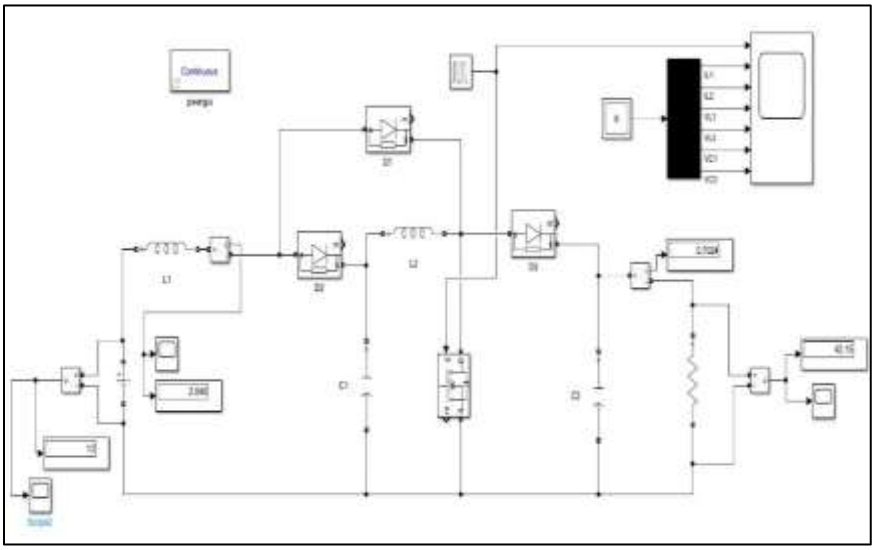

Figure 3: Simulated quadratic Boost Converter

Table. 1 displays the simulated results of Boost converter at different duty ratio and input voltages, table shows that boost converter shows a maximum efficiency of 83.8 % for the given set of input parameters.

Table 1: Efficiency and Voltage Gain in Boost Converter at Different Duty Ratio

Vin(V)	Iin(A)	D	Vout(V)	Iout(A)	Pin(W)	Pout(W)	Efficiency	Volt Gain
12	0.6514	30%	19.46	0.3243	7.8168	6.310	80.73%	1.42
	1.29	50%	27.36	0.4564	15.48	12.49	80.72%	2
	7.903	80%	66	1.1	94.836	72.6	76.53%	5
24	1.318	30%	39.61	0.6601	31.632	26.196561	82.65%	1
	2.602	50%	55.47	0.9244	62.448	51.276468	82.11%	2
	15.86	80%	132.7	2.211	380.64	293.3997	77.08%	5
48	2.653	30%	79.92	1.332	127.34	106.453	83.59%	1.41
	5.226	50%	111.6	1.86	250.848	207.576	82.749%	2
	31.76	80%	266	4.434	1524.48	1179.44	77.366%	5

Table 2: Efficiency and Voltage Gain in Quadratic Boost Converter at Different Duty Ratio

Vin(V)	Iin(A)	D	Vout(V)	Iout(A)	Pin(W)	Pout(W)	Efficiency	Volt Gain	$\frac{VIN}{(1-D)^2}$
12	1.019	35%	25.49	0.4249	12.228	10.83	88.56%	2.124	28.40V
	2.961	50%	42.73	0.7122	35.532	30.43	85.64%	3.560	48V
	4.397	55%	51.86	0.8644	52.76	44.82	84.95%	4.321	59.25V
	6.827	60%	64.45	1.074	81.924	69.219	84.49%	5.3708	75V
24	2.099	35%	53.74	0.8956	50.376	48.129	95.53%	2.239	56.80V
	6.186	50%	88.96	1.483	148.46	131.92	88.85%	3.706	96V
	14.22	60%	134.3	2.239	341.28	300.69	88.10%	5.59	150V
	39.38	70%	205.2	3.419	945.12	701.57	74.23%	8.55	266.64V
48	8.532	45%	152.6	2.543	409.53	388.06	94.75%	3.179	158.67V
	12.6	50%	182.1	3.034	604.8	552.49	91.35%	3.793	192V
	29.01	60%	274	4.567	1392.4	1251.3	89.86%	5.708	300V
	225.8	80%	522.1	8.701	10838.4	4542.7	41.91%	10.877	1200V

Table. 2 displays the simulated results of Quadratic Boost converter at different duty ratio and input voltages. It clearly shows an efficiency range of 84 to 95 when the converter is performing within a duty cycle range of 30 to 65 but when the duty cycle is further increased, efficiency reduces significantly.

