Comparison of DC-DC converter for wind energy

By

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Thesis
Submitted to Flinders University
for the degree of

Master of Engineering (Electrical and Electronic)

College of Science and Engineering
3rd June,2024

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ABSTRACT

The performance analysis of wind energy applications with battery charging: A comparison thesis of three non-isolated DC-DC converter topologies (Buck, SEPIC and Cuk) The research focuses on operating possible variable input voltages from a wind turbine to deliver a constant output voltage suitable to charge batteries. The suggested method is compared with the closed-loop control and with the widely used PI and FLC controllers. This study concentrates on finding the best converter topology in battery charging operation and control strategy coupling to minimise the ripples of voltage and current and accompany with improved voltage regulation and avoiding the battery charging in low wind speed. Simulation results indicate the efficiency of the Fuzzy Logic Controller (FLC) to reduce ripple performs better than PI and closed-loop control for all converter topologies in terms of voltage regulation. It should be noted that the Cuk converter with FLC is the best suitable configuration for the minimum Ripple voltage to battery during the charging operations. These results illustrated the importance of selecting power converter topologies and control strategies to improve the performance and efficiency of wind energy systems with battery storage, which is very effective in actual application when wind is uncertain. Since this information would be helpful in investigating the wind energy conversion and storage technologies. The paper provides important knowledge regarding the design and practice of effective and sturdy DC-to-DC converters when use to charge batteries.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university.
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

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I certify that I have read this thesis. In my opinion it is/is not fully adequate, in scope and in quality, as a thesis for the degree of Mater of Engineering (Electrical and Electronics). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully.

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Print name of Principal Supervisor.

Date......3/6/2024......

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Dr. Amin Mahmoudi for their electrical expertise and invaluable guidance, support, and encouragement throughout my research journey. Their expertise and insightful feedback have been instrumental in shaping this thesis.

I am also grateful to the faculty and staff of the College of Science and Engineering at Flinders University for providing a stimulating academic environment and the resources necessary for my research.

I would like to extend my thanks to my fellow students and colleagues for their camaraderie and helpful discussions, which have enriched my learning experience.

Finally, I am deeply indebted to my family and friends for their unwavering love, support, and belief in me. Their encouragement has been my constant source of motivation throughout this endeavour.

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1. INTRODUCTION

In the recent past, the world has faced a problem of increasing energy demands and at the same time the negative impacts of using fossil fuels have also been a cause of concern thus leading to search for new and renewable sources of energy the world over, especially wind power. (Mohammad Faisal Akhtar, 2023). However, it is cheaper and friendly to the environment, not very dependable and is usually distributed most of the time. When considering the capability of wind energy system to play a main role in all energy supply chain, efficient energy storage systems which allow optimal utilization of the power potential should be mentioned. Nevertheless, integration of wind power and battery storage requires development of advanced power electronic converters to facilitate the proper and reliable flow of power.

DC-DC converters are inevitable components of renewable energy systems since through these converters the non-uniform characteristic of the output voltage of the wind turbine can be adjusted according to the specific needs of the battery charging process. DC-DC converter assist in maintaining the voltages, reducing the ripple voltage and current and improving the power conversion efficiency. There are various types of DC-DC converters available in the market which can be changed depending on the application of wind energy to reduce the ripple and maintain the voltage.

Various literature has been produced dealing with the problem of voltage regulation of wind energy systems. DC-DC converters have long been regarded as a feasible way to regulate the fluctuating output voltage from wind turbines. These converters are very important as they help in converting the changing input voltage into an output voltage which is appropriate for the charging of batteries or any other use. Dong et al., 2017 analysed various DC-DC converter topologies, including buck, boost, buck-boost, SEPIC, and Cuk converters for suitability in wind energy applications. Studies have investigated the usage of fuzzy logic-based controllers for enhancement DC-DC converters dynamic behaviour (Dong, et al., 2017). Fuzzy logic controllers are seen to overcome traditional PID controllers in preventing from overshoot, ripple, and settling time in a variety of the studies (Maity, et al., 2019).

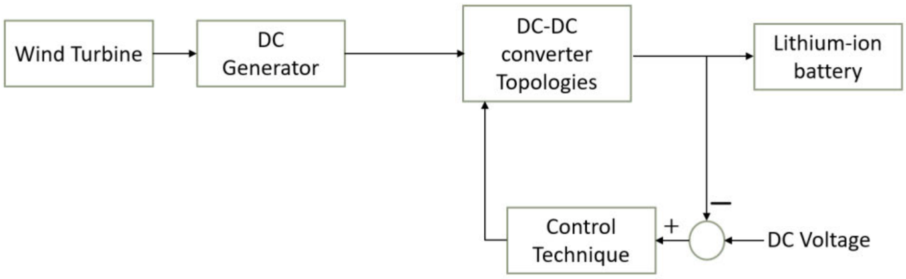

Figure 1 block diagram of basic system

The basic diagram shows a wind-powered battery charger. The wind energy-based DC generator runs at various speed and is interfacing with the fuzzy PI controller and DC-DC converter (buck, SEPIC, or Cuk). A voltage feedback loop keeps the output of the converter in ideal charging conditions, and the voltage it supplies is used to charge a lithium-ion battery.

The thesis compares three non-isolated DC-DC converter topologies, i.e., buck, SEPIC and Cuk, for wind energy application with battery charging. The converters receive a wind turbine input voltage that varies and uses it to generate an output voltage at the battery charging voltage. In this study, relay control (closed loop), PI control, and fuzzy logic control strategies are implemented to decrease the ripple in voltage, current, and regulation.

DC-DC converters and control strategies for wind energy applications have been extensively studied however there is no thorough comparative analysis of non-isolated topologies and advanced control techniques for battery charging from variable wind turbine sources. ripple reduction, effective battery charging and better voltage regulation under various wind condition may not be addressed by current technologies.

This thesis addresses the design and implementation of the closed-loop-controlled non isolated DC-DC converters for wind energy applications. The experimentation is carried out by designing and modelling of Buck, SEPIC and Cuk converters with Closed loop controllers PI (Proportional-Integral) and fuzzy logic controller (FLC) for simulating the performance of converters for different wind speed scenarios and the ripple voltage, settling time and overshoot for different converter topologies with different controllers are analyses and compared with each other. Performance-based topology and control method screening for wind energy applications. The main objective of this project is to determine the best converter topology and control mechanism for the wind application.

When it comes to lowering ripple voltage and current in DC-DC converters for wind energy systems, fuzzy logic controllers will perform better than PI controllers. Though the SEPIC converter is best for voltage control at low wind speeds and attenuated overshoot, however, it provides large ripple voltage and poor voltage regulation at high wind speeds. The choice of control strategy and converter topology for wind energy conversion will largely determine how cost-effective and efficient the system will be in total.

In methodology, the experimental steps of modelling a wind turbine system at varying wind speeds and as a result various voltage level. These voltages will be passed through three non-isolated DC-DC converter topologies: Buck, SEPIC, and Cuk convertor to regulate it. The existing converters feature closed-loop PI (Proportional-Integral) and Fuzzy Logic controllers. Simulations will be performed to evaluate the converter's performance in different wind conditions, and data on ripple voltage, settling time and overshoot will be collected. More in-depth investigation and comparison of this data will determine the optimal converter topology and control strategy for wind energy applications.

1.2 Organisation of Thesis

Section II presents the Literature review about DC-DC converter. Section III represent the experimental methodology of this research. Section IV represents all the MATLAB simulation for the different DC-DC converter with different control technique and take technical data. Doing comparative analysis of the DC-DC converter topologies in section V. In last section present the conclusion and future work for this study.

2. LITERATURE REVIEW

Electric/electronic systems have been advanced, so that a history of trying to decrease ripple voltage and current have been existed for a long time. Energy Storage in Widescale requires scalable and reliable power for a growing number of solutions ranging from consumer to industrial machinery and renewable systems, and research in this area is ongoing. Nevertheless, remarkable advancements in semiconductor technology, control algorithms, and materials research have made significant contributions to the reduction of voltage and current ripple (Varghese, 2021). Engineers and designers combat with the ripple to work as intended and to comply with legal standards — so that it is typical to meet applications where products and systems work as expected (García-Vite, 2019).

Minimising fluctuations in current and voltage is of utmost importance for ensuring the consistent and reliable operation of various electronics and power supply systems. To reduce ripple, it is possible to utilise larger capacitors to effectively store and discharge energy. Eliminating the high-frequency components of the ripple can be achieved by employing inductors, also known as coils, to filter them out. Inductors moderate current variations and smooth them out. Capacitors and inductors are used together in LC filter topologies to achieve that, making LC filter configuration a very effective solution to lower both the voltage ripples and current ripples. Since the output varies in time, they find application in cases where some stable output voltage is needed (e.g., LM2596, switching regulators; LM78XX series, linear voltage regulators) (Iskender, 2020).

