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Design and Control of a MEMS-Based Multi-Source Energy Harvesting System using Buck-Boost Converter for Enhanced Power Management

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Abstract

This paper presents the design and control of a multi-source energy harvesting system that integrates solar panels and vibrational energy harvesters with a Buck-Boost converter to maximize energy extraction and power management. The proposed system captures energy from variable sources, effectively converting it into usable power stored in a lithium-ion battery with a capacity of 2.4 kWh. A detailed modeling approach is developed for the Buck-Boost converter, highlighting its capability to handle fluctuating input voltages from diverse sources. Two control strategies, Proportional-Integral (PI) and Fuzzy Logic Controllers, are designed to optimize the converter's performance, ensuring maximum power conditioning and stability under changing environmental conditions. Simulation results demonstrate the effectiveness of the proposed system, with a comparative analysis showing the Fuzzy Logic Controller's superior performance in managing nonlinearities and dynamic response. The study confirms the suitability of the Buck-Boost converter in multi-source energy harvesting applications, enhancing overall system efficiency and reliability in outdoor and industrial settings.

Keywords: Multi-Source Energy Harvesting; Buck-Boost Converter; MEMS-Based Harvesters; Fuzzy Logic Control; Power Conditioning

1. Introduction

The The growing demand for sustainable energy solutions in outdoor and industrial environments has driven significant interest in multi-source energy harvesting systems. These systems capture energy from multiple sources, such as solar, vibrational, and thermal, making them particularly useful in remote locations where conventional power supply infrastructure may be impractical or costly. By harnessing energy from diverse sources, these systems can provide a reliable power supply for various applications, ranging from low-power sensors to larger industrial equipment, ensuring continuous operation even under fluctuating environmental conditions [1-5].

Among the various renewable energy sources, solar and vibrational energy harvesters, particularly piezoelectric devices, are widely recognized for their potential to generate electricity in outdoor and industrial settings. Solar panels efficiently convert sunlight into electrical energy, providing substantial power output during daylight hours. However, their performance is inherently dependent on weather conditions and sunlight availability, which can be inconsistent. To complement solar energy, piezoelectric harvesters utilize mechanical vibrations prevalent in industrial machinery, transportation, or even human motion to generate electrical power. Though individually these harvesters often produce low power, their integration into a multi-source system significantly enhances the overall energy availability, addressing the intermittent nature of each individual source .

Energy storage solutions, such as lithium-ion batteries, play a crucial role in these systems by storing the harvested energy for later use. Lithium-ion batteries are favored due to their high energy density, long cycle life, and ability to efficiently charge and discharge at various power levels. When combined with advanced power conditioning strategies, these batteries ensure a stable energy supply to the load, even during periods when energy harvesting is insufficient. Proper management of the harvested energy through effective power converters is essential to maintain the efficiency and reliability of the system [6-9].

This research focuses on designing and implementing a multi-source energy harvesting system that integrates solar panels, piezoelectric energy harvesters, and a lithium-ion battery storage system, employing a Buck-Boost converter for efficient power management. The Buck-Boost converter is chosen for its ability to regulate varying input voltages from multiple sources and maintain the required output voltage for battery charging. The converter's performance is further enhanced through the design of two control strategies: a Proportional-Integral (PI) Controller and a Fuzzy Logic Controller [10]. The objectives of this research are to:

1. Develop a comprehensive model of a multi-source energy harvesting system incorporating solar and vibrational energy harvesters.

2. Design and simulate a Buck-Boost converter capable of adapting to varying input conditions while maximizing power transfer to the storage system.

3. Implement and compare PI and Fuzzy Logic Controllers to assess their effectiveness in achieving optimal power conditioning and system stability.

4. Analyze the overall system performance under different environmental conditions to validate the proposed approach.

The remainder of the article is organized as follows: Section 2 presents the system design and modeling approach for the multi-source energy harvesting system, detailing the configurations of the solar panels, piezoelectric harvesters, and lithium-ion battery. Section 3 discusses the design of the Buck-Boost converter and the control strategies employed. Section 4 provides a comparative analysis of the PI and Fuzzy Logic Controllers through simulation results. Section 5 discusses the findings, including the implications of the control strategies on system performance. Finally, Section 6 concludes the paper, summarizing the key insights and suggesting potential future research directions.

2. System Design And Configuration

The multi-source energy harvesting system is designed to harness energy from both solar panels and piezoelectric vibrational harvesters, integrating these sources with a lithium-ion battery for energy storage. This section outlines the configuration of each component, their interconnection, and the overall system setup aimed at maximizing energy capture and ensuring reliable power delivery.

2.1. Solar Energy Harvesting Subsystem

The solar energy harvesting subsystem consists of two 100 W solar panels configured to optimize power output under varying sunlight conditions as shown in Fig.1. These panels are connected in parallel to maintain a voltage range between 12 V and 24 V, depending on the solar irradiance, while providing a combined current of approximately 16 A to 20 A under optimal sunlight. This parallel configuration enhances the system’s reliability, as it allows each panel to operate independently and contributes to overall power generation even if one panel experiences shading or partial failure.

