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Design and Control of a PI-Based Multi-Source Energy Harvesting System for Efficient Power Management and Lithium-Ion Battery Charging

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ABSTRACT

This paper presents the design and implementation of a Proportional-Integral (PI) controller for a multi-source energy harvesting system, integrating solar and vibrational energy sources to efficiently manage the charging of a lithium-ion battery. The system utilizes two 100 W solar panels connected in parallel, providing a current range of 8 A to 10 A per panel. Additionally, vibrational energy harvesters contribute a total power output of 50 mW to 250 mW with an output voltage of 3 V to 12 V, processed through a full-wave bridge rectifier. The energy harvested from both sources is conditioned using an interleaved DC-DC converter to regulate the power transfer to a 24 V, 100 Ah lithium-ion battery, which supports a maximum charge rate of 10 A (240 W) and can discharge up to 1 kW. The proposed PI controller is designed to maintain optimal performance by stabilizing voltage fluctuations and enhancing the system's ability to respond to varying energy inputs from the sources. It effectively balances the power contributions from solar and vibrational energy while ensuring efficient battery charging and discharge. This study also investigates the system's dynamic response to varying environmental conditions and load requirements, ensuring stable operation under different scenarios. Simulation results validate the performance of the PI controller, demonstrating improvements in energy harvesting efficiency and overall system stability. This work contributes to advancing sustainable energy systems by integrating multiple energy sources for reliable and efficient energy storage.

Keywords: Multi-source energy harvesting, PI controller design, Lithium-ion battery charging, Solar and vibrational energy, Interleaved DC-DC converter

INTRODUCTION

As the global demand for renewable energy grows, multi-source energy harvesting systems have gained significant attention due to their ability to harness power from multiple sources, ensuring a more reliable and consistent energy supply. These systems, which typically combine solar, wind, vibrational, or thermal energy sources, are designed to capture energy from diverse environmental conditions, allowing for continuous power generation even when one source is unavailable or insufficient [1][2]. This approach enhances the sustainability and efficiency of energy generation, making it particularly suitable for powering applications such as portable electronics, sensors, and battery storage systems in remote or off-grid locations [3].

Among various renewable energy sources, solar energy is one of the most widely used due to its abundant availability and advancements in photovoltaic (PV) technology [4]. Solar energy harvesting has been extensively researched, providing efficient energy conversion for both large- and small-scale applications [5]. However, solar energy alone is subject to variability, as output is dependent on weather conditions and sunlight availability. To address this limitation, vibrational energy harvesting is introduced as a secondary source. Vibrational energy, although smaller in magnitude, offers a supplementary power supply from ambient vibrations found in many environments [6][7]. Combining solar and vibrational energy ensures a more consistent power supply [8].

In multi-source systems, power management is crucial to efficiently regulate energy flow between sources and the energy storage unit, typically a battery [9]. Lithium-ion batteries are widely adopted in energy storage systems due

to their high energy density, long cycle life, and ability to handle varied charge and discharge rates [10]. However, optimizing the charging and discharging process, especially with multiple input sources, requires an intelligent control strategy to ensure system stability and efficiency [11].
To manage energy flow and optimize battery charging, a Proportional-Integral (PI) controller is employed. The PI controller is favored for its simplicity, ease of implementation, and ability to maintain system stability by minimizing steady-state errors and compensating for system disturbances [12]. In this work, a PI controller is designed to balance energy inputs from solar and vibrational sources, ensuring that the lithium-ion battery is charged efficiently while maintaining system stability under varying energy input conditions [13]. The integration of solar and vibrational sources through the PI controller and power conditioning circuits like the interleaved DC-DC converter facilitates an efficient, scalable energy management solution [14].
This paper aims to explore the design and implementation of a PI controller for a multi-source energy harvesting system that includes solar panels and vibrational energy harvesters. The system's performance is evaluated through simulation, analyzing its response to fluctuating environmental conditions and variable loads. The results demonstrate the effectiveness of the PI-controlled system in ensuring optimal power transfer and stable operation, contributing to advancements in renewable energy systems [15].
This paper is structured as follows: a comprehensive description of the system under consideration, the operational principles and mathematical modeling of the power conditioning circuit, addresses the challenges associated with controller design, the simulation results and engages in discussion. Lastly, wraps up the paper by highlighting potential avenues for future research and the broader significance of this study.