As stated by Collura et al. (2019, p.1), there has been a continuous decline in reserves due to the growing need for fossil fuels in recent decades. Meanwhile, a study conducted by Mira et al. (2019, p.1) highlighted the importance of high efficiency and low-cost power converters in renewable energy systems, specifically for interfacing energy storage. Yodwong et al. (2020, p.2) emphasise the importance of DC-DC converters in the context of renewable energy sources (RESs) and PEMELs. They highlight that RESs often produce high DC voltage output, while PEMELs require low DC voltage input. Therefore, a DC-to-DC converter plays a crucial role in enabling renewable energy systems to generate electricity. According to Guan (2019, p.1), wind power has emerged as a significant and expanding source of renewable energy on a global scale. Singh and Tuli (2022, p.125) state that power engineering and driving investigate DC-DC conversion technology. These devices manage direct current voltage accurately with electronic platforms. A reliable voltage reference should be used for comparison in the feedback loop. Wind energy conversion systems (WECS) and photovoltaic (PV) systems with energy storage systems must be compatible to increase local load power supply dependability. Renewable energy must be converted into batteries for large-scale electric vehicle use (Teixeira, 2020).

A voltage regulator is usually used in electrical circuits to control the output voltage (Stonier et al. 2020). Voltage regulators maintain output voltage despite input voltage or current load fluctuations. The most common voltage regulators are linear and switch-mode (Stonier, 2020). It also discussed how a wind farm with batter storage reduced output power fluctuations. This concept solves output power fluctuation by connecting the energy-storage system to each wind turbine's DC connection (Aazami, 2022). Because wind and solar electricity are intermittent, integrating and using high-penetration renewable energy sources in power networks has been an issue. To introduce sophisticated technologies, wind turbine energy is stored in batteries during DC-to-DC conversion (Manikanth, 2020).

Although prior studies have explored various DC-DC converter topologies and control methods applicable to renewable energy, there remains a gap in comprehensive studies directly comparing their performance in the specific context of ripple voltage, overshoot and settling time and battery charging. However, most studies concentrate on idealized test cases which severely decreases our knowledge to design realistic wind energy systems. This combined with control methods such as PI controller and fuzzy logic controller with DC-DC converter.

3. METHODOLOGY

The methodology employed in this research aims to comprehensively investigate and compare the performance of three non-isolated DC-DC converter topologies, namely the buck, SEPIC (Single-Ended Primary-Inductor Converter), and Cuk converters, in the context of a DC wind turbine system. The study encompasses the modelling and simulation of the wind turbine, the DC-DC converters, and their respective control strategies, including both conventional proportional-integral (PI) controllers and Fuzzy Logic Controllers (FLC).

3.1 Modelling of DC Wind Turbine

A simplified DC wind turbine model will be created to simulate the power and output voltage characteristics of the turbine under conditions of variable wind speed. The model will incorporate including generator parameters, various factors, turbine blade characteristics and wind speed. Using a MATLAB simulation, implement the wind turbine model. The specification of the wound-field DC generator is shown in the table 1.

Table 1 Specification of the DC generator

Type of converter	Type of control technique
Rated power	5 HP
Rated voltage	240 V
Rated speed	1750 rpm
Field voltage	150 V
Armature resistance	0.78 Ω
Armature inductance	0.016 H
Field resistance	150 Ω
Field inductance	112.5 H
Field- armature mutual inductance	1.234 H

3.2 Modelling of DC-DC Converters

In this research, there are three non-isolated DC-DC converters are used namely Buck converter, SEPIC converter and Cuk converters. Design the detailed circuit diagram of all three converter topologies including the component selection such as inductor, capacitor, diodes and switches (IGBT) for the detailed analysis and performance evaluation based on desired specifications. These converters implement in the MATLAB simulation. After that comparing this simulation result with the desired specifications.

3.2.1 Buck Converter

The basic operation of a buck converter involves using a switching transistor and an inductor.

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Figure 2 Block diagram of Buck converter (Anon., 2015)

When the transistor is on, current flows going through the inductor, storing energy in in the magnetic field. When the transistor is off, the inductor releases their stored energy to the output capacitor and load (Marco Cupelli, 2018) . This switching action allows the buck converter to transfer energy in packets from the input to the output. Buck converters typically contain two semiconductors (a diode and a transistor, or two transistors for synchronous rectification), an inductor, and input/output capacitors for filtering. Table 2 represent the specification of the Buck converter.

Find the value of inductor and capacitor value from following equation.

$$L = \frac{V_{out}*(V_{in(min)} - V_{out})}{\Delta\, IL * f * V_{in(min)}} \;\ldots.\; (1)$$

$$C = \frac{\Delta\, IL}{\Delta\, V_{out} * 8 * f_{sw}} \;\ldots.\; (2)$$

Where, $\Delta\, IL$ = maximum inductor ripple current and

f_{sw}= switching frequency

Table 2 Specification of Buck Converter

Type of converter	Type of control technique
Input Voltage	22-180 V

Output Voltage	24 V
Inductor	8mH
Capacitor	5mF
Load Resistance	1000 Ω
Proportional (P)	100
Integral (I)	50
Switching Frequency	10KHZ
Duty Cycle	0.5

3.2.2 SEPIC converter

The SEPIC convertor is utilized in a way such that also coupled inductor or two individual inductors (L1 and L2) along with the capacitors provide an efficient bidirectional energy movement from input to output (Trivedi Bhavin, 2018). The output voltage is controlled by altering the duty cycle of the switching transistor/MOSFET (S1).

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Figure 3 Block diagram of SEPIC converter (Meryem Oudda, 2016)

The SEPIC converter requires either a coupled inductor or two separate inductors (L1 and L2) and capacitors to efficiently transfer energy from the input to the output in both directions. When the switch transistor/MOSFET (S1) is turned on, the input voltage source (Vin) delivers energy to the L1 and L2 inductors (where L1 is charged from Vin, and L2 is charged from the C1 capacitor). At the same time, the diode D1 is in reverse bias, when S1 is deactivated the energy that was stored in L1 and L2 will be transferred to the output capacitor C2 and the load. L1 delivers its energy to C1 and D1, L2 transfer energy to C2 and the Load. The coupling capacitor C1 is transferring energy from the input to the output. It gets charged by Vin during the on-state and then releases its stored energy to the output side using the L2 and D1 during the off-state. (Onur Kırcıoğlu, 2016).

Find the value of inductor and capacitor value from following equation.

$$L = \frac{V_S * K_{max}}{\Delta I * f_{sw}} \dots (3)$$

$$C = \frac{I_a * K_{max}}{\Delta v * 0.5 * f_{sw}} \dots (4)$$

Here K_{max}=duty on cycle

f_{sw}= switching frequency

Following table 3 represents the specification of the SEPIC converter.

Table 3 Specification SEPIC converter

Type of converter	Type of control technique
Input Voltage	22-2100 V
Output Voltage	24 V
Inductor ($L_1 = L_2$)	18mH
Capacitor ($C_1 = C_2$)	18mF
Load Resistance	15 Ω
Proportional (P)	6
Integral (I)	160
Switching Frequency	10KHZ
Duty Cycle	0.5

3.2.3 Cuk converter

The Cuk converter can produce a steady input and output currents. It is very proper to use in battery charging applications where low current ripple is desirable. This is done with a unique configuration of a pair of inductors, a pair of capacitors, two switches, and one diode to provide efficient energy transfer and filtering (Erickson, n.d.).

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Figure 4 Block diagram of Cuk converter (Ayse Kocalmis Bilhan, 2024)

The Cuk converter uses two inductors (L1 and L2) coupled between the input and the output and two discharging capacitors (C1 and C2) with a diode and a driver (transistor or MOSFET). Where the energy is transferred through the capacitor C1 from input to output, and where the input voltage and output voltage are converted into current form by inductors L1 and L2 respectively. When the switching device is ON, the input voltage source charge inductor L1 and the capacitor C1 charge inductor L2. Diode D is reverse biased, preventing current flow to the output. For de-activation of the switching device, the energy stored in inductor L1 gets transferred to capacitor C1 through diode D and energy stored in inductor L2 transfers to the output capacitor C2 and load (Ayse Kocalmis Bilhan, 2024).

Find the value of inductor and capacitor value from following equation.

$$L = \frac{V_S * K_{max}}{\Delta I * f_{sw}} \ldots. (5)$$

$$C = \frac{I_a * (1-K_{max})}{\Delta v * f_{sw}} \ldots. (6)$$

Following table 4 represents the specification of the Cuk converter.