7. QBC with Hybrid Input Voltages

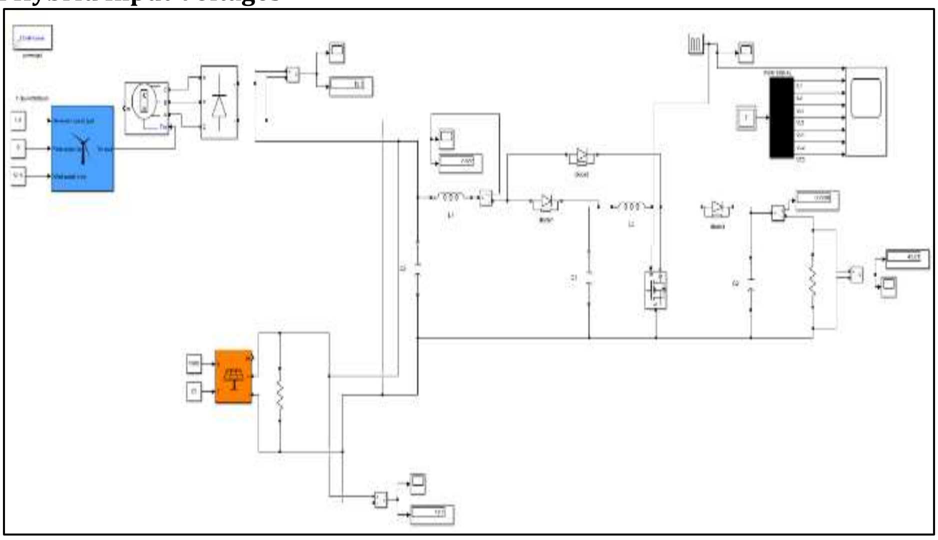

Figure. 3: Hybrid Quadratic Boost Converter with Hybrid Inputs

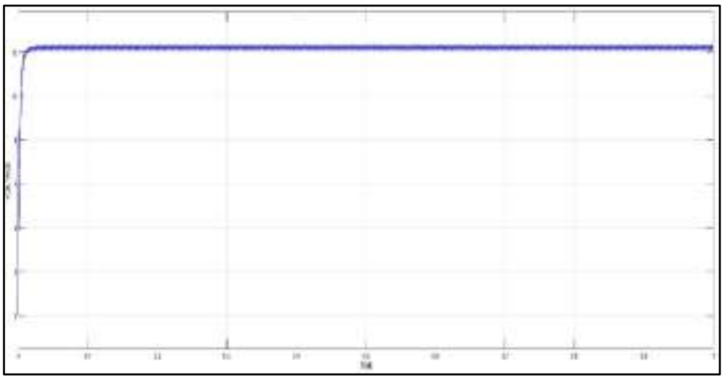

Figure.4. Quadratic Boost Converter input voltage (12V)

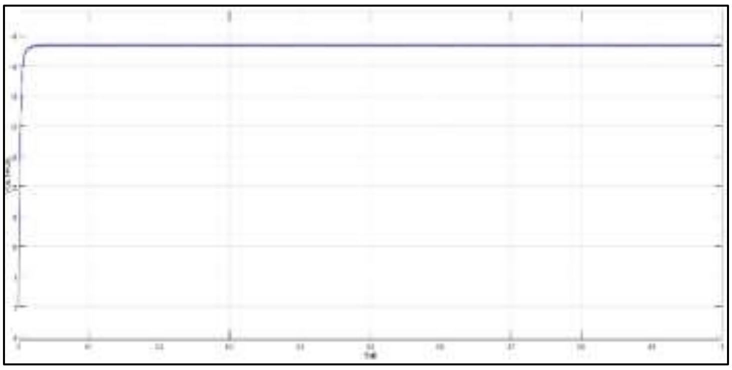

Figure.5. Quadratic Boost Converter output voltage (42V)

