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Adaptive ANFIS-based MPPT for PV-powered green ships with high gain SEPIC converter

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ABSTRACT

To align with global climate goals, the International Maritime Organization (IMO) has enforced strict measures to reduce greenhouse gas emissions from the shipping industry by promoting energy efficiency and cleaner propulsion methods. Ship engines remain major contributors to environmental pollution due to their dependence on fossil fuels and inefficient propulsion systems, highlighting the need for clean and sustainable alternatives. This study aims to design a renewable energy-based marine power system that effectively stores and utilizes solar energy, improving overall efficiency and reducing emissions for process innovation. A hybrid setup was developed using photovoltaic (PV) panels, batteries, and a bidirectional DC-DC converter to enable flexible power flow during both charging and discharging cycles. An adaptive neuro-fuzzy inference system (ANFIS)-based maximum power point tracking (MPPT) algorithm was employed alongside a SEPIC converter to enhance energy extraction from the PV system under dynamic conditions. The integrated system achieved a power extraction efficiency of 97.12%, confirming the effectiveness of the ANFIS-based MPPT strategy and showcasing the viability of intelligent renewable energy solutions in maritime applications.

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1. INTRODUCTION

In their quest of "green ships," research organizations from several maritime nations are actively investigating alternative forms of energy as vital components of ecologically friendly ship designs. In accordance with Jain *et al.* [1], the investigation looks at a variety of prospective energy sources, such as solar energy, wind power, nuclear, biomass, and fuel cells. The notion of "green ships" is strongly related to the sustainable design of vessels and is thought to have enormous potential for future growth.

Because of its characteristics like as rapid performance and inherent fault tolerance, the switched reluctance motor (SRM) is seen as a possible option for marine applications. In this study, solar-powered SRM powers the ship's propeller. To function properly, the SRM requires a constant and continuous source of power, as recommended by Narendra *et al.* [2]. The literature describes several converters with efficient controllers for this purpose. This study applies a single-ended primary inductance converter (SEPIC) to boost the DC voltage generated by the photovoltaic (PV) system. An adaptive neuro-fuzzy inference system based maximum power point tracking (MPPT) algorithm is presented to route the input signal to the converter's integrated pulse width modulation (PWM) generator.

The maritime sector is a significant contributor to global greenhouse gas (GHG) emissions, accounting for approximately 2–3% of global CO_2 output. In response, the International Maritime Organization (IMO) has mandated aggressive emission reduction strategies to drive the shipping industry toward more sustainable and energy-efficient practices. Among the alternatives being explored, renewable energy integration, particularly solar energy, has emerged as a promising avenue to reduce fuel consumption and environmental impact. Photovoltaic systems offer a clean and sustainable energy source, especially when deployed on ships with ample surface area for panel installation. However, the highly dynamic maritime environment characterized by fluctuating irradiance and temperature poses challenges for consistent and optimal power extraction from photovoltaic systems. To address this, various maximum power point tracking (MPPT) algorithms have been developed. Traditional MPPT techniques, while useful, often fail to deliver high tracking accuracy under rapidly changing conditions.

Recently, intelligent control methods such as adaptive neuro-fuzzy inference systems (ANFIS) have gained attention for their ability to adaptively optimize power tracking in nonlinear environments. When combined with power electronic converters like SEPIC, these systems provide stable voltage output and efficient energy transfer, making them ideal for marine applications.

Despite advancements in MPPT algorithms and power conversion techniques, existing studies on renewable energy integration in marine propulsion systems have several limitations:

- Limited use of intelligent MPPT techniques: Most maritime PV systems still rely on conventional MPPT algorithms (e.g., P&O, incremental conductance), which underperform in rapidly changing sea conditions. The use of adaptive AI-based control systems like ANFIS in this context remains underexplored.
- Lack of bidirectional power management: Many designs focus solely on unidirectional power flow, neglecting the operational flexibility offered by bidirectional DC-DC converters for dynamic energy storage and load balancing.
- Insufficient real-time validation in maritime conditions: While several studies have modeled PV-battery systems theoretically, few have addressed the control stability and efficiency of these systems in the real-world fluctuating environment encountered at sea.
- Integration of SEPIC with AI-based MPPT is rarely addressed: There is a clear gap in the literature where ANFIS-based MPPT is used in conjunction with SEPIC converters specifically designed for maritime solar systems.