Table 4 specification of the SEPIC converter

Type of converter	Type of control technique
Input Voltage	22-2100 V
Output Voltage	20 V
Inductor ($L_1 = L_2$)	18mH
Capacitor ($C_1 = C_2$)	18mF
Load Resistance	1 Ω
Proportional (P)	6
Integral (I)	160
Switching Frequency	10KHZ
Duty Cycle	0.5

3.3 Modelling of the Controllers

In the DC-DC converter, controller plays crucial role. Controller is much more important to reduce the ripple voltage and current, improve the voltage regulation at the output side. In this experiment implement the proportional-integral (PI) controller and FUZZY Logic Controller (FLC) for better output response for the battery charging.

3.3.1 PI (Proportional -Integral) controller

PI controller is designed for the Buck, SEPIC and Cuk converter topology. There are two parameters in the PI controller will be designed using the different methods such Ziegler-Nichols or frequency response analysis. PI controller performance will examine with different parameters such as transient response, stability and steady-state errors. Implement the Pi controller in the MATLAB with three converter topologies.

3.3.2 Fuzzy Logic Controller (FLC)

Develop the Fuzzy Logic controller for each DC-DC converter topology. Define the output an input variable, function of membership and define the fuzzy based ruled on the converter’s operating characteristic. Implement the Fuzzy rule-based controller in the MATLAB simulation environment with three converter topologies.

3.4 Comparison of DC-DC converter topologies

Simulate the non-isolated DC-DC converter topologies (SEPIC, buck and Cuk) with closed loop system, PI controller and Fuzzy logic Controller (FLC) controller with various condition. Check the performance of the converter based on the ripple voltage and current, voltage regulation, overshoot and settling time**.** Lastly, identify the most suitable DC-DC converter topology and control strategy accordance to comparison of the converter.

4. SIMULATION AND RESULT

4.1 Simulation of Wind turbine

A Simulink model was also built to verify the turbine system with a 5 hp, 240V, 1750 RPM wound-field DC generator. The model takes an input of wind speed changing with time sent from the model, which is then converted to per unit (pu) and sent to DC machine block. This block evaluates the speed of the generator, the mechanical torque, and the Voltage outputs for the given field excitation & load torque. The model contains logic for control that can simulate different wind conditions such as braking or a-typical behaviour when the wind speed goes above 400 m/s or below 270 m/this simplified model offers a solid basis for comprehending the fundamental behaviour of the system in different wind conditions. It can be further optimized by adding control algorithms and a charging battery. The basic MATLAB simulation of the wind turbine with DC generator and turbine power characteristics are demonstrated in fig 4 and 5 respectively.

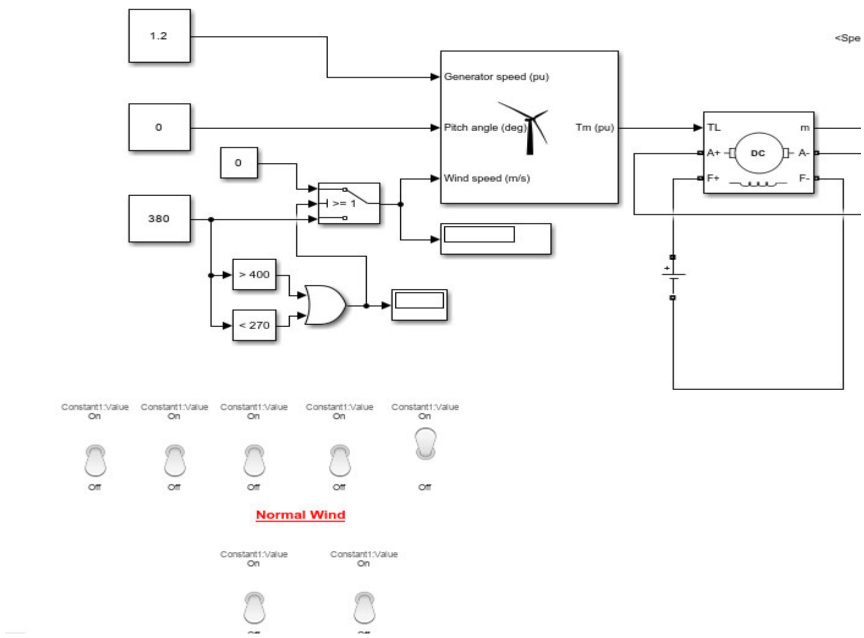

Figure 5 Designing the wind turbine at different speed

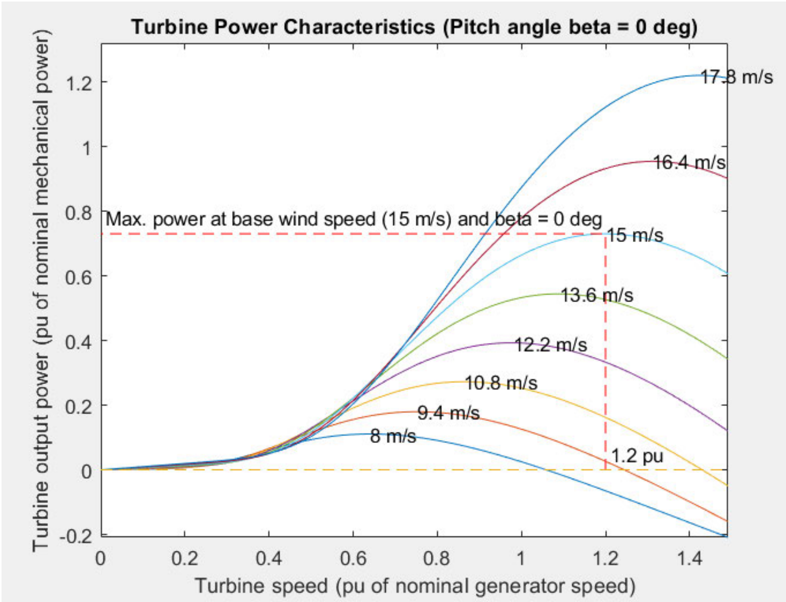

Figure 6 MATLAB generated turbine power characteristics

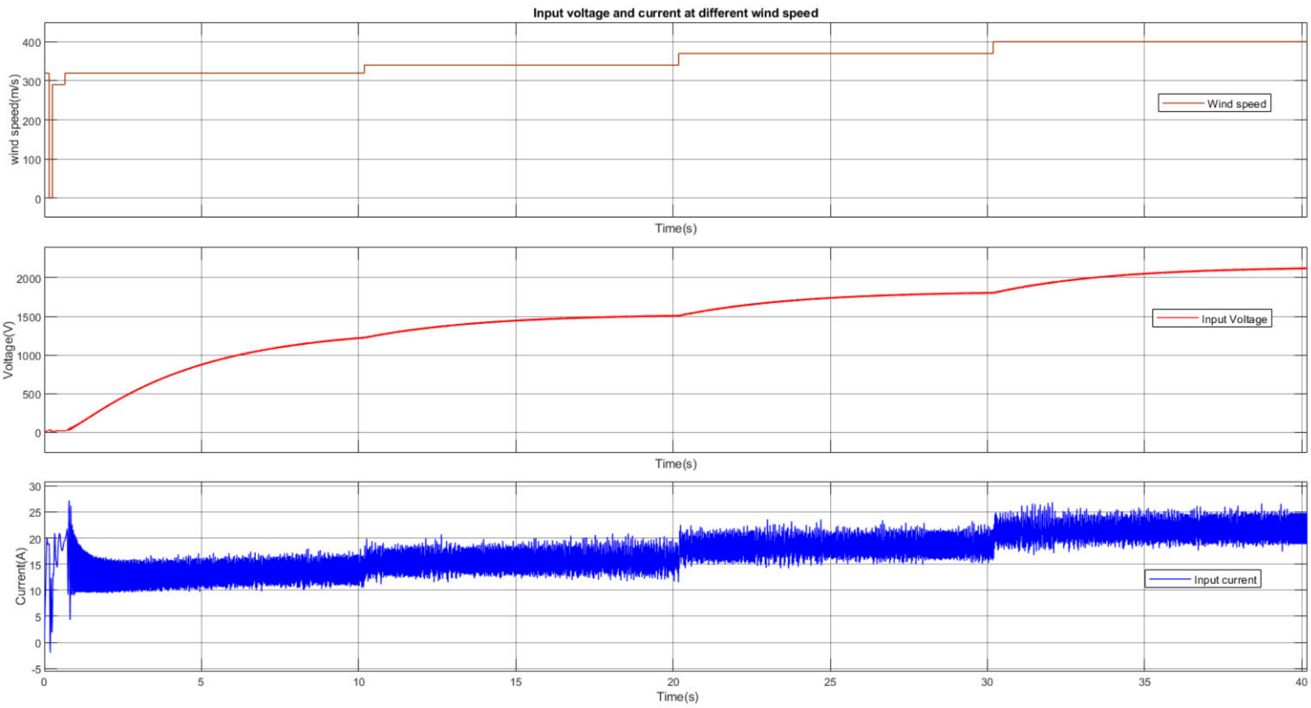

Figure 7 Voltage and current at different wind speed

4.1 Simulation of control technique

For DC-DC converters are used in wind energy battery charging system an efficient and accurate regulation of the output voltage is essential. For these two different controller strategies are investigated in this study, namely Proportional-Integral (PI) control and Fuzzy Logic Control (FLC).