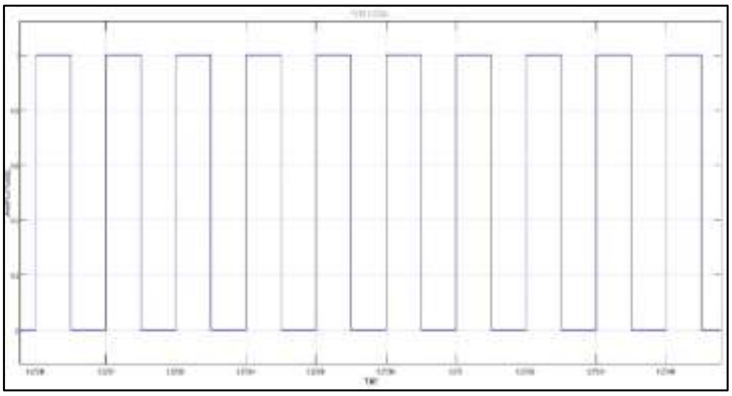

Figure.6. Waveform of the gate pulse (duty cycle 0.5)

Vin=12 V
Duty cycle=0.5
Frequency=1/50000 Hz
Figure. 3: Shows simulation of Quadratic Boost Converter with Hybrid Inputs of solar panel and wind turbine as input. Figures 4 and 5 shows the input and output waveforms of the simulated QBC with hybrid inputs. Figure 6 shows the PWM waveform.

Table 3 shows the simulated result of hybrid inputs in QBC at different duty ratio and input voltages, it shows an efficiency range of 68 to 75 when the converter is performing within a duty cycle range.

8. Hardware Model & Results of QBC with Different Inputs

Figure 7 highlights the hardware model of QBC. The results are analyzed with different input sources such hybrid sources of solar panel and wind turbine connected in parallel at different duty ratio of 40% to 50% but when the duty cycle is increased, efficiency reduces significantly.

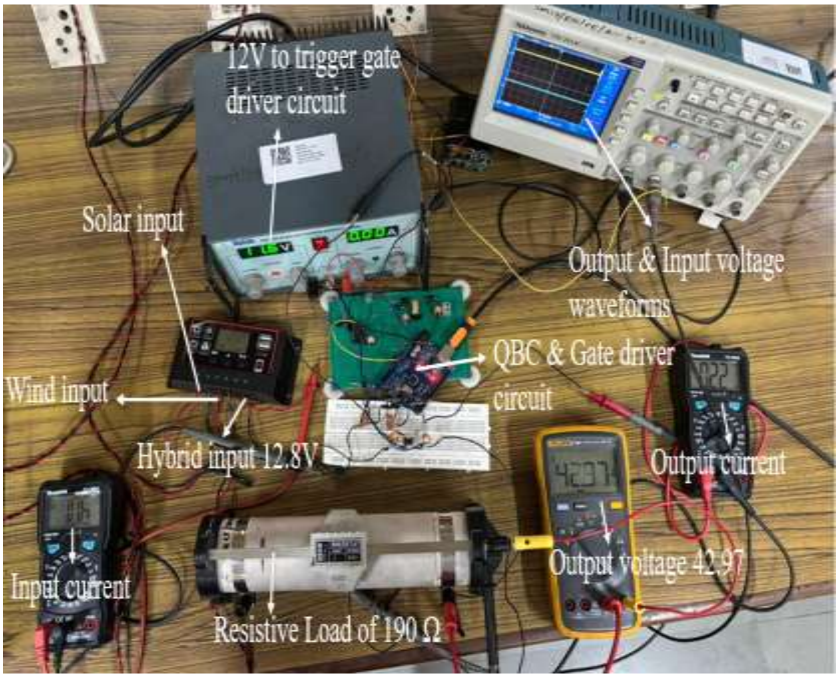

Figure 7: Hardware setup of Quardratic Boost with solar and Wind inputs

Table.3 Observations of hybrid input to Simulated model of Quadratic Boost Converter at different duty ratio