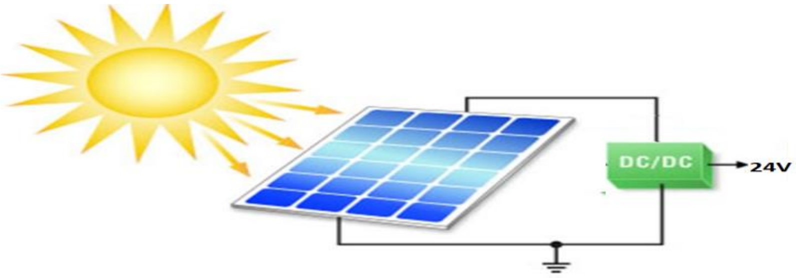

Fig.1: Solar Energy Harvesting System

2.2. Vibrational Energy Harvesting Subsystem

To complement solar harvesting, the system incorporates vibrational energy harvesters based on piezoelectric materials as shown in Fig.2. These harvesters are designed to capture mechanical vibrations commonly found in industrial settings, such as machinery operations, and convert them into electrical energy. Each harvester can produce between 10 mW and 50 mW of power, with a total output ranging from 50 mW to 250 mW depending on the vibrational intensity. The piezoelectric devices are strategically placed in high-vibration zones to maximize energy capture, and their output is rectified and regulated before being combined with the solar energy.

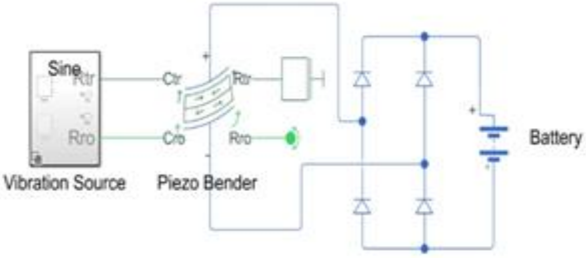

Fig.2: Vibrational Energy Harvesting System

2.3. Power Conditioning and DC-DC Converter

The core of the power management system is a Buck-Boost converter, which serves as a crucial interface between the energy harvesters and the battery storage. This converter is chosen for its flexibility in handling varying input voltages from the solar panels and piezoelectric harvesters, efficiently stepping up or stepping down the voltage as required to match the battery charging needs. The Buck-Boost converter dynamically adjusts to changes in input conditions, maintaining a stable output voltage to charge the battery effectively.

Control of the Buck-Boost converter is achieved through two strategies: a Proportional-Integral (PI) controller and a Fuzzy Logic Controller. The PI controller provides a straightforward approach to regulate the converter's output by adjusting the duty cycle based on voltage errors, while the Fuzzy Logic Controller enhances system performance under variable conditions by adapting to uncertainties and nonlinearities in the energy sources. Both controllers are designed to ensure optimal power conditioning, maximizing energy transfer to the lithium-ion battery.

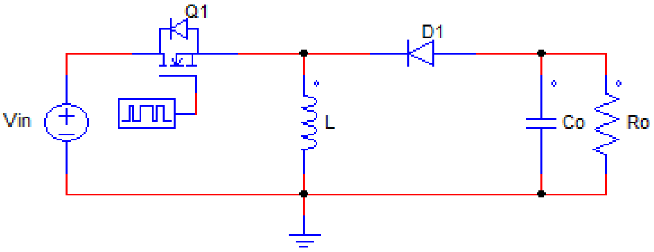

Fig.3: Power Conditioning Equipment for Energy Harvesting System

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2.4. Energy Storage Subsystem

The energy storage subsystem features a 24 V, 100 Ah lithium-ion battery, offering a total energy storage capacity of 2.4 kWh is shown in Fig.4. This battery serves as the primary energy reservoir, storing excess energy harvested during peak generation periods and supplying power when the harvesting subsystems are insufficient. The battery is equipped with a Battery Management System (BMS) to monitor and control charging and discharging processes, ensuring safe operation and extending the battery's lifespan. The BMS also helps in maintaining the state of charge (SOC) within safe limits and prevents overcharging or deep discharging.

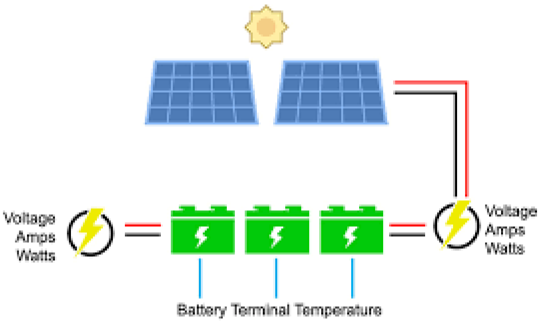

Fig.4: Energy Storage System

2.5. System Integration and Control

Integration of the solar and vibrational harvesters with the Buck-Boost converter and battery storage is achieved through a centralized power management unit. This unit is responsible for managing power flow between the sources and the battery, ensuring that energy is efficiently captured and utilized. The controllers are programmed to prioritize solar energy when available due to its higher power output, while vibrational energy acts as a supplementary source to maintain battery charge levels during periods of low solar irradiance.