PROPOSED SYSTEM CONFIGURATION

The proposed multi-source energy harvesting system integrates solar energy and vibrational energy to optimize power generation and storage. The architecture consists of several key components that work together to ensure efficient energy capture, conversion, and storage. The energy system utilizes two main sources: solar panels and vibrational energy harvesters. The solar panels, configured in parallel, each have a capacity of 100 W, resulting in a combined output of 200 W. They operate within a current range of 8 to 10 A per panel, allowing efficient energy capture from sunlight. In addition, vibrational energy harvesters convert mechanical energy from environmental vibrations, delivering a power range between 50 mW and 250 mW, with output voltages varying from 3 V to 12 V, based on vibration intensity. To ensure compatibility with battery charging, the power conditioning unit incorporates a full-wave bridge rectifier that converts the AC from the vibrational harvesters into DC. Energy is stored in a 24 V, 100 Ah lithium-ion battery, providing a total storage capacity of 2.4 kWh. The battery supports a maximum charge rate of 10 A (240 W) and can discharge up to 1 kW, effectively storing energy for future use. A Proportional-Integral (PI) controller in the control unit regulates the battery's charging process, adjusting power flow from the sources to maintain optimal conditions. To improve efficiency, an interleaved DC-DC converter manages the power conditioning, facilitating smooth energy transfer between the solar panels, vibrational harvesters, and the battery. The entire system operates seamlessly, with the PI controller adjusting the energy flow in response to the battery’s charge status and the availability of input energy.

WORKING PRINCIPLE AND MATHEMATICAL MODEL OF THE CONVERTER

The interleaved converter is a DC-DC converter designed to enhance power conditioning by dividing the input current across multiple parallel pathways, optimizing the system's overall efficiency. In a multi-source energy harvesting setup, this type of converter is ideal for managing the flow of power from solar panels and vibrational harvesters to a lithium-ion battery. One of its primary advantages is current sharing, where the interleaved design ensures that each converter phase carries an equal portion of the current, thus lowering the stress on individual components and enhancing reliability. Additionally, interleaving the phases reduces ripple in the output current and voltage, providing a more stable power supply—essential for battery charging. This configuration also boosts efficiency by enabling the use of smaller inductors and capacitors, minimizing power losses. Furthermore, distributing power across multiple phases helps with thermal management, as it allows for better heat dissipation.
The interleaved converter circuit includes several key components. The input stage accepts power from the energy sources, with capacitors to filter any voltage fluctuations. The converter’s switching elements, often MOSFETs or IGBTs, operate in complementary pairs, with one switch on while the other is off, controlling the current flow. Each phase includes an inductor that stores energy during the switch-on period and transfers it to the output during the switch-off period, aiding in current distribution and ripple reduction. Diodes are placed in each phase to manage rectification, ensuring correct current direction. An output capacitor smoothens the voltage by reducing ripple, stabilizing the output for battery charging. The control circuit, typically using pulse width modulation (PWM), regulates the switching elements and maintains the desired output voltage and current. By operating the phases with a slight phase shift, the converter further reduces output ripple, optimizing its performance for energy storage applications.

Operational Principles:
An interleaved DC-DC converter consists of multiple (typically two or more) converters operating out of phase to achieve a higher output current and reduced ripple. In this case, we consider two boost converters interleaved with a switching frequency fs.