4.1.1 PI controller (proportional controller)

The Ziegler-Nichols closed-loop method, a commonly used scientific approach, was utilised to calculate the controller parameters (K_p and K_i). This method provides a practical and intuitive approach to tuning the PI controller without the need for a complex mathematical model of the system (Manoj Kushwah, 2014) . The Ziegler-Nichols closed-loop method requires creating sustained oscillations in the system's output by gradually increasing the proportional gain (K_p) while keeping the integral gain (K_i) at zero. With these values, the PI gains can be calculated using specific formulas to achieve the desired closed-loop performance.

PI controller:

$$K_p = 0.45 \times K_c \qquad \text{…. (7)}$$

$$K_i = \frac{1.2 \times K_c}{P_c} \qquad \text{…. (8)}$$

Here, $K_c$is critical gain is known as the value of K_p at which the start the oscillation.

P_c is the period of the oscillation. It means this is time to take to complete one cycle.

4.1.2 Fuzzy Logic Control (FLC)

Following fig 6 represent the block diagram of the Fuzzy logic controller.

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Figure 8 Block diagram of Fuzzy logic controller (Mohamed Boutouba, 2016)

1) FLC membership function

To design the fuzzy logic controller the Mamdani style is choose for designing the FLC. ‘error’ and ‘Derror’ are taken as input variable and variable ’D’ taken as output variable for switch (IGBT). For a DC-DC converter, each input must be divided into seven groups to precisely regulate the converter (Mohamed

Boutouba, 2016) (Sen, 1997). Following figure 7,8 and 9 shows the input and output of the membership function.

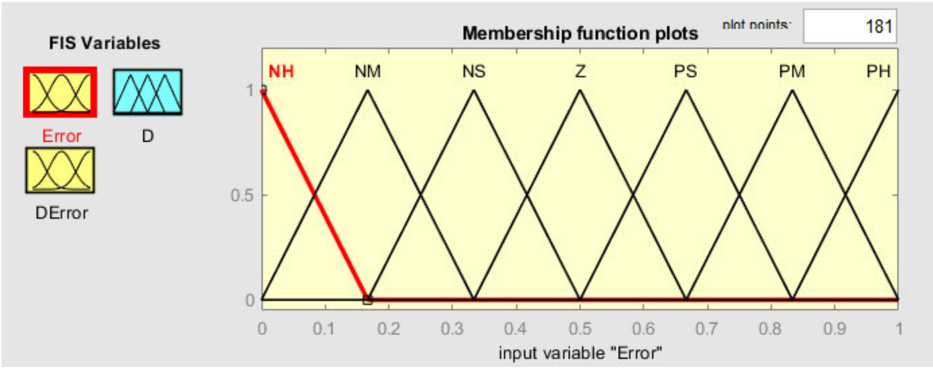


Figure 9 Membership function for input 'error'

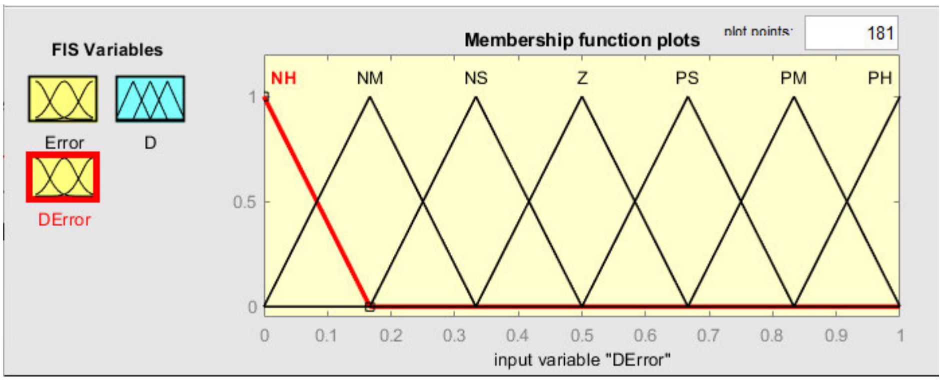


Figure 10 Membership function for input 'derror'

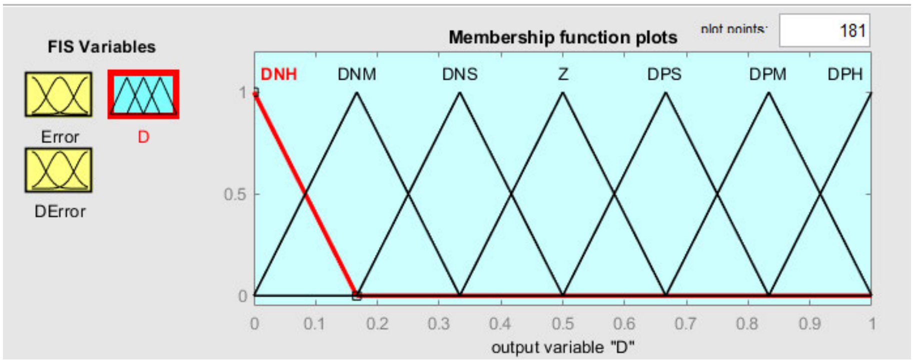


Figure 11 Membership function for output 'D'

2) Fuzzy logic controller rule base

There are two inputs for the FLC rule based (‘error and ‘Derror’) are divided into seven part(NB: negative small ,NM: negative medium ,NS: negative small ,Z: zero ,PS: positive small ,PM: positive medium ,PB: positive big) precisely scaled this part as shown in the figure 7,8,9 (Mohamed Boutouba, 2016) (Sen, 1997). Following figure 10 represent the rule for ‘error’ and ‘Derror’.

e' \ e	PB	PM	PS	Z	NS	NM	NB
NB	0	-5	-50	-100	-100	-100	-100
NM	5	0	-5	-50	-100	-100	-100
NS	50	5	0	-5	-50	-100	-100
Z	100	50	5	0	-5	-50	-100
PS	100	100	50	5	0	-5	-50
PM	100	100	100	50	5	0	-5
PB	100	100	100	100	50	5	0

Figure 12 Rule for 'error' and 'Derror'

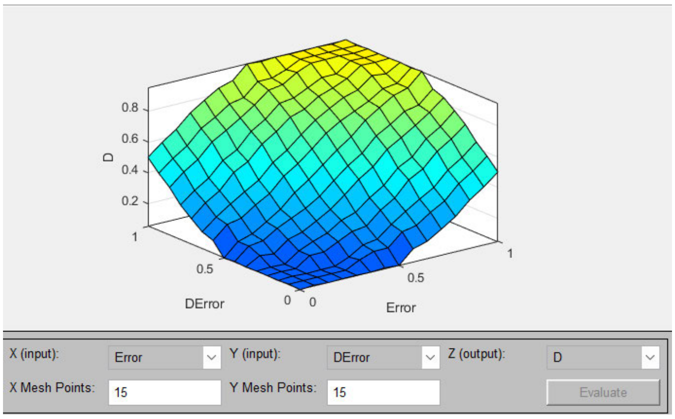


Figure 13 Surface view of rule base

4.2 Simulation of DC-DC converter

Here, presents the waveform of all three converters with simulation at high wind speed. While low wind speed simulation figure attached in the appendix.