2. METHOD

The suggested technology uses a solar-powered switched reluctance (SR) motor to drive a mechanically attached propeller. This device is intended to solve unexpected spikes in speed and torque caused by a conventional induction motor-based propulsion system. The SR motor is used to rectify and stabilize irregularities in speed and torque, resulting in more regulated and responsive operation. This combination of photovoltaic power with an SR motor primarily harvests green energy from solar sources, but it also assures a reliable and effective propulsion system by reducing unexpected changes in motor performance. The integrated PV-powered SR motor improves the overall efficiency and steadiness of the electric propulsion system, especially in the face of rapid variations in speed and torque.

To optimize the output power of the solar-powered system, a highly effective maximum power point tracking technique is required. Traditional MPPT systems suffer issues such as fluctuations around the maximum power point and decreased efficiency owing to fluctuations in solar energy and temperature. The proposed solution to these challenges is an adaptive MPPT system based on the adaptive neuro-fuzzy inference system (ANFIS).

In this design, a SEPIC converter is used to increase the fluctuating and low-level DC voltage generated by the PV system. An adaptive neuro-fuzzy inference system-based MPPT method generates a control signal using the PV cells' real voltage (V_PV) and current (I_PV) as inputs, successfully minimizing mistakes. This control signal is then supplied to a PWM, which produces PWM pulses that control the SEPIC Converter's switching processes. This produces a controlled DC output voltage.

The study presents an adaptive neuro-fuzzy inference system-based maximum power point tracking technique designed for a SEPIC, which achieves a remarkable efficiency of 97.12%. Figure 1 depicts the block diagram for integrating the ANFIS-based MPPT algorithm with the SEPIC Converter in the framework of an SR motor-driven maritime propulsion system. This figure depicts the interrelated components and their functions in the system, demonstrating how the suggested method may be used to optimize the effectiveness of the SEPIC Converter for maritime propulsion using a switching reluctance (SR) motor.

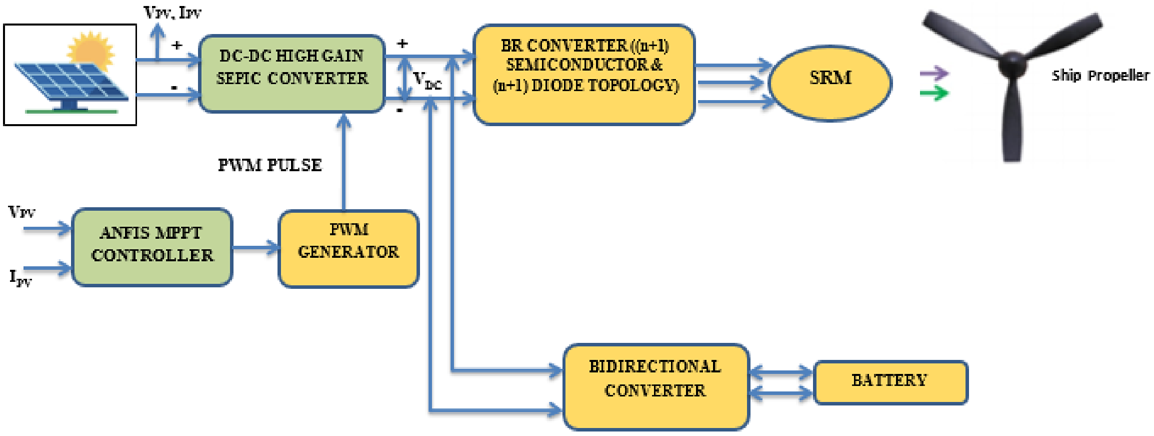

Figure 1. Proposed framework: solar-powered SRM for ship propulsion system

2.1. Sepic converter design

A single-ended primary inductor converter is a form of DC/DC converter introduced by Alexander *et al.* [3] produce an output voltage that can be greater, lower, or equal to the input voltage. The SEPIC converter's duty cycle determines how much electricity it generates. The SEPIC, which consists of two inductors, L1 and L2, works as a boost or buck converter, allowing input voltage to be transformed to output voltage without altering polarity, as was suggested by Mutarraf *et al.* [4]. The energy communicated by capacitor C1 and inductor L1 produces a greater switching voltage than that of a normal boost converter. Figure 2 depicts the circuit design of the SEPIC converter.

