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Operational Verification of DC-DC Converters Used in Ecologically Sound Non Polluting Renewable Systems

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Abstract: This research delves into the intricate control mechanisms governing renewable energy sources through the application of three distinct DC-DC converter technologies: the buck, boost, and buck-boost converters. Renewable energy sources like wind and solar can be pivotal in the future and become the primary source of energy for global energy requirements. Renewable sources are pollution-free and have minimal impact on the environment. This research illuminates the efficacy of these converters in orchestrating the optimal utilization of renewable energy sources, offering valuable contributions to the advancement of sustainable power systems. Open and closed loop control of a buck converter is studied along with its operation for the voltage regulation of an emulated PV panel. For the boost converter, a comprehensive exploration ensues through two closed-loop control methods: Perturb and Observe (P&O) algorithm and the incremental conductance method. Simulations are meticulously executed in MATLAB Simulink, interfacing with PV arrays and directing power toward battery charging. Meanwhile, the buck-boost converter undergoes simulation and evaluation, fed by a DC source and delivering power to a resistive load. Experimental validation is conducted for the buck converter, providing tangible insights into real-world performance. Conventional sources, primarily coal, which is the most used source of energy in Asian countries, including India, have adverse effects on the environment. Coal contributes to a huge proportion of pollutants in the environment and also the release of large quantities of greenhouse gases. Renewable energy resources can play a huge role in addressing the energy demands of Asian countries. They hold the ability to alleviate the environmental burden caused by conventional energy sources. Renewable energy sources also mitigate pollution and eliminate various hazardous effects of conventional energy sources. This study emphasises the adoption of such sources and underscores the pivotal role of DC-DC converter technologies in this adoption.

Key words: Asian, DC-DC converters, environment, optimisation, pollution, renewable energy, sustainable.

Introduction

Power generation has undergone a paradigm shift as a result of the global search for ecologically acceptable and sustainable energy solutions, with a growing reliance on renewable energy sources. Sophisticated control methods are required to fully utilise these sources, and DC-DC converters are at the forefront of facilitating effective power transfer and management. In the context of renewable energy systems, this study examines the crucial roles that three different DC-DC converter technologies—boost, buck, and buck-boost—play.

Solar and wind powers are two examples of renewable energy, which provides a strong solution for meeting the growing need for energy while reducing the detrimental polluting effects of traditional energy sources. India has terrific potential for the harnessing of

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wind and solar energy. The recent assessment indicates a gross wind power potential of 695.50 at 120 meters and 1163.9 GW at 150 meter above ground level (data accessed on 09 April 2024) (https://mnre.gov.in/wind-overview/). The geographic location and tropical monsoon climate make these sources of great importance to the southeast Asian region. The great benefit arising from utilisation of renewable energy resources is the conservation of the environment. Renewable sources have a significantly lower impact on the environment and are much more sustainable. The source of energy is endless and they do not have any contribution to any form of environmental pollution. In fact, on a larger scale, due to the abundance, the cost of energy in these sources is also much lower than conventional sources. This paper aims to add to the work done on the methods of harnessing these energy sources.

Many nations in tropical and temperate climates, including India have a direct solar concentration above 1000W/m^2, hence sunlight is a key resource for the future. Solar harvesting hardware, the panels composed of solar cells, is robust in nature and last for an average of 25 years, so their cost is being reduced with advancing manufacturing techniques. Along with solar, wind energy equipment is also robust with long lives providing great scope for profitability to the stakeholders.