4.2.1 Buck Converter

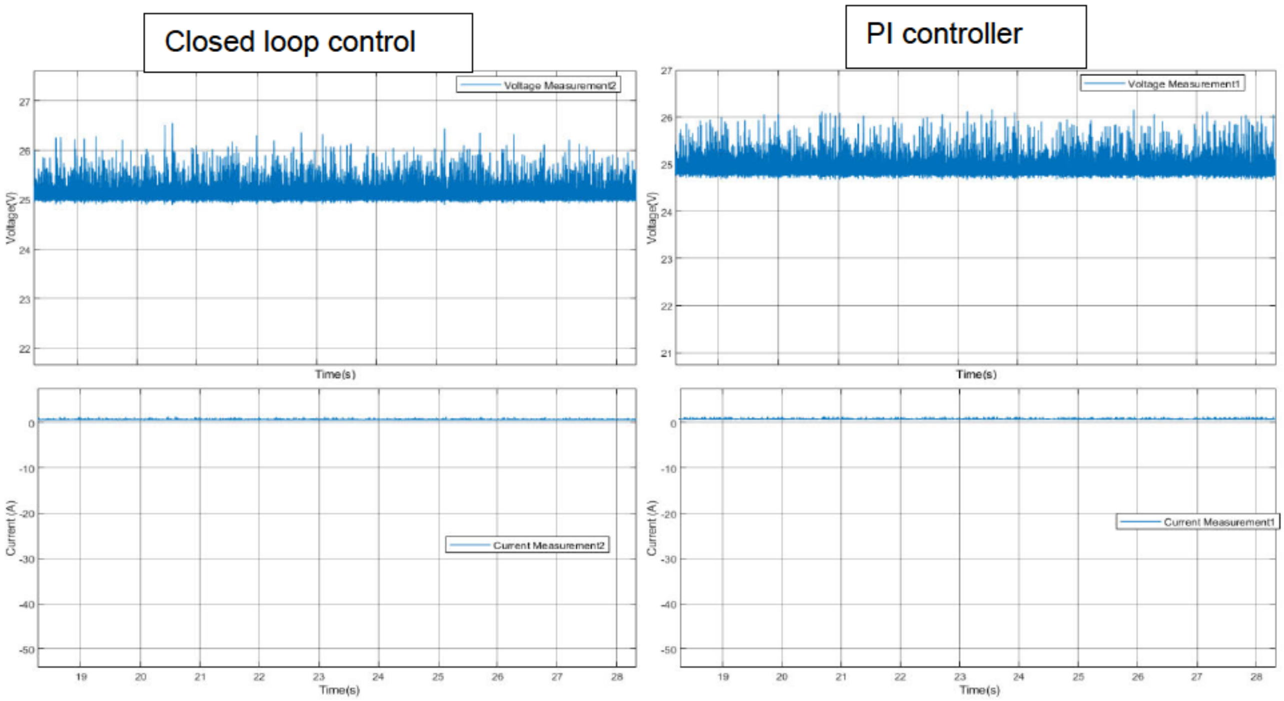


Figure 14 Voltage and current waveform of closed loop and PI control (high wind speed(400m/s))

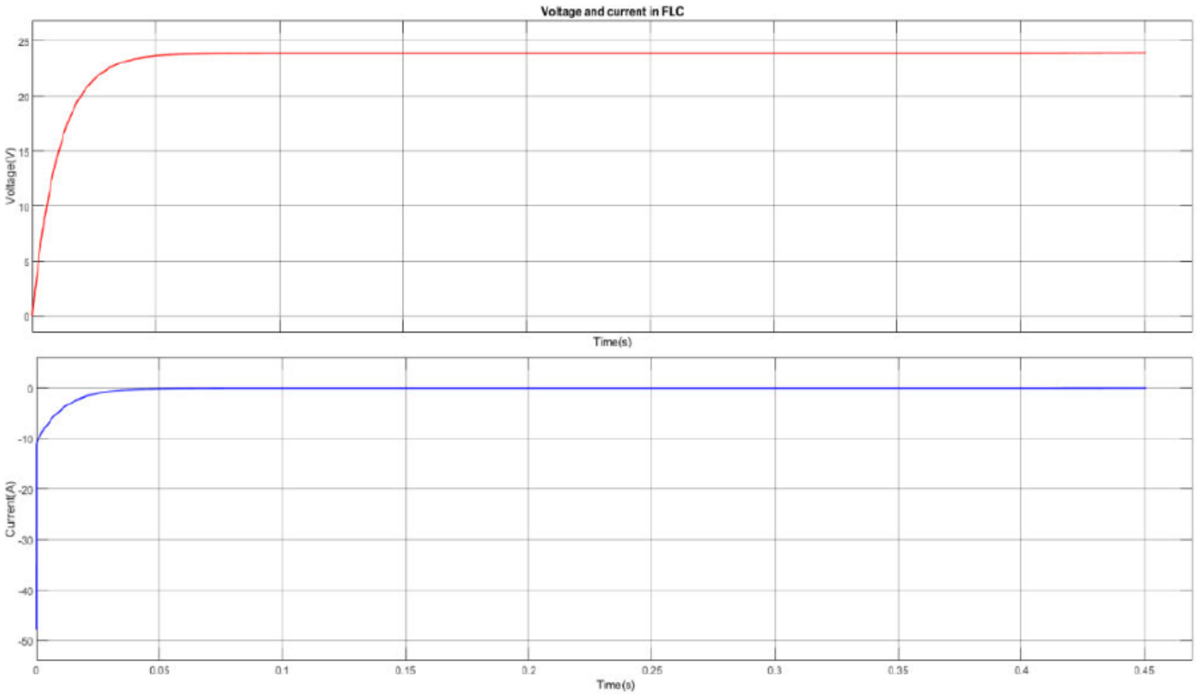


Figure 15 Voltage and current waveform of FLC (high wind speed(400m/s))

Voltage and Current Waveform of a Closed Loop, PI and FLC at a Wind speed of 400m/s are given in the Figures 14 and 15 respectively. it can be inferred from this that the ripple voltage and Current are higher in closed loop control compared to the PI Controller. It is around 1.5 V in closed loop control and 1.2 V in PI controller. In closed loop control there is 16.38% overshoot in the waveform at high wind speed. While in PI controller and FLC, there is no overshoot in the settling time is reduced. At low wind speed(270m/s), ripple voltage is around 0.3 V in closed loop controller and 0.15 V ripple at low voltage from the input. While there is no overshoot in the closed loop and PI controller.

4.2.2 SEPIC Converter

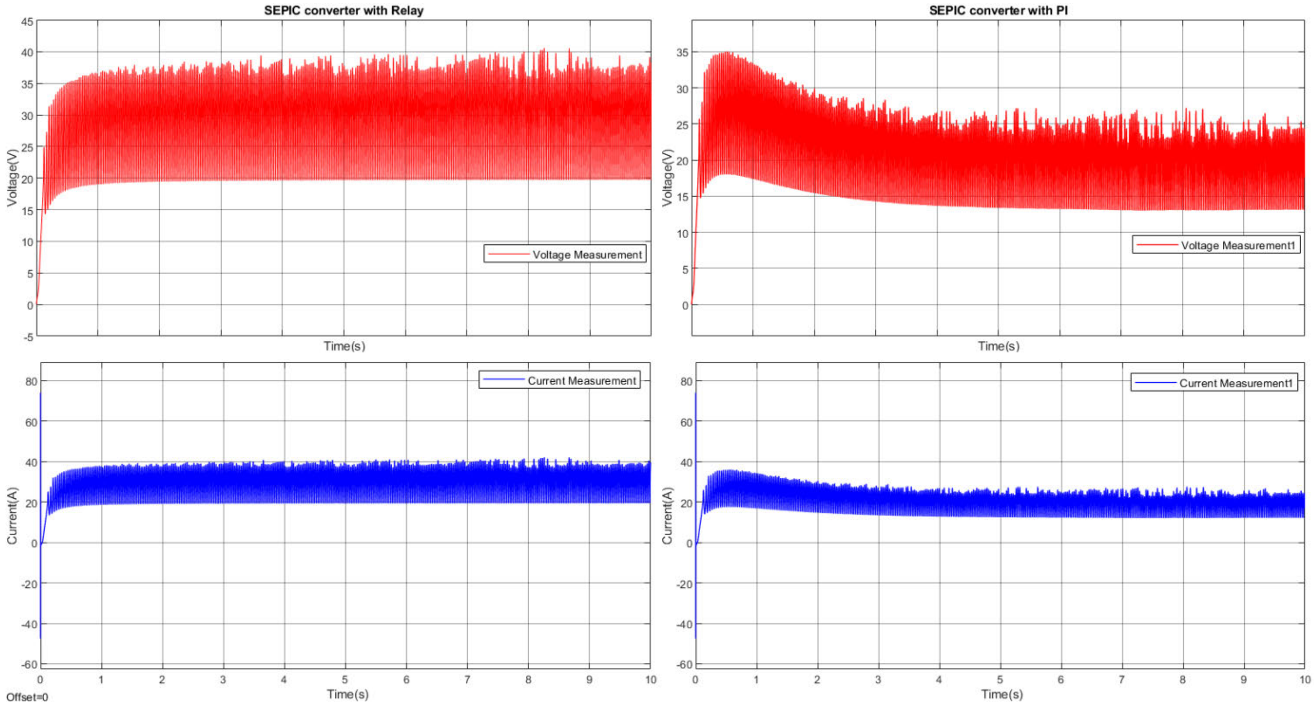
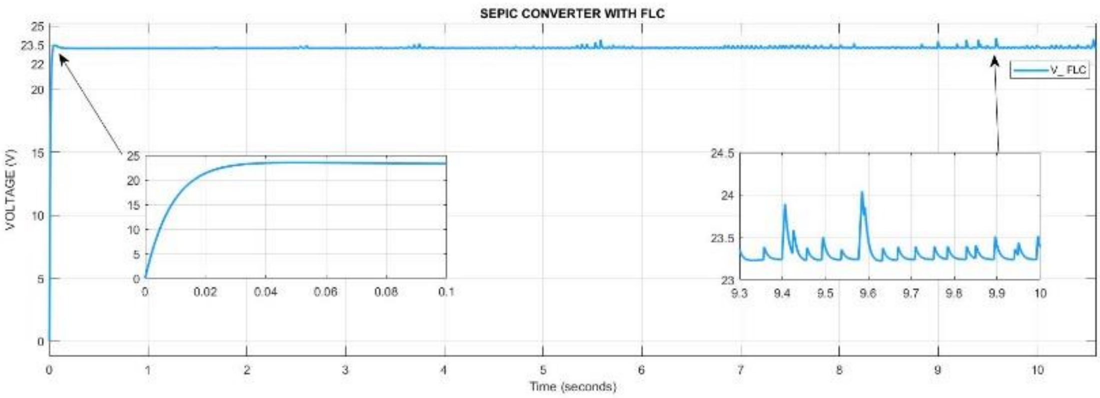