According to Karafil [5] as well as Shukla and Singh [6], the converter's static gain is stable across a wide range of input voltages. The sum of the voltages at the input and output in a SEPIC converter is about identical to the voltage that exists across the switch. In the suggested design, the converter runs with a 140 V source voltage and produces a 450 V output was designed by Killi and Samanta [7]. This setting guarantees that the converter performs efficiently and consistently, allowing the predetermined input as well as output levels of voltage within the design constraints.

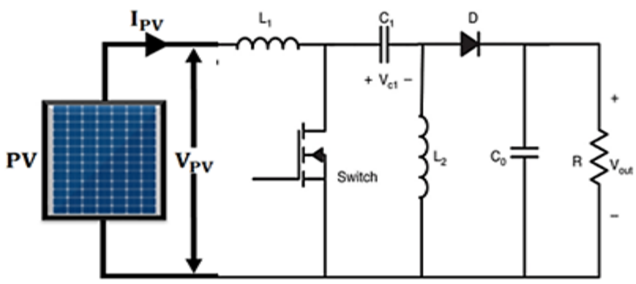

Figure 2. SEPIC circuit topology

Ponnusamy *et al.* [8] created the duty cycle and intrinsic components inside the circuit, which play an important part in deciding how much the SEPIC converter steps up or down the voltage in 2020. These elements help to improve the converter's overall performance and efficiency. The output of an ideal SEPIC converter may be expressed as (1).

$$V_0 = \frac{D*V_i}{1-D} \tag{1}$$

SEPIC converters have been developed to generate voltages at the output that can be higher or lower than the voltage being converted, all while sustaining the same polarity, as recommended by Singh *et al.* [9] and Falin [10]. SEPIC converters are excellent for a variety of applications due to their versatility. Applying Kirchhoff's voltage law to the circuit route containing Vs, L1, C1, and L2 makes it easier to describe and analyze voltage properties within the SEPIC converter. Kirchhoff's voltage law, which is a fundamental concept in circuit analysis, states that the total of voltages in every loop that is closed in a circuit matches the sum of electromotive forces inside that loop. Applying this formula to the given elements in the SEPIC converter provides insight into the system's voltage dynamics and behavior.

$$-V_s + V_{L1} + V_{C1} - V_{L2} = 0 \quad (2)$$

The diode will be turned off when the switch is closed, as shown in Figure 3. The DT intervals cross voltage L1 are as in (3).

$$V_{L1} = V_s \quad (3)$$

The diode will be turned on when the switch is opened, as shown in Figure 4. The KVL on the outside lane is as (4).

$$-V_s + V_{L1} + V_{C1} + V_0 = 0 \quad (4)$$

At interval (1 - D) T, the average voltage transverse to an inductor is zero in periodic operation, is becomes (5).

$$\mathrm{V_S}(\mathrm{DT}) - \mathrm{V_0}\,(1 - \mathrm{D})\mathrm{T}{=}0 \quad (5)$$

When the duty cycle of the ratio switch is D, the outcome is as (6).