Hasanpour et al. (2023) studied a new DC-DC converter with a non-isolated soft switching coupled inductor. The approach uses a three-winding coupled inductor and a voltage multiplier circuit. Joseph et al. (2022) presented an overview of various DC-DC converter technologies in renewable and EV charging technologies and brought forward the best out of the studied topologies in terms of ripple current and efficiency. Asl et al. (2023) proposed a novel non-isolated high gain step up DC-DC converter based on voltage lift-switched inductor cells. Sun and Bae (2022) presented a novel soft switching Cuk converter in multiple input configurations. The converter can step up as well as down, different voltage levels to produce constant DC output in a DC microgrid. Folmer and Stala (2019) presented a novel resonant DC-DC converter using resonant switched capacitors to achieve desirable characteristics like high gain and efficiency at low switching frequencies. Bejenar and Afanasov (2020) studied the simulation of a full bridge DC-DC converter using a hard switching control algorithm. Kumar et al. (2022) evaluated a configuration of isolated bidirectional dual active bridges on the basis of efficiency, loss distribution, ratings and cost of the semiconductor devices used. Harsha et al. (2021) studied the applications of DC-DC converters in renewable energy systems for the purpose of voltage level conversion. The converter under observation has unidirectional step up as well as step down capabilities. It also presents a comparison of the proposed configuration with conventional devices. Zhang et al. (2023) studied a dual inductor isolated configured DC-DC converter with direct current control. Rahimi et al. (2022) proposed a novel interleaved high step-up DC-DC converter. The configuration involves a coupled inductor and built-in transformer. Mousavi et al. (2021) proposed a multistage switched capacitor converter for step up applications. It studies the performance characteristics of the converter using a systematic approach. Zhao et al. (2021) demonstrated the process of high frequency wide range LLC resonant DC/DC converter using wide band gap devices. Mohammed and Jung (2021) reviewed the state of art soft switching techniques for power-switching devices. The switching techniques achieve zero voltage switching and zero current switching. Soheli et al. (2018) proposed a DC-DC buck boost converter topology presenting a downbeat lower output voltage than the input voltage. Chhabra et al. (2022) performed a study of grid integration of doubly fed induction machines using indirect field-oriented control. Seth et al. (2023) studied a protection scheme for fault ride-through in a DFIG. Varma et al. (2023) made an investigation on modelling and control of induction machines. The work involves the use of control strategies similar to this work.

This study examines the integration of a buck converter with a simulated photovoltaic (PV) panel to replicate real-world scenarios. The buck converter, which uses a closed-loop control system with a reference voltage programmed into the code, is a prime example of precisely controlling voltage output under dynamic input conditions. Furthermore, the behaviour of boost converters is investigated using two distinct closed-loop control techniques: the incremental conductance approach, and the Perturb and Observe (P&O) algorithm. These strategies' effectiveness in maximising power transfer, especially when it comes to battery charging, using MATLAB Simulink simulations is studied.

In addition, a simulation analysis of the buck-boost converter is conducted to further enhance our comprehension of its flexibility with respect to various input circumstances. Simultaneous hardware validation is provided via buck converter tests, which close the simulation-to-reality gap and validate the usefulness of our results.

Methodology

Buck Converter

Both hardware and software implementation of a buck converter have been studied as part of this work. For the hardware setup, a buck converter is fabricated using components mentioned in Table 1 and it is connected to an emulated solar panel. The emulation for the solar panel is done through a separate buck converter whose output voltage is varied to emulate real world variation of voltage in a solar panel output with the variation of environmental factors like irradiation.

Both open loop and closed loop characteristics have been studied for the buck converter. Under open loop operation, a 24V constant DC supply is fed into the buck converter and the output is observed under various duty cycles. The control signal to the switch is provided using an Arduino Mega board whose code is done through the Arduino IDE. The Arduino is able to drive the MOSFET at a high frequency of 10 kHz with the implementation of a bit manipulation technique allowing for high-frequency PWM using the Arduino's PWM pins. PID control was implemented in the Arduino board to achieve closed loop functionality. The hit and trial method was used in the buck converter simulations to achieve ideal values of the plant parameters. As for the simulation setup, a buck converter of the same rating is developed and is connected to a variable DC supply to feed a resistive load. This is done in order to observe the ideal characteristics of the buck converter so that a comparative analysis can be done between the hardware and software implementation of the buck converter setup. Using the simulation, various gain values for the PID controller were used to test the converter characteristics.

Boost Converter

MATLAB Simulink is used to do simulations in order to evaluate the behaviour of the boost converter. PV arrays are coupled to the boost converter, which replicates the unpredictability of solar electricity. The incremental conductance approach and the perturb and observe (P&O) algorithm are two closed-loop control techniques that are examined.