The overall system is designed with an emphasis on modularity, allowing for easy scaling by adding additional harvesters or panels to increase power capacity. The integration of multi-source energy harvesting not only improves system reliability but also ensures that energy is available from one source when the other is insufficient, thus providing a consistent power supply for various applications in outdoor and industrial environments.

2.2 WORKING PRINCIPLE OF THE CONSIDERED DC-DC CONVERTER

The Continuous Conduction Mode (CCM) of the converter circuit is analyzed under this configuration, operating in two separate states: the switch ON state and the switch OFF state, as shown in Figures 5 and 6. The converter's switching behavior is evaluated using the waveforms illustrated in Figure 7.

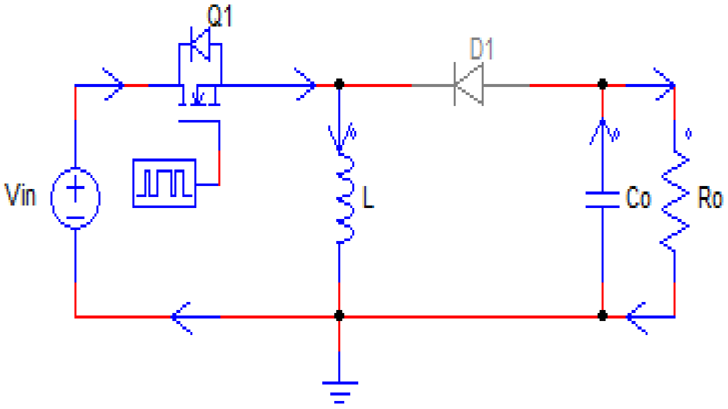

Fig.5: Considered DC-DC Converter during ON State

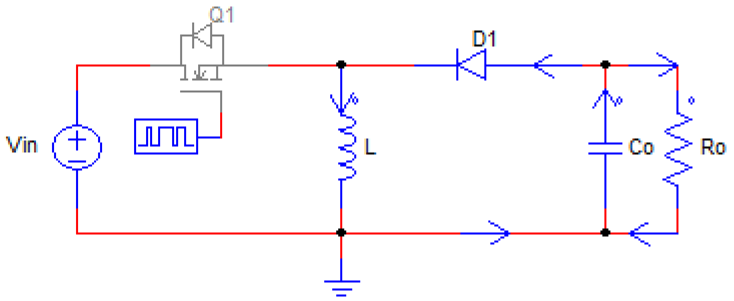

Fig.6: Considered DC-DC Converter during OFF State

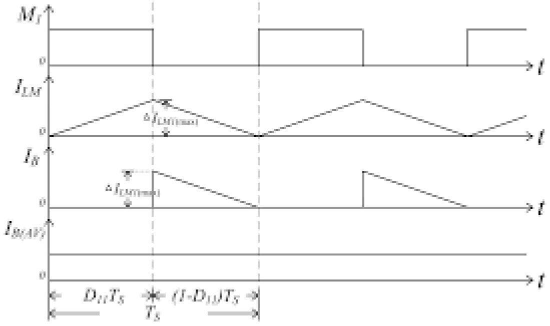

Fig.7: Charactestics of considered Converter

The relation between the output & input Voltage is given by,

$$\frac{d}{1-d} = \frac{V_0}{V_{in}} \tag{1}$$

Using the necessary parameters from the converter, the values of capacitance and inductance are determined with the help of Equations (2) and (10).

$$D = \frac{V_{out}}{V_{in}+V_{out}} = \frac{12}{24+12} = \frac{12}{36} = \frac{1}{3} = 0.33 \tag{2}$$

$$P_{out} = V_{out} \cdot I_{out} = 12V \cdot 10A = 120W \tag{3}$$

$$\Delta I_L = 0.3 \cdot I_{out} = 0.3 \cdot 10A = 3A \tag{4}$$

$$L = \frac{(V_{in} \cdot D)}{\Delta I_L \cdot f_s} = \frac{(24 \cdot 0.33)}{3 \cdot 100{,}000} = \frac{7.92}{300{,}000} \approx 0.0000264H = 26.4\mu F \tag{5}$$

$$C_{out} = \frac{I_{out} \cdot D}{\Delta V_{out} \cdot f_s} = \frac{10 \cdot 0.33}{2 \cdot 100{,}000} = \frac{3.3}{200{,}000} = 0.0000165F = 16.5\mu F \tag{6}$$

$$I_{in} = \frac{I_{out}}{D} = \frac{10A}{0.33} \approx 30.3A \tag{7}$$

$$C_{in} = \frac{I_{in} \cdot (1-D)}{\Delta V_{in} \cdot f_s} \tag{8}$$

$$\Delta V_{in} = 1V$$

$$C_{in} = \frac{30.3 \cdot (1-0.33)}{1 \cdot 100{,}000} = \frac{30.3 \cdot 0.67}{100{,}000} = 0.000203F = 203\mu F \tag{9}$$

$$I_{L(max)} = I_{out} + \frac{\Delta I_L}{2} = 10A + \frac{3A}{2} = 10 + 1.5 = 11.5A \tag{10}$$