$$D = \frac{\mathrm{V_0}}{\mathrm{V_0} + \mathrm{V_S}} \quad (6)$$

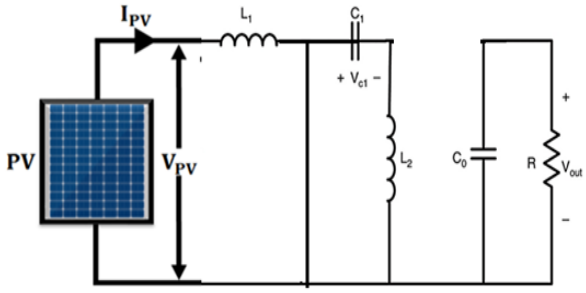

Figure 3. SEPIC at the closing switch and diode off

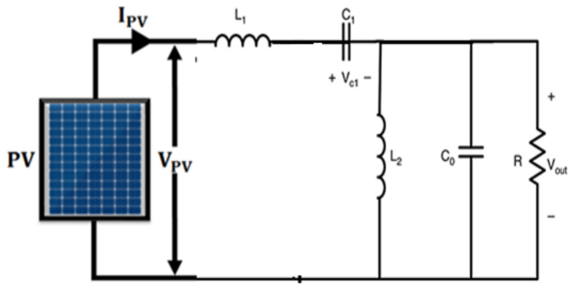

Figure 4. SEPIC when switch ON and diode ON

2.2. ANFIS-based MPPT controller

Photovoltaic (PV) systems are widely used to deliver power to the electrical grid as environmentally beneficial alternatives to fossil fuel-based energy sources. Min *et al.* [11] suggested them in 2008 as ecologically beneficial, sustainable, and requiring low maintenance. Despite these benefits, two major obstacles prevent broad adoption: the high cost of installation and limited energy conversion efficiency, particularly under variable climatic conditions. The energy conversion efficiency of solar PV systems generally ranges from 9% to 17%, and researchers in [12] note that this unpredictability, together with the initial expenses, limits the larger implementation of solar PV systems into power networks. Addressing these difficulties is critical to increasing the economic feasibility and overall efficacy of solar power generation technology. MPPT methodologies are divided into two categories: classic methods for MPPT and soft computing. Alassi and Massoud [13] suggested MPPT approaches. The decision between conventional and soft computing approaches is influenced by system complexity, environmental unpredictability, and the necessity for consistent performance under a variety of operating situations. Integrating these approaches can considerably improve MPPT efficiency and flexibility in photovoltaic systems.

To address issues such as oscillations at the greatest power point and lower efficiency caused by unexpected solar radiation and temperature fluctuations, Jegadeeswari [14] advocated using soft computing approaches such as fuzzy logic controllers and artificial neural networks. These approaches provide more flexible and resilient control strategies than classic MPPT algorithms, resulting in improved performance under varied environmental circumstances.

The adaptive neuro fuzzy inference system, developed by Deepak *et al.* [15], is a hybrid system that incorporates the strengths of the two previously stated systems. Fuzzy logic controllers succeed in dealing with unpredictable data without depending on a highly accurate mathematical model, successfully managing nonlinear data, and achieving quick convergence. Jegadeeswari *et al.* [16] introduced artificial neural networks (ANN) in 2024, which use learning algorithms to function in ill-defined and time-varying situations, depending on learned data rather than previous knowledge of PV parameters.

Figure 5 depicts an MPPT controller overseeing a converter connected to a photovoltaic (PV) system. Zhang [17] developed the application of ANFIS for MPPT controllers. ANFIS is particularly good at dealing with fluctuations in solar temperature and radiation by instructing the MPPT controller to modify the operating point closer to the maximum power point (MPP). This strategy is anticipated to increase the efficiency and resilience of MPPT systems amid changing environmental circumstances. The dynamic control mechanism enables the system to continually adjust to changing environmental circumstances, ensuring the PV system runs at or near its maximum power production regardless of fluctuations in sunshine intensity and temperature.