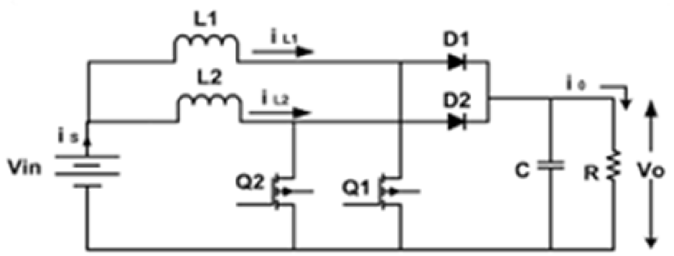

Fig.1 *Interleaved Boost Converter*

1) Phase Operation:
In Phase A of an interleaved boost converter, when the first switch is turned on, its corresponding inductor begins to accumulate energy from the input source. At the same time, the second switch remains off, which allows the inductor associated with it to discharge the previously stored energy to the output.

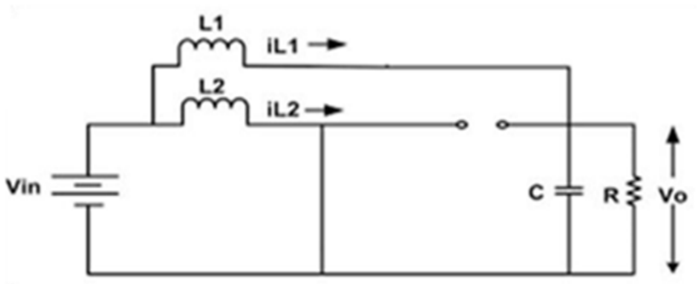

Fig.2 *Phase Operation Mode*

2) Energy Transfer:
Moving into Phase B, the first switch is turned off, which directs the stored energy from its inductor to the output, while the second switch is turned on, enabling its inductor to begin charging from the input source. By switching between these two phases, the interleaved boost converter effectively maintains a steady power supply to the output. This alternating action helps minimize ripple and enhances efficiency by balancing the energy transfer between the two inductors.

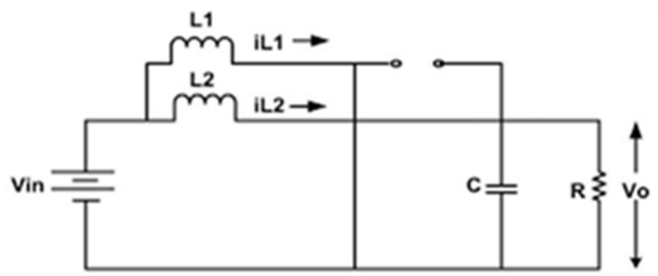

Fig.3 *Energy Transfer Mode*

State-Space Model of an Interleaved DC-DC Converter
To develop a state-space model of an interleaved DC-DC converter suitable for your multi-source harvesting system, we need to define the system dynamics based on the circuit configuration, component values, and operational principles. Here, I'll outline a simplified approach to formulating the state-space model, particularly focusing on a typical interleaved boost converter. For this interleaved boost converter, the state variables will be:
$x_1=i_{L1}$ Current through inductor L_1.
$x_2=i_{L2}$ Current through inductor L_2.
$x_3=V_{out}$: Voltage across the output capacitor C.
State Equations: The state equations for the interleaved boost converter can be described as follows:

For each inductor:

$$\frac{dx_1}{dt} = \frac{-V_o}{L_1} + \frac{V_{in}}{L_1}u_1 \quad (1)$$

$$\frac{dx_2}{dt} = \frac{-V_o}{L_2} + \frac{V_{in}}{L_2}u_2 \quad (2)$$

For the output voltage:

$$\frac{dx_3}{dt} = \frac{1}{C}(x_1 + x_2 - \frac{x_3}{R_o}) \quad (3)$$

State-Space Representation: The state-space representation can be formulated in matrix form as follows:

$$\begin{bmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \\ \frac{dx_3}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} \\ 0 & 0 & -\frac{1}{L_{21}} \\ \frac{1}{C} & \frac{1}{C} & -\frac{1}{R_0 C} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{V_{in}}{L_1} & 0 \\ 0 & \frac{V_{in}}{L_2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (4)$$