In order to replicate the real-world variability of solar power, the boost converter module is connected to photovoltaic (PV) arrays in the simulation configuration. To allow for application-based results, the PV characteristics such as the irradiance and shading are varied through the simulation.

Buck Boost Converter

With MATLAB Simulink, the buck-boost converter is simulated. The buck-boost converter has been researched in two closed loop configurations: voltage feedback closed loop control and bidirectional charging. In the simulation setup, a resistive load is powered by the buck-boost converter, which is fed by a DC supply. The purpose of the simulation is to evaluate the converter's adaptability to changing input circumstances, which makes it a useful part of renewable energy systems.

The buck-boost converter, a versatile part of renewable energy systems, is examined and simulated to see how effectively it can adapt to changing input conditions. This section provides a thorough analysis of the performance characteristics of the buck-boost converter along with a comprehensive simulation setup. Figure 1 is an illustration of the switching states of the basic DC-DC converters.

Table 1: Parameters of components used in the power electronic converters

Component	*Parameter*	*Definition*
MOSFET	Internal Resistance	0.85 Ω
	Voltage rating	500 V
	Current Rating	8A at 25°C and 5.1A at 100°C
	Maximum Power Rating	4.8 kW
Load	Resistance	30 Ω
Electrolytic Capacitor	Capacitance	47μF
Inductor	Inductance	1.6 mH
Diode	Current	8A
	Reverse Voltage	600V
	Recovery Time	70 ns
Input supply	Voltage	24V DC
	Current	1A
PV Array	Output Voltage	36.3V
	Peak Power	213.5W

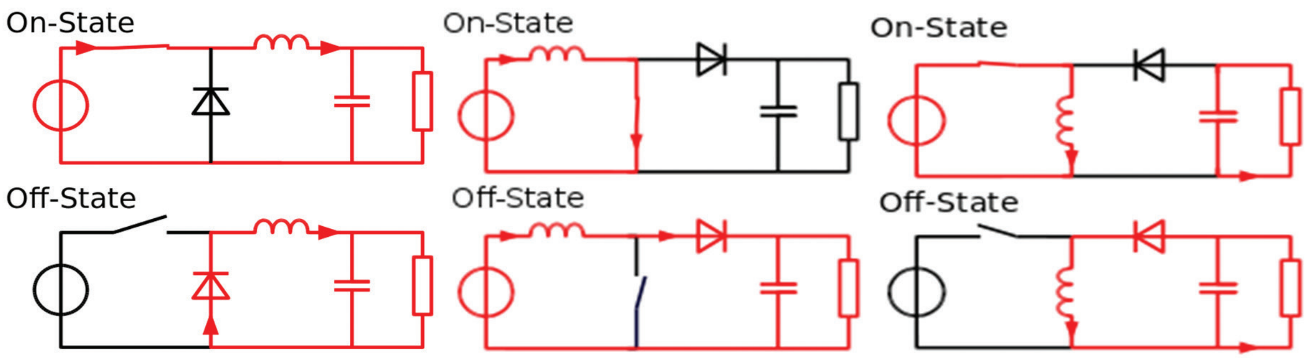

Figure 1: On and off state representation of DC-DC converter topologies (L to R: Buck, Boost and Buck-Boost).

Results and Discussion

Buck Converter

In terms of open loop performance, the hardware setup of the buck converter showed outputs close to theoretical expectations. The duty cycle to output voltage curve is linear and proportionality is maintained at extreme values also. The overall performance of the converter is satisfactory for further closed loop setup and even charging applications. In comparison, the closed loop and open loop configurations of the buck converter have different applications. The open loop topology would be applicable to scenarios when the input voltage is constant and a lower, or stepped down voltage is required on the load side. The advantage of using a buck converter over a linear voltage regulator would be that in high power scenarios, the converter losses would be negligible in comparison to the non-linearly rising power dissipation loss of the regulator. The open loop buck converter is a useful constant power device that can be used to step down the voltage from constant voltage devices like a battery. In applications where the input voltage is variable but a constant output voltage is required, closed looping of the converter is necessary. The closed loop topology ensures that the output voltage remains constant even when there is a variation in the input voltage. This would be applicable to current source devices like solar panels.