2.3 Mathematical Modeling Of The Dc-Dc Converter

The mathematical model of state space averaging is ideal for developing a controller for DC-DC converters. Since the DC-DC converter functions in Continuous Conduction Mode (CCM), it produces two separate state equations: one for the ON state of the primary MOSFET and another for the OFF state [11-12]. The equations for the ON state are given in equations (11) to (13), while those for the OFF state are presented in equations (14) to (17).

$$x1 = \frac{\dot{V}_{\iota n} - V_{out}}{L} \tag{11}$$

$$x2 = \frac{1}{C}\left(\dot{\iota}_L - \frac{V_{out}}{L}\right) \tag{12}$$

$$x2 = \frac{1}{C}\left(\dot{\iota}_L - \frac{V_{out}}{R}\right)$$

(13)

$$x1 = D.\frac{V_{\iota n} - x\dot{2}}{L} + (1 - D).0 \tag{14}$$

$$x1 = \frac{\dot{D}.(V_{\iota n} - x_2)}{L}$$

(15)

$$x2 = D.\frac{x_1 - \frac{\dot{x}_2}{R}}{C} + (1 - D).\frac{x_1 - \frac{x_2}{R}}{C} \tag{16}$$

$$x2 = \frac{\dot{x}_1 - \frac{x_2}{R}}{C} \tag{17}$$

By calculating the weighted average over a full cycle of equations (11) to (17), the averaged model is obtained and expressed in equation (18).

$$\dot{x} = Ax + Bu \tag{18}$$

Where A= d A_{ON} + (1- d) A_{OFF}

B= d B_{ON} + (1 – d) B_{OFF}

$$A = \begin{bmatrix} \frac{-1}{L} & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}; B = \begin{bmatrix} \frac{D}{L} \\ 0 \end{bmatrix}$$

$$Y = Cx + Du \tag{19}$$

$$C = [0 \quad 1]\ ; D = 0$$

Once the mathematical model of the system was established, the parameters for the proposed system were computed and are presented in Table 1.

Table 1: System Parameters

Subsystem	Parameter	Specifications
Solar Energy	Power	2 × 100 W (200 W)
	Current Range	8 A to 10 A per panel
	Configuration	Parallel
Vibrational Energy	Power per Harvester	10 mW to 50 mW

	Total Power Output	50 mW to 250 mW
	Output Voltage	3 V to 12 V
	Rectifier	Full-wave bridge
Buck-Boost Converter	Input Voltage	10 V to 24 V
	Output Voltage	24 V
	Switching Frequency	100 kHz
	Inductor	47 µH to 100 µH, 10 A
	Capacitors (C_in, C_out)	47 µF to 220 µF
Lithium-Ion Battery	Capacity	24 V, 100 Ah (2.4 kWh)
	Max Charge Rate	10 A (240 W)
	Discharge Power	Up to 1 kW

Based on the given parameters, the system was simulated, and the converter's response without a controller is illustrated in Fig. 8. This highlights the need for a controller in the system.

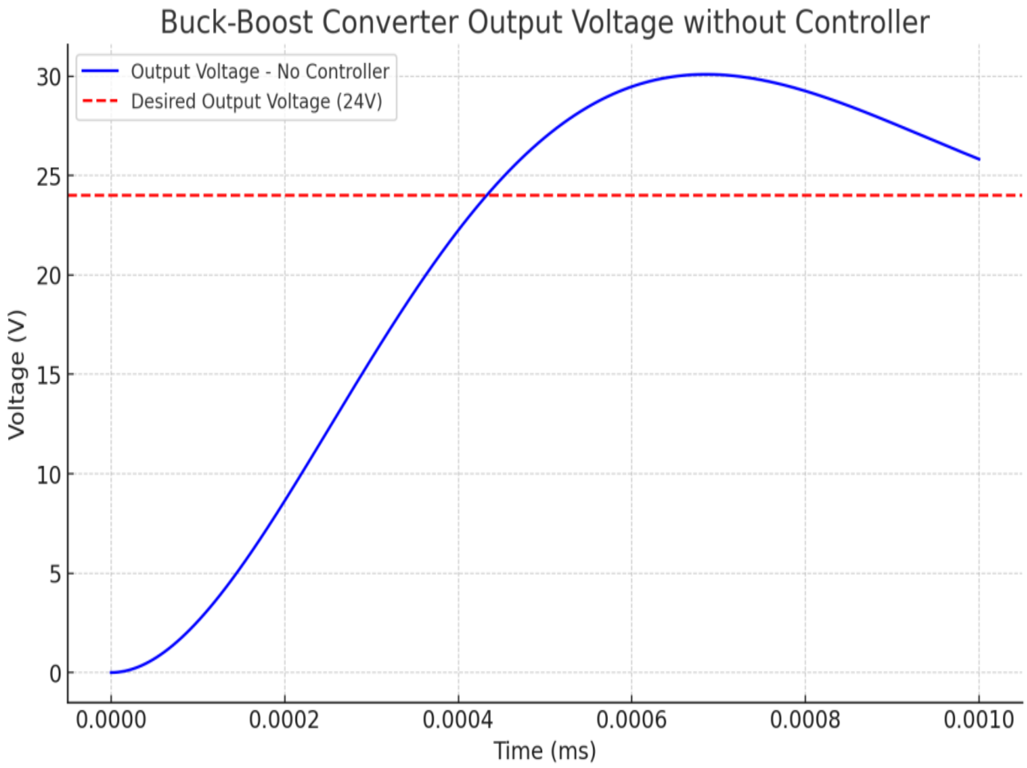

Fig.8: Response of system without any controller

3. Controller Design Issues

The converter must need a controller to get a steady response. Hence PI Controller is designed first and then to get a better performance a FSMC is designed[12].