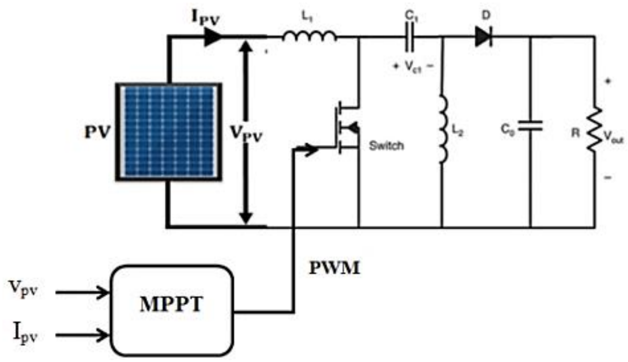

Figure 5. SEPIC converter coupled with PV

2.3. Bidirectional converter design

In accordance with Hedlund [18], Liu *et al.* [19], and Karshenas [20], energy consumption is quickly growing, as is the need for renewable power generation. Incorporating solar energy sources with battery backup, such as the batteries, is critical for addressing the intermittent nature of solar electricity. This technique enables power produced during daytime to be preserved and utilized during periods of low sunshine or high demand, increasing the dependability and predictability of renewable energy supply. Viswanatha *et al*. [21] and researchers in [22] designed a grid integration by ensuring a continuous power supply and reducing energy use during the day and night. Bidirectional DC-DC converters (BDCs) are essential components in renewable energy systems, allowing for efficient bidirectional power transfer among solar panels, batteries, and the grid. This functionality improves power supply stability and dependability, allowing for steady energy flow in and out of the storage device as needed. Figure 6 illustrates the essential layout of a bidirectional DC-DC converter designed by Leong [23]. In this configuration, a solar power (PV) panel powers the DC grid.

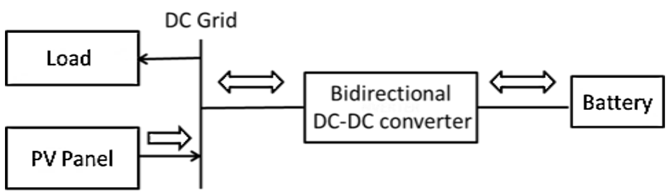

Figure 6. Bidirectional DC-DC converter

Renewable energy systems can use a non-isolated unidirectional buck-boost DC-DC converter to effectively regulate energy flow, optimize battery utilization, and interface with the grid for increased stability and dependability. To allow for bidirectional power transmission, the converter uses a single power storage unit, commonly an inductor. Vinifa *et al.* [24], [25] introduced a feature that is achieved by merging two bidirectional switches, which are generally implemented using MOSFETs or IGBTs. These switches enable the converter to efficiently regulate battery charging and discharging, responding to changing voltage levels and maximizing energy transmission between the batteries, solar cells, and the grid as needed.

Figure 7 illustrates the non-isolated bidirectional DC-DC converters used in our research. To further comprehend their operation, consider the two types of operation. Bidirectional operation replaces diodes with controlled switches. Switch S1 is triggered in buck mode, and switch S2 is triggered in boost mode.

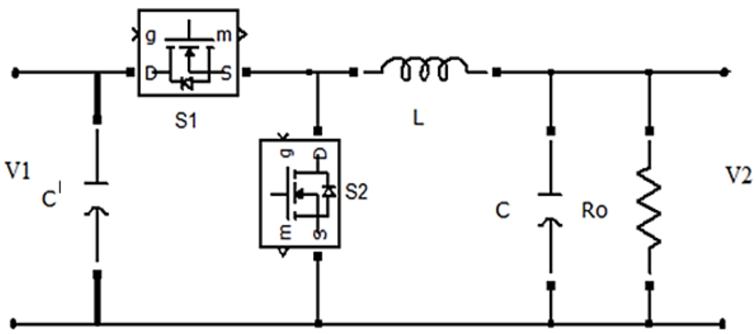

Figure 7. Bidirectional converter circuit

2.3.1. Buck mode of operation

The buck mode of operation is a DC-DC converter configuration designed to step down the input voltage to a lower output voltage with high efficiency. This section presents the design and analysis of the key parameters involved, as outlined below:

– Duty cycle: the (1) delivers the switch's duty cycle, which is estimated to be 90-95% efficient.

$$D = \frac{V_{OUT}}{V_{IN}*\eta} = \frac{24}{48*0.9} = 0.55 \quad (7)$$

The (7) includes V_{IN} (input voltage), V_{OUT} (desired output voltage), and η (converter efficiency, estimated at 90-95%).