A number of tests were carried out in order to assess the buck converter's closed loop performance. The outcomes are displayed as follows:

- Voltage Regulation: The ability of the buck converter to control the output voltage in a dynamic environment was evaluated. Even with changing input conditions, the closed loop configuration of the buck converter is able to provide constant output. A variation of 8 volts in the input was implemented and it was observed that the output was constant at the set reference voltage of 12V.
- Efficiency Analysis: Power losses and total energy transfer efficiency were measured in order to assess the buck converter's efficiency. Due to low resistance MOSFET and highly rated inductor, high overall efficiency was observed in the converter. The total power loss is surmounted by the internal resistance drops of the components. Overall, a total resistive drop of approximately 0.36W was observed in the entire system to achieve an overall efficiency of 98.5%, while maintaining an output voltage of 11.91V, at 0.5 duty cycle.
- Reaction to changing loads: The buck converter's reaction to variations in resistive loads was investigated through experiments. The high-rated inductor and capacitor were able to compensate for any variation in the load and provide a stable, constant DC output suitable for battery charging and DC power applications. The PID controller implemented was more than capable of maintaining a constant output voltage. Table 2 is a record of the Buck Converter performance while operating in the open loop.

Table 2: Recorded values of buck converter open loop performance

	Buck Converter open loop performance	
	Input Duty Cycle	*Output Voltage(V)*
1	0.2	5.15
2	0.3	7.3
3	0.4	9.73
4	0.5	11.91
5	0.6	14.24
6	0.7	16.51
7	0.8	18.54

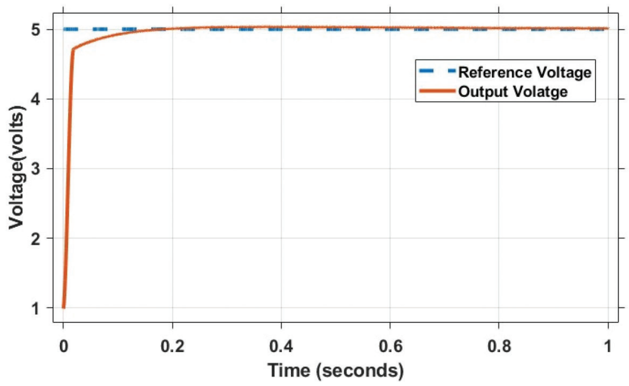

Figure 2: Simulation results of closed loop control of buck converter.

The results of these tests advance our knowledge of the buck converter's usefulness in real-world scenarios where it is intended to maximise power transfer from photovoltaic panels to resistive loads. The biggest challenge with solar energy harvesting is that it is variable and changes with varying conditions like weather, shading and physical conditions of the panel. The application of a closed loop DC-DC converter can be used to stabilise the output voltage so the output from the panels can be connected to the grid. The converter topologies can also be used for photovoltaic setup research and development.

Boost Converter

The following presentation of the simulation data provides a thorough knowledge of the boost converter's performance under various closed-loop control techniques:

- The simulation employs the Perturb and Observe (P&O) algorithm to assess the boost converter's performance in response to fluctuations in solar irradiation. The perturb and observe algorithm is a popular maximum power point tracking algorithm used in DC-DC converters and photovoltaic cells. The algorithm creates perturbations, or small variations in the input and then observes the characteristics. Further, if found desirable, the algorithm moves the operating point of the converter to the maximum power point.
- Incremental Conductance Method: The simulation employing the incremental conductance method assesses how well the boost converter responds to changes in solar irradiation. The incremental conductance also proves to be an excellent method for the governance of the closed loop boost converter, providing efficient control, constant output and high efficiency.