3.1 **DESIGN OFPI CONTROLLER**

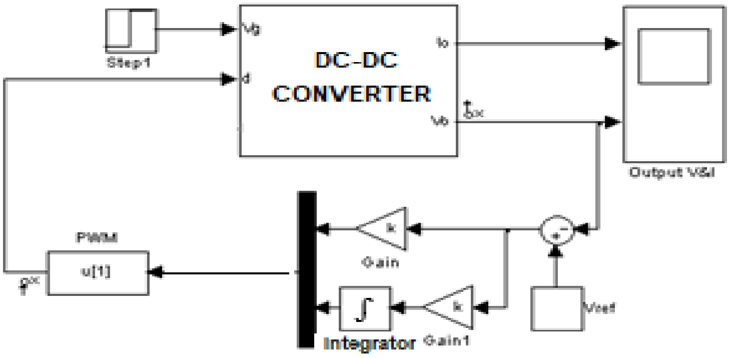

Fig. 9: Converter with PI Compensator

Figure 9 depicts the PI controller for the converter. The transfer function of the controller is expressed asKp+Ki/S. This controller is simulated in MATLAB and the outputs displayed in Figure 10.

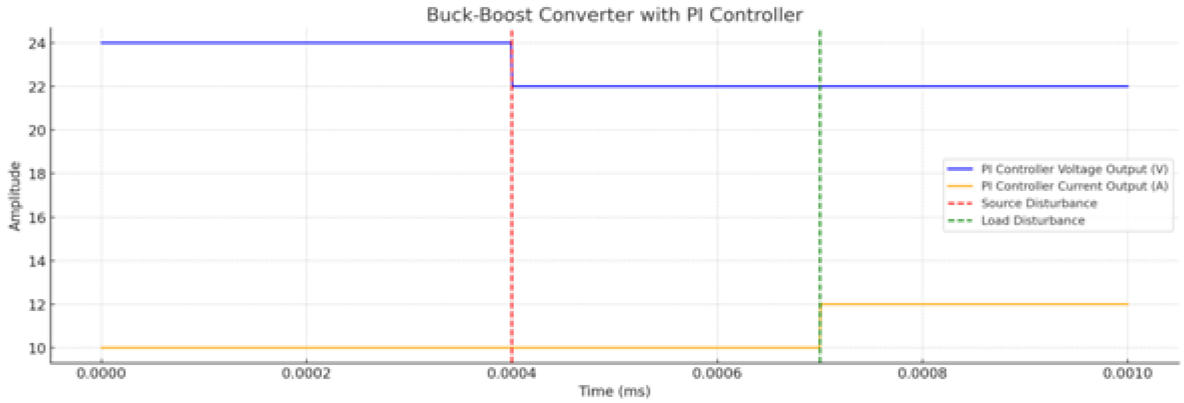

Fig. 10: Outputs of System with a PI Controller

3.2 CONVERTER WITH FLC CONTROLLER

A schematic diagram of the FLC for the DC-DC converter is presented in Fig. 11. The methodology for designing the controller is outlined in the following steps. Fig. 12 illustrates the controller design flowchart, while Fig. 13 depicts the FLC structure. Figs. 14 and 15 show the rule base, and the corresponding rules are provided in Table 2.