– Selecting an inductor: An inductor's fluctuation current ranges from 10% to 20% of the output current. The (8) explains an inductor's ripple current.

$$\Delta I_L = (0.1\ to\ 0.2) *\ I_{OUT}$$
$$\Delta I_L = 0.1\ x\ 2$$
$$\Delta I_L = 0.2\ A \quad (8)$$

I_{OUT} denotes the application's needed output current. Because of the reduced output current ripple, the maximum output current increases with increasing inductor value. The inductor value is calculated using (9).

$$L = \frac{DTs*(V_d-V_o}{\Delta I_L})$$
$$L = \frac{0.5*40*10^{-6}*(48-24)}{0.2}$$
$$L = 2.4\ mH \quad (9)$$

– Selecting an output capacitor: To reduce output voltage ripple, choose low ESR capacitors. In general, the generated ripple voltage is 10% of the total output voltage. The (10) is used to compute the capacitor's output values given a certain output voltage ripple.

$$C_{OUT} = \frac{(1-D)*V_{OUT}*TS^2}{8L*\Delta V_{OUT}}$$
$$C_{OUT} = \frac{(1-0.5)*24*(40*10^{-6})^2}{8*(2.4*10^{-3})*0.24}$$
$$C_{OUT} = 4.16\ \mu F \quad (10)$$

Where C_{OUT} = output capacitance, ΔV_{0UT} = desired output voltage ripple.

2.3.2. Boost mode of operation

The boost mode of operation is a DC-DC converter configuration that increases the input voltage to a higher output voltage while maintaining high conversion efficiency. This section discusses the design and calculation of the main parameters as described below:

– Duty cycle: the (11) delivers the switch's duty cycle, which is estimated to be 90-95% efficient efficiency.

$$D = 1 - \frac{V_{OUT}}{V_{IN} * \eta} = 1 - \frac{24}{48 * 0.9} = 0.55 \quad (11)$$

The (11) includes V_{IN} (input voltage), V_{OUT} (desired output voltage), and η (converter efficiency, estimated at 90-95%).

– Selecting an inductor: An inductor's ripple current varies between 10% and 20% of the output current. The (12) describes the ripple current of an inductor.

$$\Delta I_L = (0.1\ to\ 0.2) * I_{IN}$$
$$\Delta I_L = 0.1\ x\ 2$$
$$\Delta I_L = 0.2\ A \quad (12)$$

I_{IN} indicates the program's needed input current. Because of the lower output current ripple, the inductor's value rises, allowing for the maximum permissible output current. The inductor's value is calculated using (13).

$$L = \frac{DTs * (V_d}{\Delta I_L})$$
$$L = \frac{0.5 * 40 * 10^{-3} * 24}{0.2}$$
$$L = 2.4\ mH \quad (13)$$

– Selecting an output capacitor: To decrease output voltage ripple, use low ESR capacitors. In general, the produced ripple voltage equals 10% of the overall output voltage. The (14) is used to calculate the capacitor's output values based on a certain output voltage ripple.

$$C_{OUT} = \frac{I_O * D}{f * \Delta V_O}$$
$$C_{OUT} = \frac{1 * 0.5}{(25 * 10^3) * 0.48}$$
$$C_{OUT} = 41.6\ \mu F \quad (14)$$

C_{OUT} stands for output capacitance, while ΔV_{0UT} represents the desired output voltage ripple. Table 1 displays the design values for the specified BDC.

Table 1. Calculated values for BDC circuit components

Parameters	Values
Duty cycle	0.55
Switching frequency	25 KHz
Output power	24 W
Battery voltage	24 V
Inductor	2.4 mH
Ripple in Inductor current	0.2 A
Input and output capacitor	4.16 μ F & 41.66 μF
Ripple in capacitor voltage	5%

3. RESULTS AND DISCUSSION

This study focuses on the speed management of an 8/6 SR motor powered by a PV-fed SEPIC converter. The converter is controlled using an ANFIS-based MPPT technique, and its performance is examined. Numerous characteristics for PV systems are explored, including temperature, electromagnetic radiation, current, voltage, and the corresponding waveforms are developed.