The comparative analysis of control strategies emphasises the role of the boost converter in maximising photovoltaic array power extraction and provides helpful information for creating adaptable and effective renewable energy systems. Both the methods of governance prove to be equal with minor differences in the output waveforms. Hence, the difference between the two is inconsequential in terms of output and the choice between the two control algorithms can be made solely on the basis of code efficiency and ease of operation in terms of control hardware.

Buck-Boost Converter

The buck-boost converter's operation under various input conditions is explained in the presentation of the simulation results that follows:

- Voltage Regulation: The simulation results show how well the buck-boost converter works to control the output voltage when the input conditions change. The buck boost converter is able to operate in both step up and step down modes hence it proves to be useful for a wide range of inputs. With greater variation in input than the buck and boost setups, it is able to achieve constant output.
- Adaptability to Input Variations: By investigating the buck-boost converter's response to changes in input voltage, the simulation offers a thorough grasp of the device's suitability for managing variable renewable energy sources. The buck boost converter has a low response time and hence operates quickly, adapting to any variations in the input and providing constant and stable output.
- Power Transfer Efficiency: To evaluate the buck-boost converter's overall energy transfer efficiency, an efficiency analysis is done. Like the boost and buck converters, the efficiency of the buck boost is also observed to be quite high, proving the converter a highly efficient and capable device.

The measured performance under various closed-loop control techniques in the boost converter simulations is consistent with the theory. While the P&O algorithm and incremental conductance approach offer alternate paths to efficient energy transfer, the MPPT algorithm proves its effectiveness in power extraction optimisation. The reliability of the control algorithms used to boost converters is supported by the agreement between theoretical predictions and simulation results.

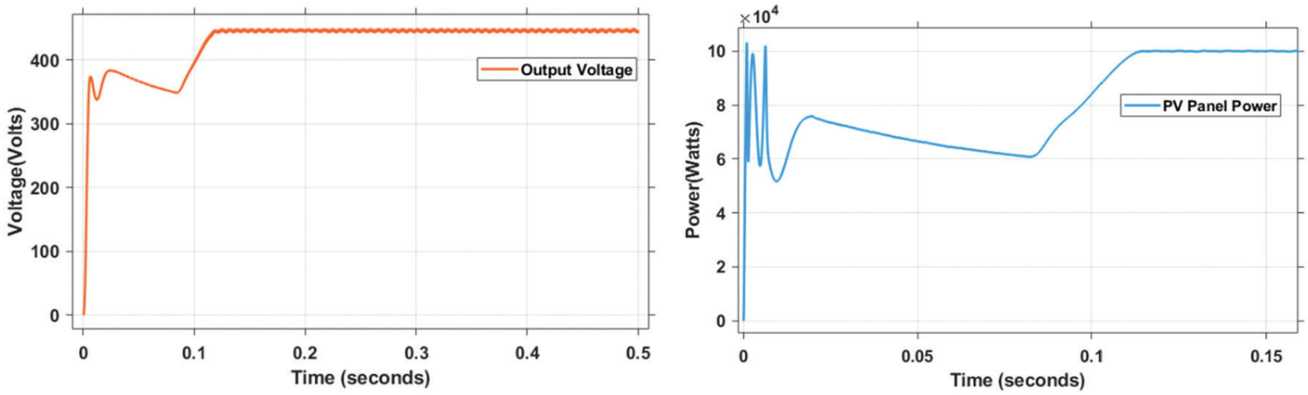

Figure 3: Voltage and Power waveforms of boost converter with P&O algorithm.