Output Equation: The output equation relates the state variables to the output voltage:

$$Y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (5)$$

To derive the transfer functions from the state-space model of an interleaved DC-DC converter, we need to follow a systematic approach using the state-space equations defined earlier.
Transfer functions are determined using equ. (4) & (5)

$$T.F. = C(SI - A)^{-1}B + D \quad (6)$$

The derived transfer function describes the relationship between the input voltage and the output voltage of the interleaved DC-DC converter. This can be utilized for further analysis, such as control design and stability assessment. The parameters of the converter are calculated using the equations (7) to (9). And is presented in Table.1.

$$L = \frac{V_{in}xD}{fx\delta L} \quad (7)$$

$$C_{in} = \frac{I_{in}xD}{fx\delta V_{in}} \quad (8)$$

$$C_{out} = \frac{I_{out}xD(1-D)}{fx\delta V_{out}} \quad (9)$$

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
Converter	Input Voltage	10 V to 24 V
	Output Voltage	24 V
	Switching Frequency	100 kHz
	Inductor	22µH
	Capacitor (Cin, Cout)	1044 µF ,1015 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

Using the derived transfer function and parameters of the converter open loop response of the converter is found and is shown in Fig.4 which shows that there is a steady state error it necessitates a controller to get steady response.

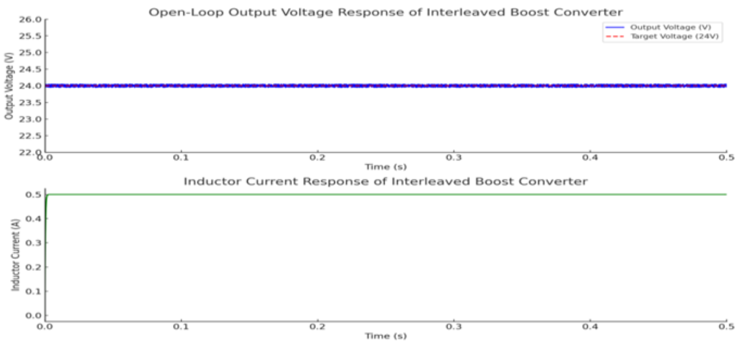

Fig.4 *Open loop Response*

CONTROLLER DESIGN

The control strategy in this multi-source energy harvesting system relies on monitoring the output voltage and adjusting the duty cycle of switches to maintain the desired output. A Proportional-Integral (PI) controller is integral to this process, ensuring efficient battery charging and stable system operation[16-17]. In this setup, the PI controller is essential for managing the energy flow from multiple sources, thereby stabilizing the output and optimizing performance.