Figure 16 Current and voltage waveform of closed loop and PI controller at high wind speed(400m/s)

Figure 16 shows the SEPIC waveform for PI control system with a closed loop to output voltage and current target relations. It is noticeable the ripple voltage is too much high as compared to Buck converter. The ripple voltage and current in SEPIC converter are 16-18 V, 15-16 A at wind speed 400m/s. It will decrease to 7~8 V, 5~6 A by installing PI controller in DC-DC converter for high wind condition. At low wind speed of 290 m/s, the voltage ripple of relay control is significantly lower than that the high wind speed, about 0.4V. But there is a small over-shoot in low wind speed There is inadequate voltage regulation in two cases of the closed loop and the PI controller as well. Use Fuzzy Logic Controller (FLC) in the DC-DC converter to efficiently reduce the voltage and current ripples and improve the voltage regulation.



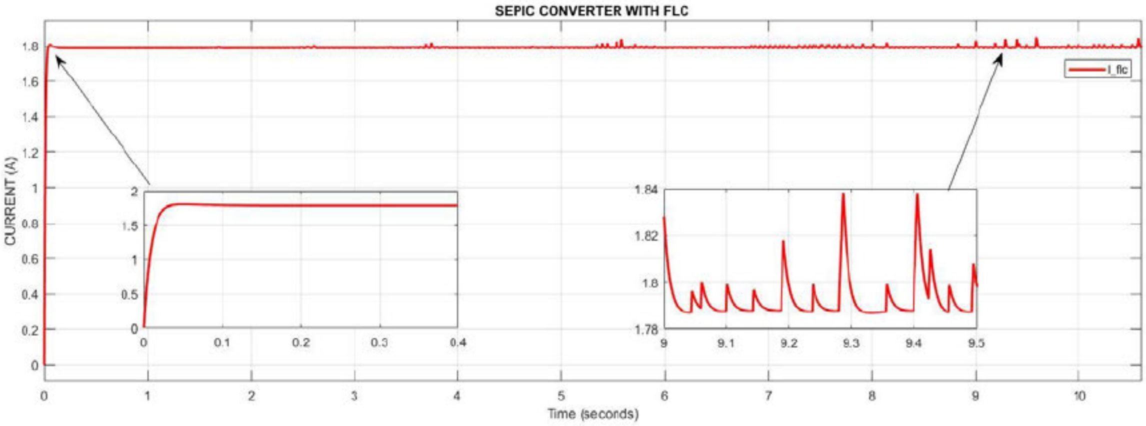


Figure 17 Voltage and current waveforms for SEPIC converter with FLC (400 m/s)

Figure 17 represents the voltage and current waveform of the SEPIC converter using Fuzzy Logic Controller (FLC). Ripple voltage is around 1.5V, which is quite good as compared to closed loop controller and PI controller. Voltage regulation is too good to comparative to other controller while settling time is also reduce which is quite good for the battery charging.

4.2.3 Cuk Converter

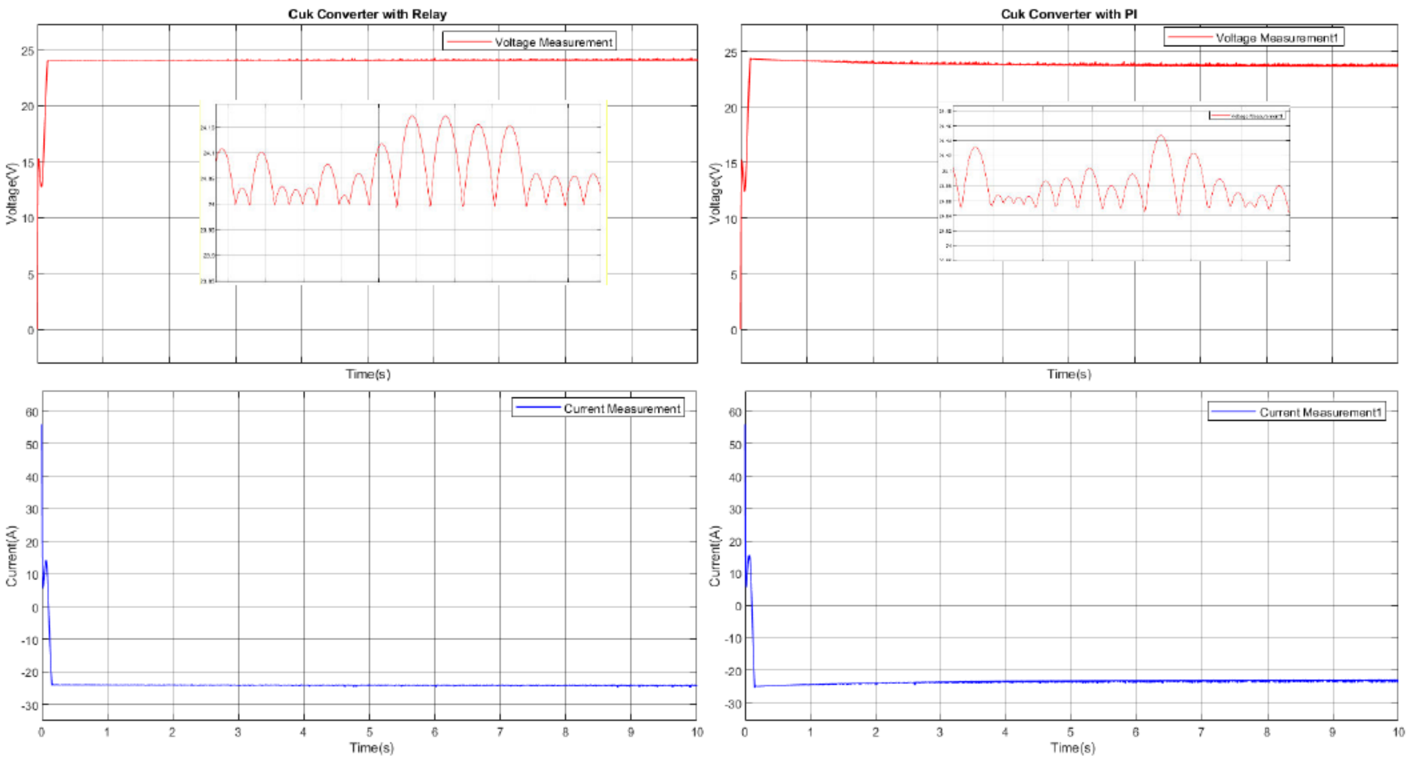


Figure 18 Voltage and current waveform of Cuk converter with closed loop and PI controller(400m/s)

The output voltage and current waveform of the Cuk converter with closed loop and PI control technique is shown in Figure 17. Compared with the buck and SEPIC converter, the ripple voltage and current under the higher wind speed are accommodated at about 0.15 V and 0.10 A. The Cuk converter with installed PI controller reduces the ripple voltage and current to 0.5 V. Voltage regulation performance, between the PI controller and the closed loop is better than the previous converter. To increase the battery charging ability, incorporate the Fuzzy Logic Controller in the Cuk converter to control the voltage and current ripples within the battery.