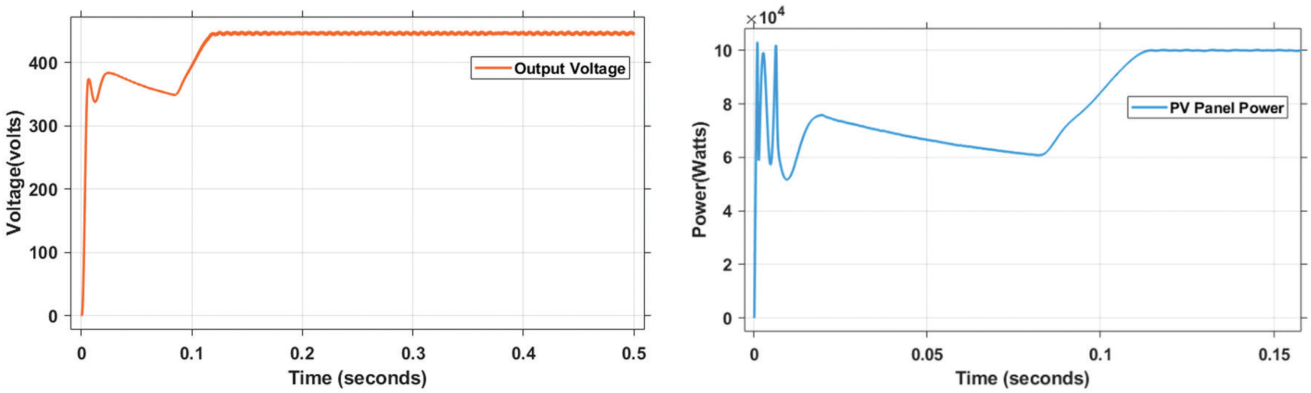

Figure 4: Voltage and power waveforms of boost converter with incremental conductance method.

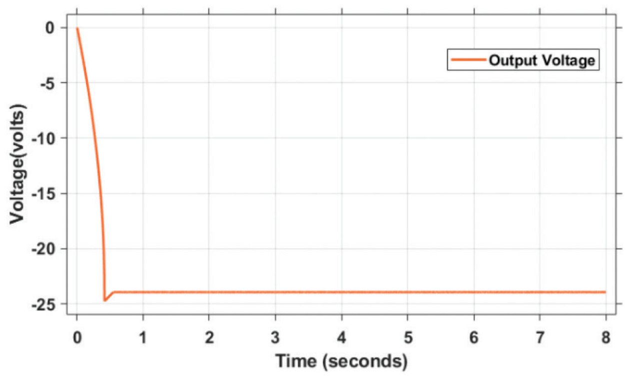

Figure 5: Voltage waveform of closed loop buck – boost converter feeding resistive load.

The simulations of the boost converter highlight its applicability in solar energy harvesting by evaluating several closed-loop control strategies. The boost converter's capacity to adjust to fluctuating solar circumstances, as exemplified by simulations, validates its function in maximising power transfer to batteries in practical situations.

Simulations and evaluations of the converters demonstrate their flexibility and effectiveness with a range of input situations. This adaptability highlights the converters' utility in sustainable power systems and places them in a valuable position for controlling energy flow between various renewable energy sources and loads.

Conclusion

As a conclusion, the performance of three essential DC-DC converter technologies—boost, buck, and buck-boost—in the context of renewable energy applications has been effectively investigated and assessed in this study. The buck converter's capacity to precisely control voltage output was validated through experimentation, and the results closely matched theoretical predictions. The closed-loop control system's effectiveness in maintaining stability under varying input conditions underscores the reliability of the buck converter for real-world solar power integration. Simulations of the boost converter employing MPPT, P&O algorithm, and the incremental conductance method showcased their collective ability to optimise power extraction from photovoltaic arrays, emphasising the adaptability and versatility of the boost converter in diverse solar energy harvesting scenarios. Furthermore, the buck-boost converter simulations highlighted its efficiency and adaptability, positioning it as a valuable component for managing energy flow between various renewable sources and loads.

All of these results support the researched DC-DC converter topologies' practicality and usability in renewable energy systems that are non-polluting in nature. A strong basis for incorporating these converters into sustainable power solutions is provided by the agreement between theoretical predictions and experimental/simulation results. The environmental factor also needs to be reiterated. Renewable energy resources are significantly less polluting than their non-renewable conventional counterparts. Environmental pollution is rising day by day and the energy demand is increasing across the globe. This is resulting in an energy crisis which will be prominent in the upcoming years. Research needs to be accelerated to increase the adoption of these renewable resources which will serve as our energy sources for coming years. This work aims to add value to the work done to study the methods for successful harvesting of energy from renewable energy sources.

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