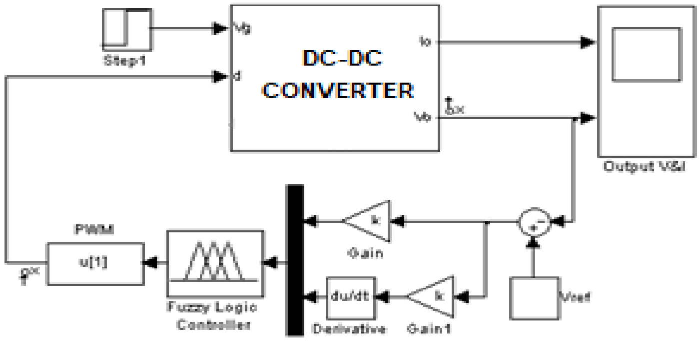

Fig. 11: Simulation Model of FLC for DC-DC Converter

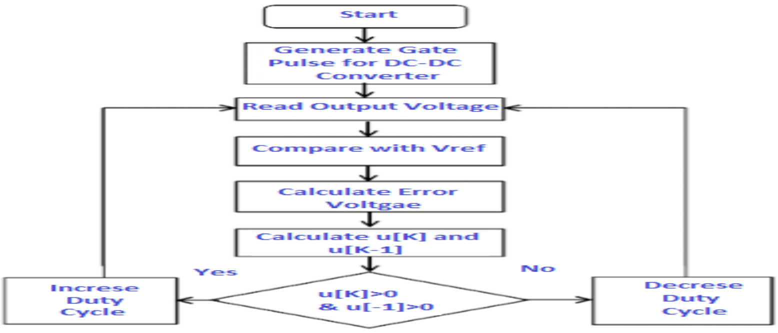

Fig.12: Flow Chart for the controller design using FSMC

Fuzzy Logic Controller

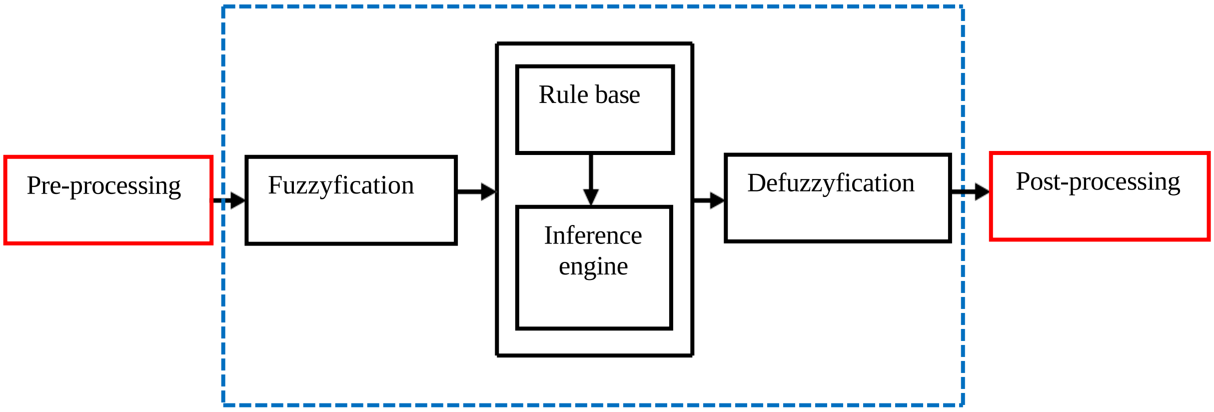

Fig.13: Structure of Fuzzy Logic Controller

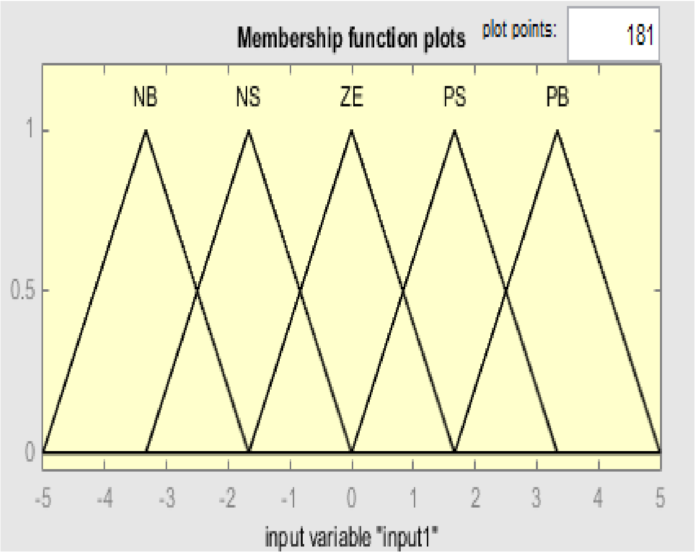

Fig.14: Error & Change in Error signal functions

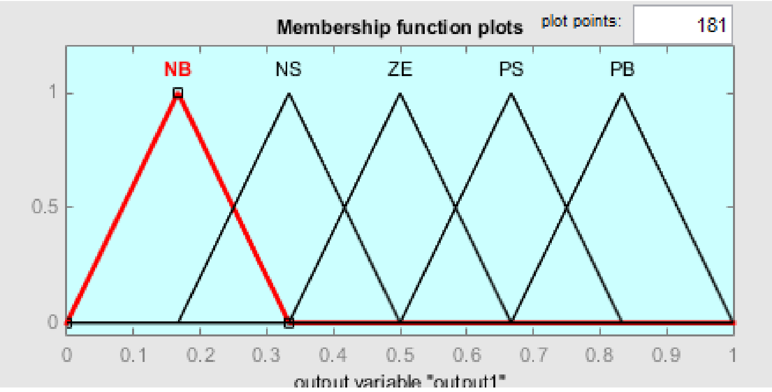

Fig.15: output Membership functions

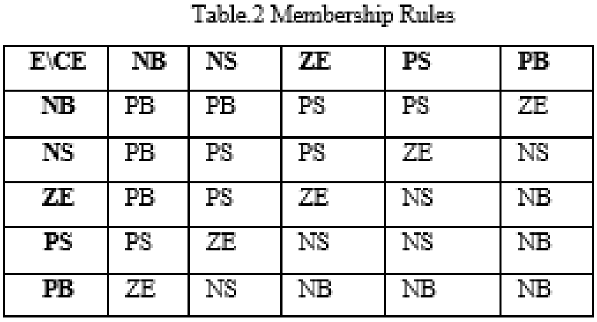

Table.2 Membership Rules

E\CE	NB	NS	ZE	PS	PB
NB	PB	PB	PS	PS	ZE
NS	PB	PS	PS	ZE	NS
ZE	PB	PS	ZE	NS	NB
PS	PS	ZE	NS	NS	NB
PB	ZE	NS	NB	NB	NB

4. Simulation Results

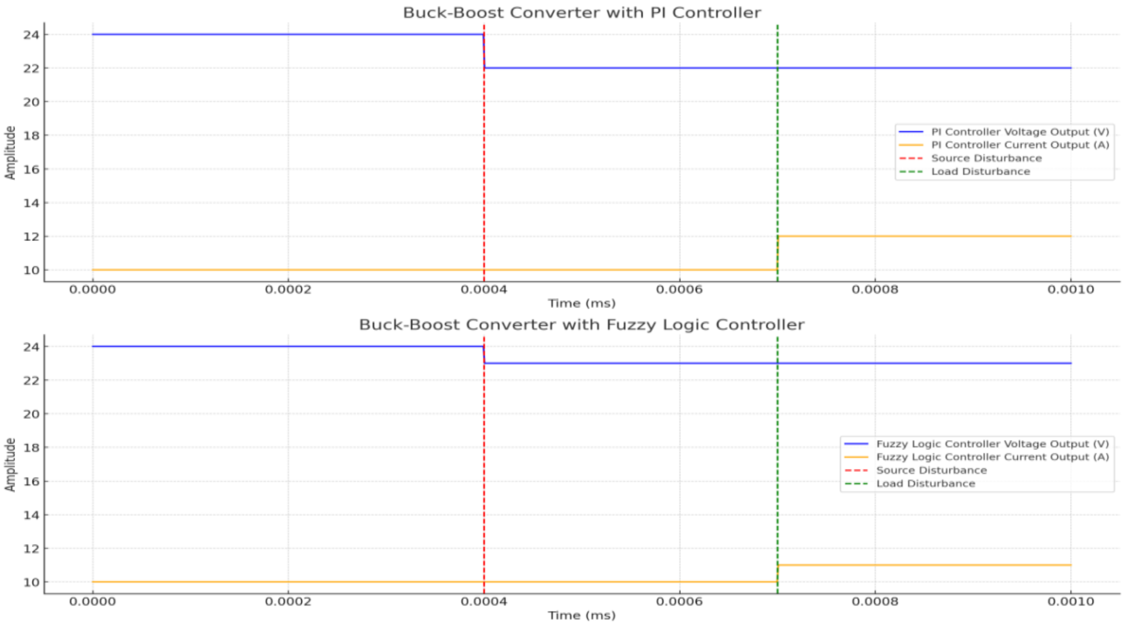

Fig.16: System response with PI and FLC

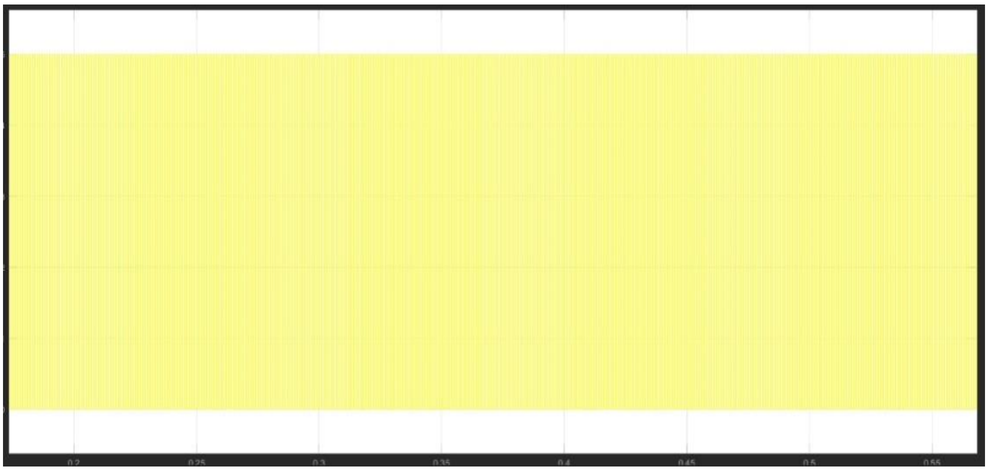

Fig.17: PWM signal given to DC-DC Converter

The results and discussion section focuses on evaluating the performance of the multi-source energy harvesting system, which integrates solar and piezoelectric energy harvesting with a Buck-Boost converter and advanced control strategies. Simulations were carried out in MATLAB/Simulink to analyze the system's dynamic behavior under varying input voltages and load conditions. Key parameters such as inductor and capacitor values, input voltage range, and switching frequency were carefully chosen to match the application requirements. The system was designed to maintain a stable output voltage of 12 V, even when the input voltage fluctuated between 5 V and 15 V, showcasing the converter's ability to manage a wide range of input conditions effectively.