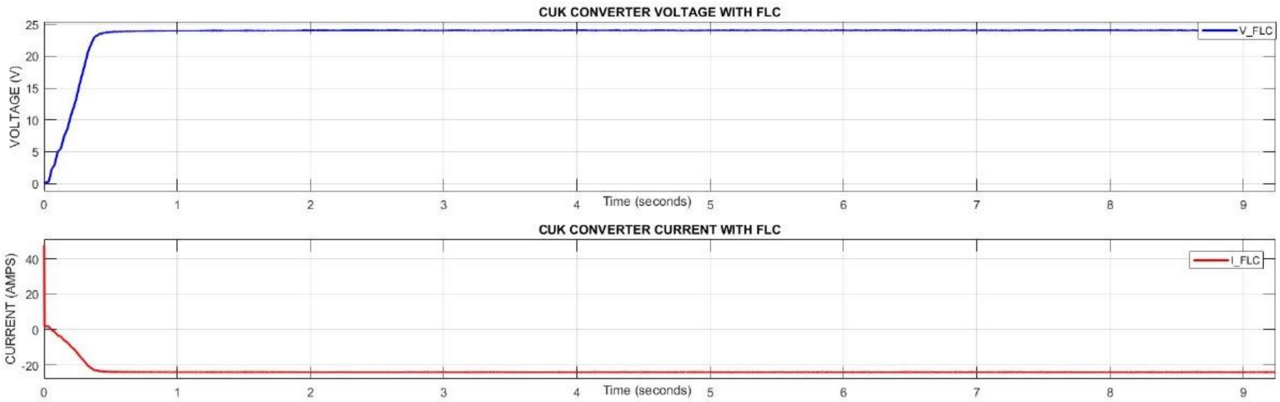


Figure 19 Voltage and current waveform of CUK converter with FLC (400 m/s)

Figure 19 represent the voltage and current waveform of Cuk converter with Fuzzy Logic Controller. it represents it is very neglected ripple voltage and current in the voltage and current waveform. Voltage regulation is superior with FLC as compared the other converter.

5. COMPARISON OF CONVERTER

Figure 19,20 represent the response of the closed loop (Relay control), PI controller and Fuzzy Logic Controller (FLC) of Buck and Cuk converter. Relay controller, PI and Fuzzy Logic Controller are compared in each of the responses.

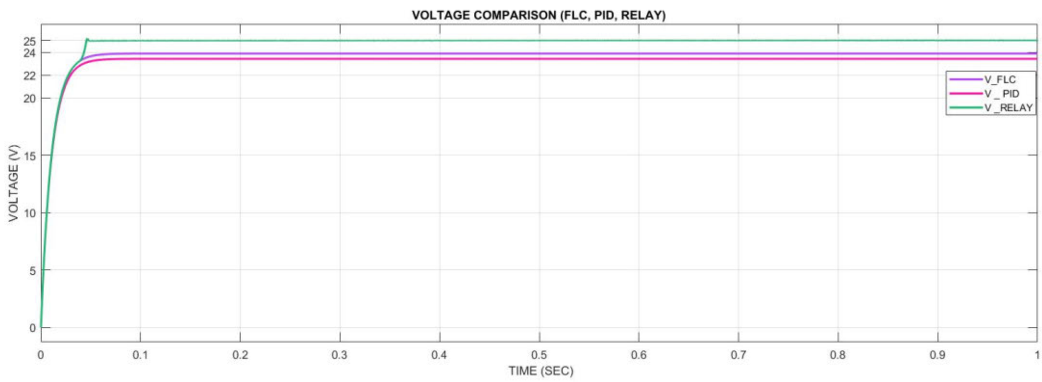


Figure 20 Voltage comparison of Buck converter high speed

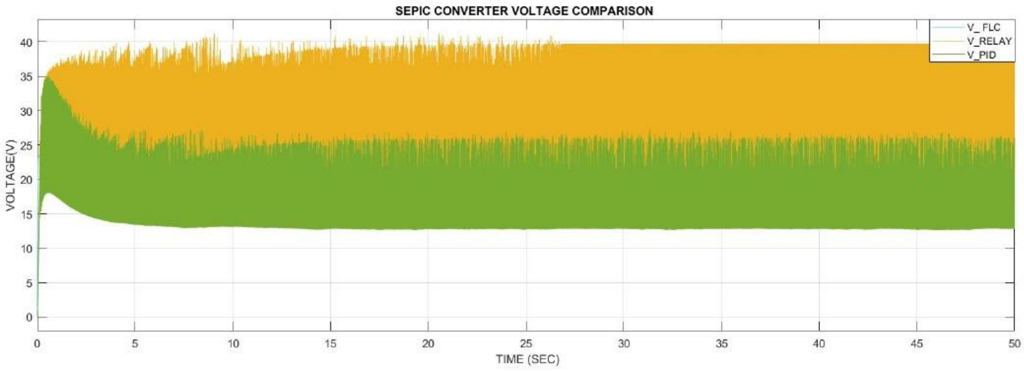


Figure 21 Voltage comparison of SEPIC converter at high wind speed

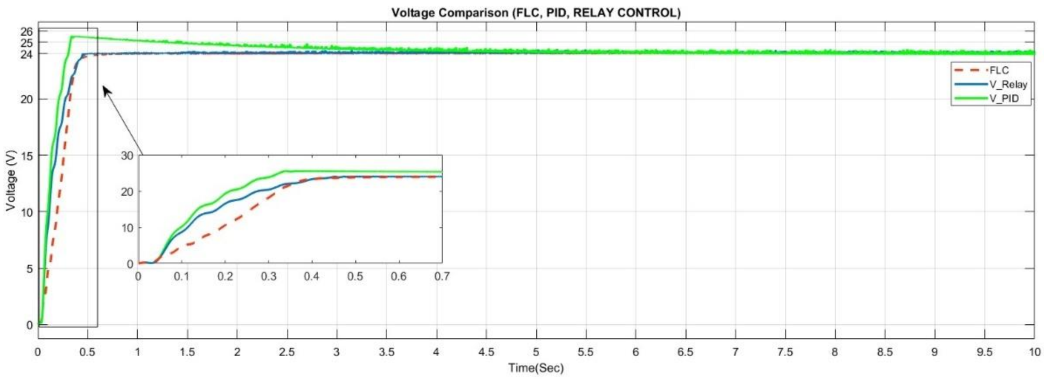


Figure 22 Voltage comparison of CUK converter at high wind speed

Following Tabel 5 represent the comparison of Buck, SEPIC and Cuk converter for high wind speed and low wind speed.

Table 5 Comparison table

Type of converter	Type of control technique	Important result (high wind speed-400m/s)	Important result (low wind speed-270m/s)	Comments
Buck	Closed loop (Relay)	Ripple – 1.4V Settling Time- 0.032 Overshoot- 16.38% Voltage regulation-Good	Ripple – 0.3V Settling Time- 0.032 Overshoot- Nill Voltage regulation-Excellent	At high wind speed, ripple and settling time is less in FLC as compared to relay and PI controller. There is overshoot present in the closed loop but not into PI and FLC. Voltage regulation is excellent with FLC. However, at low wind speed ripple voltage is too low as compared to high wind speed. Regulation of output voltage is excellent with all controllers at low wind speed.
	PI controller	Ripple – 1.1V Settling Time- 0.027 Overshoot-Nill Voltage regulation-Good	Ripple – 0.15V Settling Time- 0.027 Overshoot-Nill Voltage regulation-Excellent	
	FLC controller	Ripple – 0.047V Settling Time-0.025s Overshoot- Nill Voltage regulation-Excellent	Ripple – 0.04V Settling Time-0.025s Overshoot- Nill Voltage regulation-Excellent.	