Figures 8(a)-8(d) depict the waveform of a solar panel. Figure 8(a) shows that the temperature is steadily maintained at 25 °C before suddenly increasing to 35 °C and remaining constant. The irradiation progressively kept constant at 800 w/sq.m and a rapid spike to 1000 w/sq.m at 0.2 s, which is further maintained constant in Figure 8(b). Figure 8(c) shows that the voltage progressively stabilizes at 125 V before rapidly increasing to 149 V after 0.2 seconds, where it remains constant. Figure 8(c) shows the voltage obtained from the solar panels.

The current rises significantly in the beginning. However, the current gradually falls and settles at 60 A before surging again with a 70 A spike at 0.2 s and remaining steady after that. Figure 8(d) shows the current produced from the solar energy system. Figures 9(a) and 9(b) illustrate the solar side converter's output current as well as voltage waveforms utilizing the ANFIS-based MPPT approach provided by the SEPIC converter.

Using a 140 V solar panel input, the SEPIC converter produces an output voltage of around 450 V. The addition of a high-gain SEPIC DC-DC converter boosts the electrical output of the PV panel, resulting in a conversion efficiency of around 97%. The SEPIC converter's output is then sent to the switched reluctance motor (SRM) by means of the bridge resonant converter, also known as the (n+1) semiconductor and (n+1) diode converter, which drives the SRM's phase windings. Figure 9(a) displays the voltage received from the converter. This voltage is crucial for powering the SRM and has a substantial impact on the motor's performance. The high-gain SEPIC converter, combined with BR converter, contributes to achieving the desired voltage levels for effective operation of the switched reluctance motor.

In the specified setup, the SEPIC converter achieves an output current of roughly 22 A. Figure 9(b) shows the current obtained from the converter. The output current is an important parameter because it controls the flow of electrical power to the switching reluctance motor (SRM), affecting its torque and speed characteristics.

Figure 10(a) (see Appendix) shows that the output voltage received from the battery is about 24 V. Figure 10(b) (see Appendix) illustrates the battery's output current of around 1.2 A. Figure 10(c) (see Appendix) shows that the battery's state of charge (SOC) is approximately 80%.

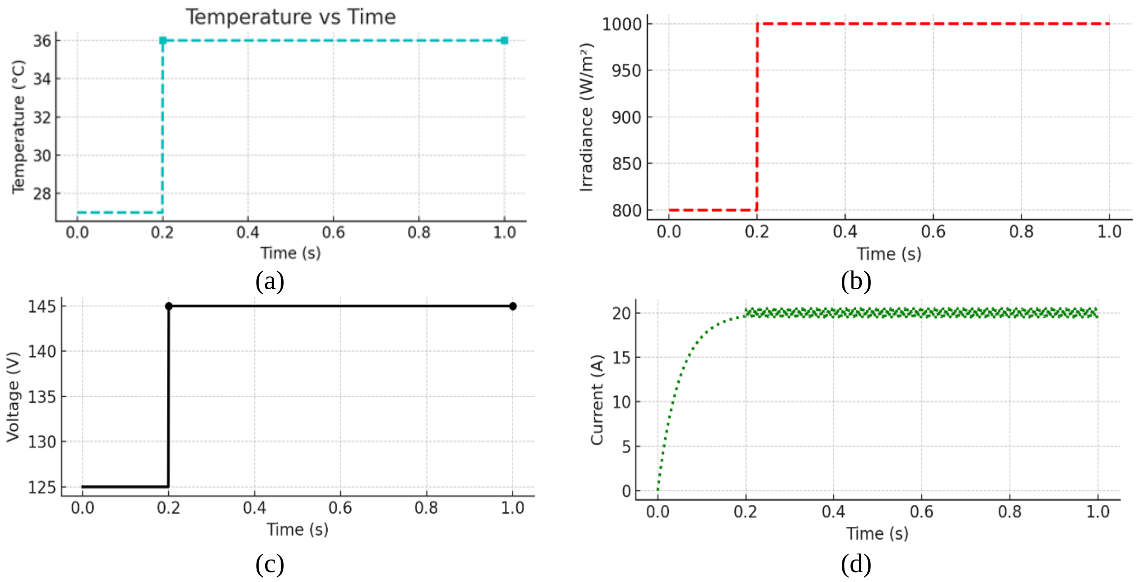

Figure 8. Various performance analysis of solar panels: (a) solar PV temperature, (b) solar PV irradiation, (c) solar PV voltage, and (d) solar PV current