Vin(V)	Iin(A)	D	$Vout$(V)	$Iout$(A)	Pin(W)	$Pout$(W)	$Efficiency$	$Volt$ $gain$	$\frac{VIN}{(1-D)^2}$
12	0.8013	30%	23	0.3929	9.61	9.036	94.02%	1.916	24.48V
11	1.981	45%	34.2	0.57	21.791	19.38	88.93%	3.109	36.36V
10	2.67	50%	38.63	0.6439	26.7	24.87	93.14%	3.863	40V
8	4.906	60%	45.06	0.751	39.248	33.84	86.22%	5.63	50V
7	6.336	65%	45.28	0.7546	44.35	34.16	77.02%	6.46	57.14V
5	7.996	70%	41.87	0.6978	39.98	29.21	73.06%	8.37	55V

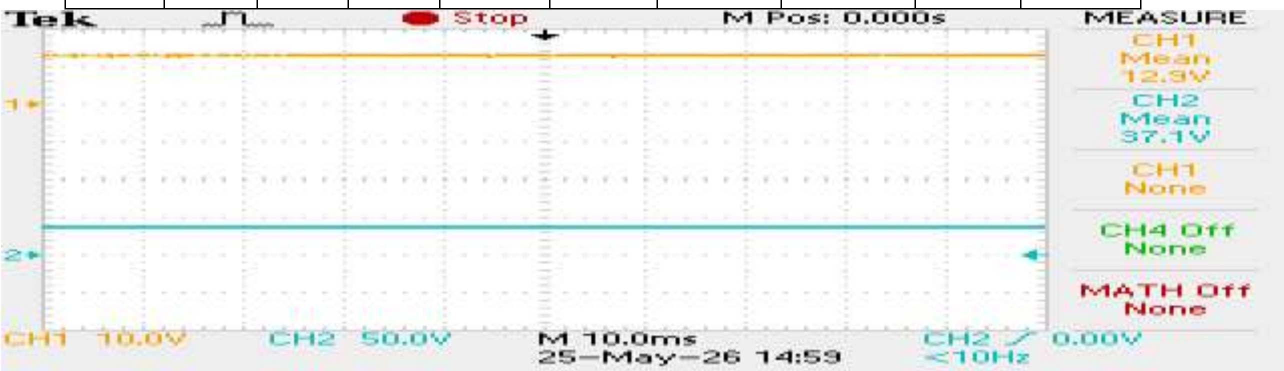

Figure 8: Hybrid input & output signal at 45% duty ratio

Figure 8 shows the 12.9Volts (Hybrid input from the parallel connection of solar and wind) and the 37.1Volts as an output voltage at a 45% duty ratio. Table 4 shows the results achieved from the hardware setup of QBC with inputs from solar and wind at different duty ratios.

Table.4 Observations of hybrid input to Quadratic Boost Converter at different duty ratio

Vin(V)	Iin(A)	D	$Vout$(V)	$Iout$(A)	Pin(W)	$Pout$(W)	$Efficienc$	$Volt$ $gair$	$\frac{VIN}{(1-D)}$
12.8	0.52	40%	31	0.16	6.6	4.96	75%	2.42	35V
13	0.72	45%	36	0.18	9.36	6.48	69%	2.7	42V
12.7	1.03	50%	42	0.21	13.08	8.82	67%	3.30	50V
12.5	1.46	55%	48	0.24	18.25	11.52	63%	3.84	61V
12.4	2.12	60%	54	0.28	26.2	15.12	57%	4.35	77V

9. Conclusion

The design and implementation of a quadratic boost converter (QBC) for hybrid renewable systems particularly solar photovoltaic and wind applications demonstrates substantial improvements in both voltage gain and component efficiency compared to conventional topologies. The QBC achieves a boost factor up to four times the input voltage at moderate duty cycles, significantly reducing voltage stress on switches, diodes, and capacitors while minimizing output ripple and system losses. The quadratic boost converter is a highly effective, energy-efficient solution for boosting low-voltage renewable sources to levels suitable for practical use, delivering superior performance over conventional DC–DC converters in hybrid renewable energy system applications.

The comparative analysis finally highlights that the performance of the quadratic boost converter is better than the conventional boost converter in terms of efficiency and voltage gain. However, the converter with the hybrid input works with a high efficiency only within the duty ratio of 40 to 60%, beyond which the efficiency reduces. Future work will be related to the practical implementation of the hybrid system.

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