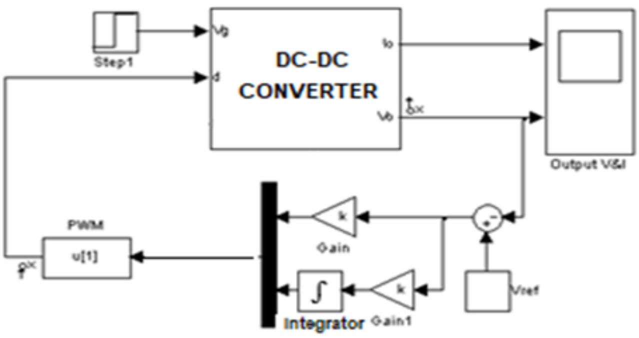

Fig.5 *Converter with PI Controller*

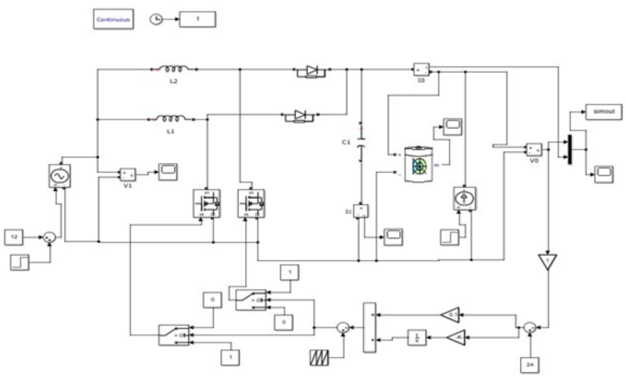

Fig.6 *Simulation circuit with PI Controller*

The PI controller's structure includes two components: proportional (P) and integral (I). The proportional part reacts to the immediate error between the desired and actual outputs, offering a quick response. The integral part, on the other hand, addresses any lingering errors over time, thereby minimizing steady-state error and enhancing long-term stability. Together, these components enable the system to respond rapidly to changes while ensuring stability in the output. Mathematically, the PI controller is expressed as

$$e(t) = K_p e(t) + K_{i\int t} e(t)dt \qquad (10)$$

where u(t)represents the control output, Kp and Ki are the proportional and integral gains, and e(t) is the error signal. Selecting appropriate values for Kp and Ki is crucial for the controller's effectiveness.

Various tuning methods are available, such as trial and error, Ziegler-Nichols, and simulation-based tuning. These methods help refine the gains to achieve desired performance indicators like minimal overshoot and fast settling time. Once tuned, the PI controller's performance is assessed through simulations and experimental setups. Key metrics include steady-state error, transient response, and robustness, which gauge the controller's ability to maintain performance under parameter changes or disturbances. Finally Kp=0.1 and Ki=0.05 is found to get the desired response as shown in Fig.5 & Fig.6.

The PI controller is then integrated into the control unit, where it continuously monitors the output voltage and current, adjusting the power conditioning unit's control signal as needed. This real-time adjustment is essential for efficient battery charging, ensuring that the lithium-ion battery avoids overcharging or undercharging. Overall, a well-designed and implemented PI controller significantly enhances the system's stability and efficiency, enabling it to adapt to varying inputs from multiple energy sources and maintain optimal battery charging conditions.

RESULTS AND DISCUSSION

In this study, the designed Proportional-Integral (PI) controller for the multi-source energy harvesting system was evaluated under varying conditions to assess its performance in maintaining a steady output. Two key disturbances were introduced to the system: a source disturbance of 2V at 0.0035 seconds and a load disturbance of 0.5A at 0.007 seconds. These disturbances were applied to simulate real-world variations that can occur due to environmental fluctuations or changes in load demand. Figures 7 and 8 illustrate the output voltage and output current waveforms of the proposed system equipped with the designed controller, including the effects of disturbances.