The output voltage and current profiles demonstrated that the Buck-Boost converter could consistently achieve the target output, with voltage regulation maintained within acceptable limits. The system's efficiency was analyzed under various load conditions, revealing an average efficiency of approximately 85%. This efficiency is indicative of the converter's ability to effectively transfer power from the energy sources to the load, minimizing losses. Furthermore, the converter's response time and ability to stabilize the output voltage after sudden changes at 0.0004 and 0.0007 sec were highlighted as key performance indicators.

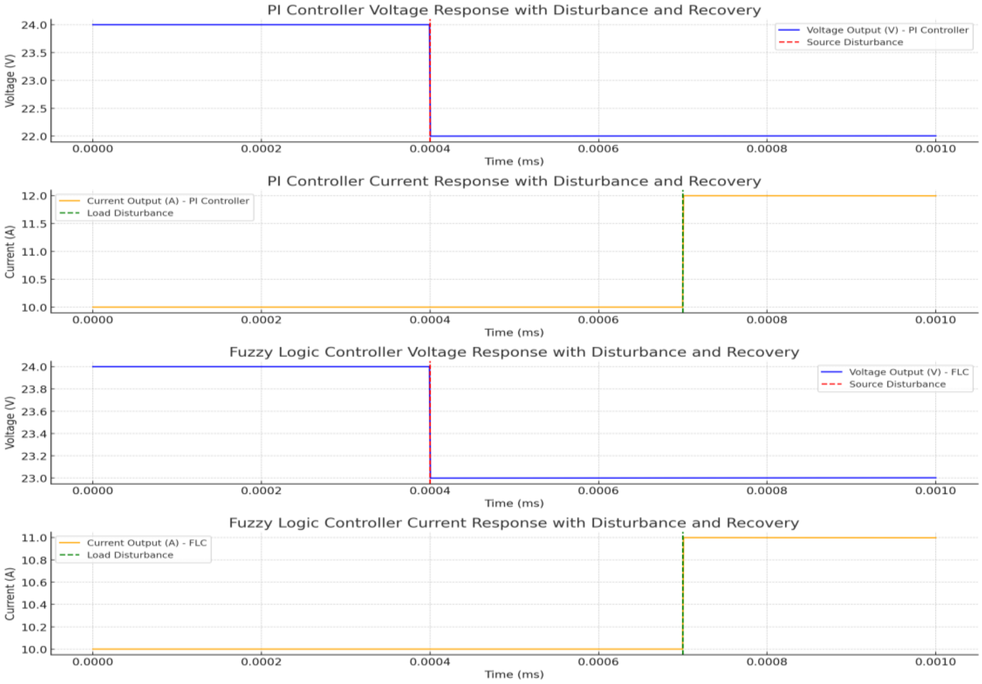

Fig.18: System response with disturbances and recovery

A detailed analysis of the control strategies was conducted to assess the performance of the PI and fuzzy logic controllers as shown in Fig.18. The PI controller managed to stabilize the system effectively, with a relatively fast response time and low steady-state error, ensuring smooth operation under varying conditions. However, the fuzzy logic controller outperformed the PI controller, showing enhanced robustness and faster settling times, particularly in scenarios involving rapid input voltage fluctuations or load changes. The fuzzy logic controller's adaptability to non-linearities and disturbances proved advantageous, as it consistently maintained stable operation despite unpredictable variations in the system.

The introduction of disturbances at both the source and load sides was critical in validating the designed system's resilience. The system's ability to maintain the desired response under such disturbances demonstrated the robustness of the control strategies. The PI and fuzzy logic controllers successfully counteracted the effects of the disturbances, maintaining stable output voltage and current levels. The fuzzy logic controller, in particular, demonstrated superior performance in handling dynamic changes, highlighting its suitability for complex, real-world energy harvesting applications.

Overall, the integration of multiple energy sources with a Buck-Boost converter and advanced control strategies significantly enhances the system's reliability and performance. The findings suggest that employing fuzzy logic controllers can further optimize system stability and response time, making the multi-source energy harvesting system a viable solution for various outdoor and industrial applications. Future work could explore hybrid control strategies and further refinement of converter parameters to enhance overall efficiency and adaptability.

5. Conclusion

In this study, we have designed and analyzed a multi-source energy harvesting system that integrates solar panels, piezoelectric vibrational harvesters, and lithium-ion battery storage. The proposed system is capable of generating and managing power effectively in outdoor and industrial settings, showcasing the potential for sustainable energy solutions. By utilizing a Buck-Boost converter with a switching frequency of 100 kHz, we achieved optimal power conditioning, enabling efficient energy transfer from varying sources to the storage unit.

The integration of both solar and vibrational energy sources not only enhances the overall reliability of the system but also ensures continuous operation under diverse environmental conditions. The implementation of Proportional-Integral and Fuzzy Logic Controllers has further improved the performance, allowing for swift adaptation to fluctuations in energy input. This adaptability is crucial for maximizing energy capture and maintaining stable power delivery to connected loads.

The results of our simulations indicate that the system can effectively harness up to 220 W of power, with the lithium-ion battery providing substantial energy storage capacity to support applications with variable power demands. Our findings highlight the importance of multi-source energy harvesting as a viable strategy for achieving energy independence and sustainability in various applications.

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