SEPIC	Closed loop (Relay)	Ripple – 18 V Settling Time-0.02s Overshoot- Nill Voltage regulation-Poor	Ripple – 0.4 V Settling Time-0.02s Overshoot- 2.1% Voltage regulation-Poor	Highest ripple voltage in closed loop and PI controller as compared all three converters. While voltage regulation is poor in closed loop and PI while FLC provide less ripple and better voltage regulation. At low wind speed, overshoot is present with all three controllers. Voltage regulation is good in PI and excellent regulation in FLC.
	PI controller	Ripple – 8V Settling Time-0.023s Overshoot- 64.25% Voltage regulation-Poor	Ripple – 0.27V Settling Time-0.023s Overshoot- 3.25% Voltage regulation-Good	
	FLC controller	Ripple – 1.2V SettlingTime-2.00E-3 Overshoot- 2.6 % Voltage regulation-excellent	Ripple – 1.2V SettlingTime-2.00E-3 Overshoot- 1.75% Voltage regulation-excellent	
Cuk	Closed loop (Relay)	Ripple – 0.18 Settling Time-0.29 Overshoot-Nill Voltage regulation-excellent	Ripple – Neglected Settling Time- 0.6 Overshoot-Nill Voltage regulation-excellent	There is minimum ripple present in all three controllers with closed loop and PI while in FLC controller ripple is neglected, but settling time is more in FLC as compared to closed loop and PI controller. At low wind speed, ripple voltage is neglected in all three controllers, while voltage regulation is good in both at high speed and low speed.
	PI controller	Ripple – 0.12 Settling Time-0.21 Overshoot- Nill Voltage regulation-excellent	Ripple – Neglected Settling Time- 0.4 Overshoot- Nill Voltage regulation-excellent	
	FLC controller	Ripple – Neglected Settling Time-0.3 Overshoot- Nill Voltage regulation-excellent	Ripple – Neglected Settling Time -0.3 Overshoot- Nill Voltage regulation-excellent	

6. CONCLUSION

This study compares the performance of three non-isolated DC-DC converter topologies—buck, SEPIC, and Cuk, compared these converters' performance utilising the three control techniques in various wind situations: closed loop, PI and Fuzzy Logic Controller (FLC). The Fuzzy Logic Controller (FLC) is clearly better at minimising ripple voltage and current across all three converter topologies. The Cuk converter and FLC were the best combo for minimising ripple voltage during battery charging. This has significant implications for wind energy applications, as consistent and well-regulated voltage output is essential for efficient and reliable battery charging, especially amid variable wind speeds.

While the buck converter with FLC also exhibited excellent voltage regulation and minimal ripple at low wind speeds, its performance deteriorated under high wind conditions, highlighting its limitations in handling extreme variations in input voltage. Even with FLC, the SEPIC converter had high ripple (1.8 V) voltage at high wind speeds and failed to regulate voltage, rendering it unsuitable for varying wind energy input applications. Consequently, the study concludes that the Fuzzy Logic Controller paired with the Cuk converter topology is the most suitable choice among the configurations evaluated in terms of controlling ripple voltage and achieving optimal performance for battery charging applications.

The findings also support the idea that converter architecture and control mechanism greatly affect wind energy conversion and storage system efficiency and performance. The Fuzzy Logic Controller outperformed the PI controller and closed-loop control in voltage regulation and settling time, demonstrating its adaptability and robustness to wind conditions. These findings show that fuzzy logic control can improve wind energy system stability and reliability, particularly during battery charging. The study also shows that converter topologies matter, with the Cuk converter minimising ripple voltage the greatest for battery longevity and system stability.

In conclusion, the thesis makes important contributions to the investigation and enhancement of wind energy application DC-DC converters. The outcomes not only justify the superior performance of Fuzzy Logic Controllers, but also emphasize that the different characteristics of each converter topologies need to be considered handling control strategies along with Fuzzy Logic Controllers to achieve the best results. The results provided in this work help to advance the development of wind energy conversion and storage technologies, improve the sustainability and reliable of our future energy sources.

7. FUTURE WORK

Develop and test a physical prototype of the most promising concept under field conditions, verify the simulation results and compare with existing solutions and generalize this study. This entails selecting the components, designing the converter circuit, and linking it into a wind turbine and battery system. This testing would allow the engineering team the ability to determine the system abilities and failures in a wide range of wind speeds, temperatures, and load situations in the real world. Advance control techniques such as adaptive Fuzzy Logic, neural network control, model predictive control may be investigated for system efficiency and in this direction real-time wind speed and load demand may be concept to be included in system model. Besides, hybrid energy sources including Solar PV and grid integration studies can further broaden the application and support energy infrastructure. Longer battery lifespan and charging, and safety could be guaranteed by also implementing an advanced battery management system (BMS) when required as well. To determine the economic and environmental sustainability of the proposed system, a full cost-benefit analysis and environmental impact assessment is needed. Moreover, also explore the other non-isolated and isolated DC-DC converter and lookout for the better wind energy conversion system.

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APPENDICES

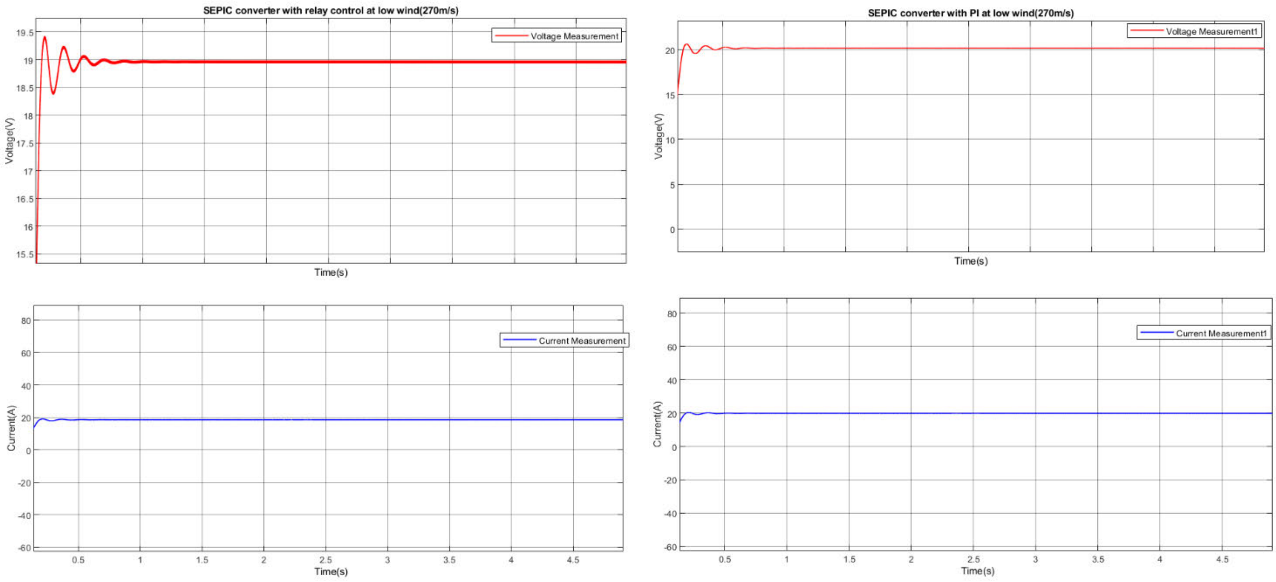

Figure 23 voltage and current for SEPIC for relay and PI at low wind speed (270m/s)

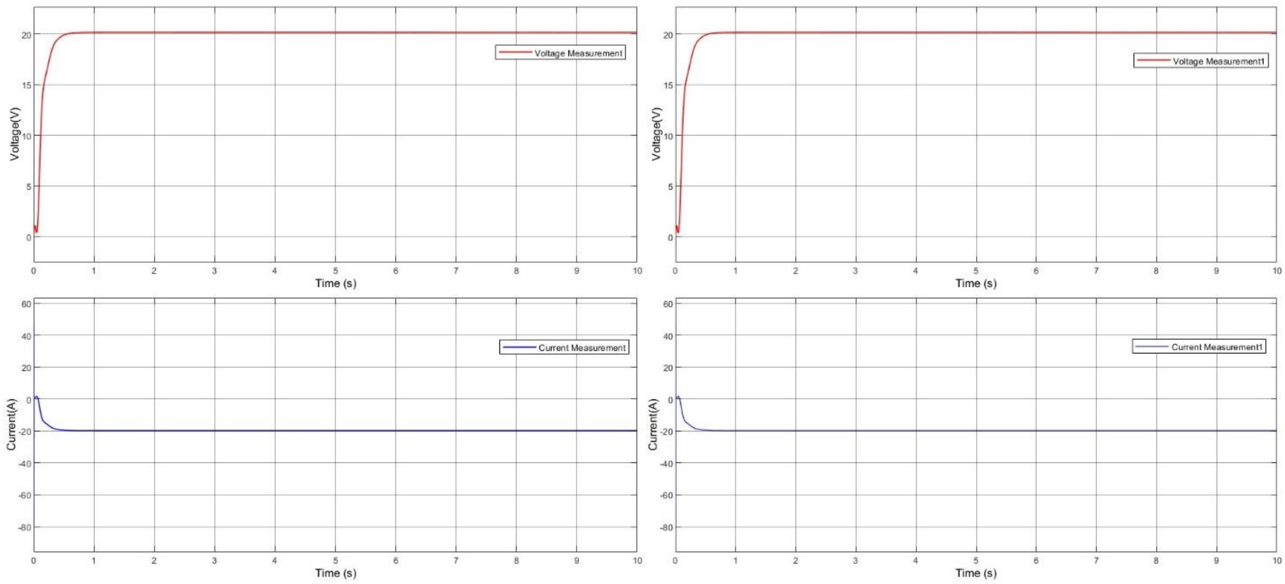

Figure 24 voltage and current for CUK for relay and PI at low wind speed (270m/s)