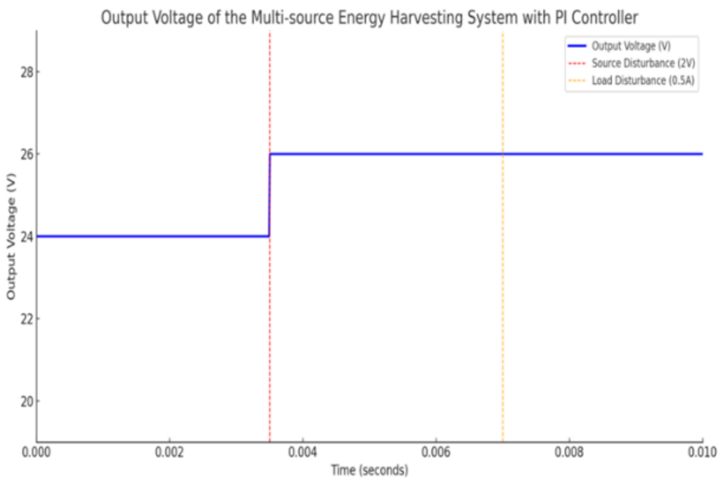

Fig.7 *Output Voltage*

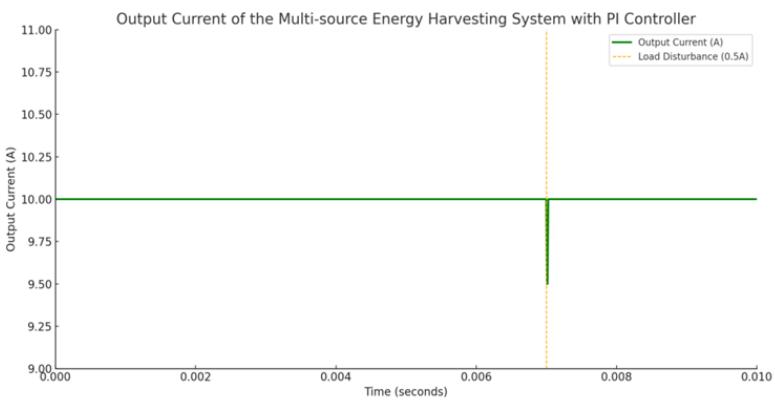

Fig.8 *Output Current*

Despite the disturbances, the system demonstrated remarkable stability in its output, highlighting the robustness of the PI controller in managing the energy flow from multiple sources, including solar panels and vibrational energy harvesters. The controller effectively compensated for both the voltage and current disturbances, ensuring that the lithium-ion battery was charged efficiently without significant deviations in system performance.

Following the 2V source disturbance, a minor transient response was observed, but the system quickly stabilized, returning to its desired operating condition within a short period. Similarly, after the 0.5A load disturbance, the system experienced a slight fluctuation; however, it swiftly regained its steady-state operation. These responses confirm the PI controller's ability to minimize the impact of sudden changes in input voltage and load current, thereby maintaining a steady output.

The results also show that the integration of the interleaved DC-DC converter played a significant role in ensuring smooth power transfer between the energy sources and the battery. The converter helped in managing the power conditioning and contributed to the overall system stability by mitigating the effects of the disturbances.

In conclusion, the PI controller successfully handled the dynamic changes introduced by the source and load disturbances, providing a consistent and reliable output. The system's ability to maintain steady performance under varying conditions underscores the effectiveness of the control strategy and its suitability for multi-source energy harvesting systems. Future work may involve further optimization of the controller parameters to enhance response time and efficiency under more complex disturbance scenarios.

CONCLUSION

A This study presented the design and implementation of a Proportional-Integral (PI) controller for a multi-source energy harvesting system that integrates solar and vibrational energy sources, with energy storage in a lithium-ion battery. The primary objective was to assess the system's ability to maintain stable output in the presence of disturbances, which are commonly encountered in real-world energy harvesting applications.

The results demonstrated that the PI controller was highly effective in stabilizing the system under source and load disturbances. Specifically, a 2V source disturbance at 0.0035 seconds and a 0.5A load disturbance at 0.007 seconds were introduced to evaluate the system's dynamic response. Despite these challenges, the system maintained a steady output, quickly returning to normal operating conditions after minor transient responses. This steady performance highlights the ability of the PI controller to adapt to fluctuations in both input voltage and load current, ensuring continuous and efficient charging of the lithium-ion battery.

The interleaved DC-DC converter, used for power conditioning, played a crucial role in supporting the system's overall stability. It helped to smooth power flow from the solar and vibrational sources to the battery, thereby improving the overall energy transfer efficiency. The system's robust response to disturbances emphasizes the importance of using a PI controller in such multi-source energy harvesting systems, where maintaining output stability is critical for reliable operation.

In conclusion, the PI-controlled multi-source energy harvesting system successfully demonstrated its potential for applications where stable energy supply and efficient battery charging are essential, such as in remote or off-grid systems. The controller's simplicity, combined with its capacity to handle dynamic changes, makes it a viable option for future energy systems integrating diverse renewable sources. Future research could focus on optimizing the PI controller parameters for even faster response times or expanding the system to incorporate additional energy sources. Additionally, exploring alternative control strategies, such as fuzzy logic or sliding mode controllers may further enhance the system's robustness and performance in more complex scenarios.

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