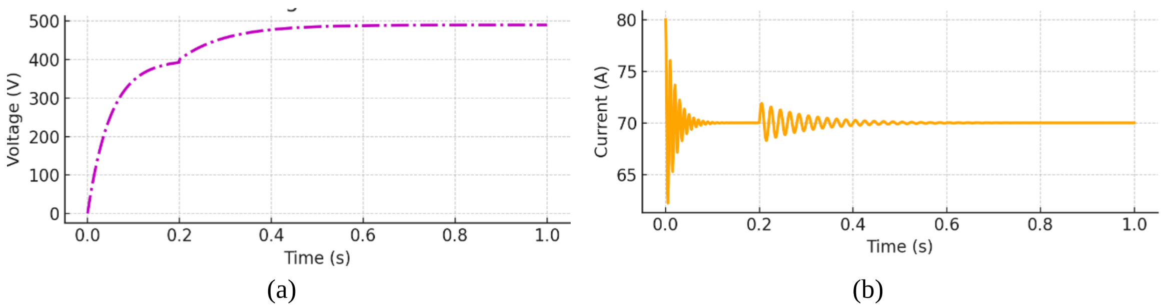

Figure 9. Performance analysis of SEPIC converter: (a) voltage waveform and (b) current waveform

4. CONCLUSION

This paper offers a novel propulsion system powered by SRM and fueled by renewable energy. Evaluate the effectiveness of the ANFIS-based MPPT technique and the SEPIC converter in solar PV and powered by batteries energy storage systems. SEPIC converters have better efficiency than conventional converters. This paper presents a 97.12% efficient MPPT approach for a SEPIC converter based on ANFIS. The simulation results show that the SEPIC converter is more effective and offers a large voltage gain. Green energy sources are perfect for battery-powered energy storage. As a result, the concept of a battery-powered energy storage system has been discussed.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

No new data were generated or analyzed in this study.

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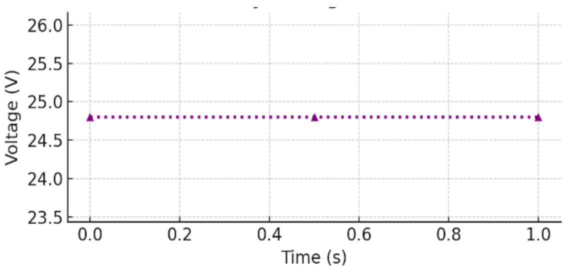
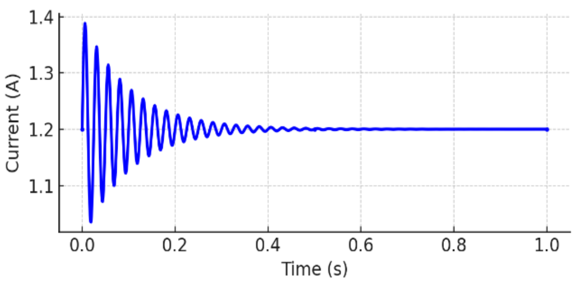
APPENDIX



(a)



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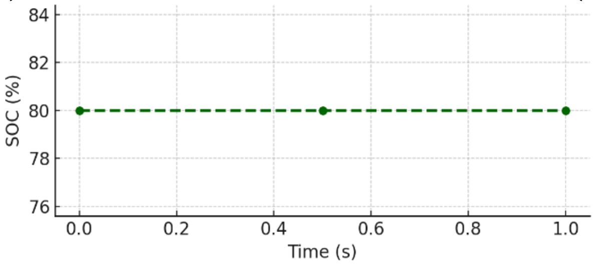

(c)

Figure 10. Performance analysis of battery: (a) voltage waveform, (b) current waveform, and (c) SOC waveform

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