



DESIGN OF A CO-LOCATED SOLAR-PIEZOELECTRIC HYBRID ENERGY HARVESTER FOR AUTONOMOUS SYSTEMS

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Abstract:

The increasing demand for reliable and sustainable power sources for decentralized and low-power applications has accelerated research into hybrid energy harvesting systems. This paper presents the design and simulation of an autonomous hybrid power system utilizing co-located solar photovoltaic (PV) and piezoelectric energy harvesters. The proposed system addresses the intermittency of single-source renewable systems by simultaneously harvesting solar irradiance and ambient mechanical vibrations. A Maximum Power Point Tracking (MPPT) controller is employed to maximize energy extraction from the PV module, while the piezoelectric output is conditioned using a full-wave rectifier. The regulated outputs from both sources are integrated through a buck-boost DC-DC converter to maintain a stable DC bus voltage under varying environmental conditions. A microcontroller/DSP-based control unit generates pulse-width modulation (PWM) signals for efficient power management and converter operation. Energy storage is achieved using a lithium-ion battery supervised by a Battery Management System (BMS) to ensure safe charging, discharging, and extended battery lifespan. The complete system is modelled and simulated using MATLAB/Simulink, and performance is evaluated under charging and discharging modes. Simulation results demonstrate stable voltage regulation, controlled state-of-charge variation, and reliable energy delivery, validating the effectiveness of the proposed hybrid architecture. The system is well-suited for autonomous applications such as IoT devices, smart sensors, and off-grid monitoring systems.

Key Words: Hybrid Energy Harvesting, Solar Photovoltaic, Piezoelectric Generator, MPPT, Buck-Boost Converter, Battery Management System, Autonomous Power System.

Introduction:

The increasing deployment of autonomous electronic systems, IoT devices, and remote sensors has created a strong demand for sustainable and maintenance-free power sources, as conventional battery-based and grid-dependent solutions suffer from limited lifespan, frequent replacement, and environmental concerns. Solar photovoltaic (PV) energy is widely adopted due to its high energy density and scalability; however, its performance is highly intermittent and dependent on sunlight availability.

Piezoelectric energy harvesting provides a complementary solution by converting ambient mechanical vibrations into electrical energy, enabling power generation during low-light or nighttime conditions, although at lower power levels. To address the limitations of single-source systems, this paper proposes an autonomous hybrid energy harvesting system utilizing co-located solar PV and piezoelectric sources. The system integrates an MPPT controller for optimal solar energy extraction, a full-wave rectifier for piezoelectric output conditioning, and a buck-boost DC-DC converter to ensure stable voltage regulation under varying input conditions.

A microcontroller/DSP-based control unit generates PWM signals for efficient power management, while a lithium-ion battery with an integrated Battery Management System (BMS) provides safe and reliable energy storage. The proposed architecture is modelled and simulated using MATLAB/Simulink, and results demonstrate stable voltage regulation, controlled charging and discharging behaviour, and reliable power delivery, making the system suitable for autonomous IoT, smart sensor, and off-grid applications.

This step-by-step design allows continuous feedback and early detection of stress, which is particularly valuable during the conservation of sensitive or endangered plants.

System Architecture:

The proposed system architecture integrates co-located solar photovoltaic (PV) and piezoelectric energy sources to provide autonomous power generation for low-power IoT and embedded applications, as shown in Fig. 1. The architecture is designed to harvest energy from multiple ambient sources, regulate the generated power, and store it efficiently to ensure uninterrupted load operation.

The solar PV module acts as the primary energy source and converts solar irradiance into electrical energy. Owing to the nonlinear characteristics of the PV module under varying irradiance and temperature, a Maximum Power Point Tracking (MPPT) controller is employed to extract maximum available power by dynamically adjusting the operating point.

In parallel, the piezoelectric energy harvester converts ambient mechanical vibrations into electrical energy. Since the generated output is alternating in nature, a full-wave rectifier is used to convert it into a DC signal compatible with the system DC

bus, thereby supplementing solar power during low-irradiance or nighttime conditions.

The DC outputs from both sources are integrated through a buck-boost DC-DC converter, which provides stable voltage regulation by stepping up or stepping down the input voltage as required. A microcontroller or Digital Signal Processor (DSP) generates pulse-width modulation (PWM) signals to control the converter and manage power flow. Energy storage is achieved using a lithium-ion battery supervised by a Battery Management System (BMS) to ensure safe charging and discharging. The regulated and stored energy is supplied to the IoT load, enabling reliable operation under dynamic environmental conditions.

Hardware Components:

The proposed hybrid energy harvesting system consists of hardware modules for energy generation, power conditioning, control, and storage, designed to supply autonomous power to low-power IoT loads.

- Solar Photovoltaic Module: The solar photovoltaic (PV) module converts incident solar irradiance into electrical energy and serves as the primary energy source. Due to variations in irradiance and temperature, the PV output is interfaced with an MPPT controller to ensure optimal power extraction.
- Piezoelectric Energy Harvester: The piezoelectric harvester converts ambient mechanical vibrations into electrical energy. The generated output is alternating in nature and characterized by high voltage and low current, providing supplementary energy during low-irradiance conditions.
- MPPT Controller: The MPPT controller tracks the maximum power point of the PV module by dynamically adjusting the converter duty cycle, thereby improving energy harvesting efficiency.
- Rectifier Circuit: A full-wave rectifier converts the alternating output of the piezoelectric harvester into DC form suitable for integration with the system DC bus.
- Buck-Boost DC-DC Converter: A buck-boost DC-DC converter regulates the combined DC inputs from the solar and piezoelectric sources. The converter provides stable output voltage under varying input and load conditions.
- Control Unit: A microcontroller or Digital Signal Processor (DSP) generates pulse-width modulation (PWM) signals for converter control. It also monitors system voltages and battery state-of-charge to manage power flow.
- Battery and Battery Management System: A lithium-ion battery is used for energy storage. A Battery Management System (BMS) ensures safe charging and discharging by protecting against overvoltage, over current, and deep discharge.
- Load Interface: The regulated output power is supplied to low-power IoT loads such as sensors and embedded controllers.

B. Workflow of the System:

- The solar photovoltaic (PV) module converts incident solar irradiance into electrical energy and acts as the primary power source.
- The PV output is processed by a Maximum Power Point Tracking (MPPT) controller to ensure maximum power extraction under varying irradiance and temperature conditions.
- The piezoelectric energy harvester converts ambient mechanical vibrations into an alternating electrical output.
- A full-wave rectifier converts the piezoelectric AC output into a DC signal compatible with the system DC bus.
- The DC outputs from the solar PV and piezoelectric subsystems are combined and supplied to a buck-boost DC-DC converter.
- The buck-boost converter regulates the input voltage by stepping up or stepping down as required to maintain a stable DC output.
- A microcontroller or Digital Signal Processor (DSP) generates pulse-width modulation (PWM) signals to control the converter operation and manage power flow.
- The regulated DC output is directed to a lithium-ion battery through a Battery Management System (BMS).
- The BMS monitors battery voltage, current, temperature, and state-of-charge to ensure safe charging and discharging.
- The stored energy is supplied to the connected IoT or embedded load during low energy availability, ensuring uninterrupted operation.

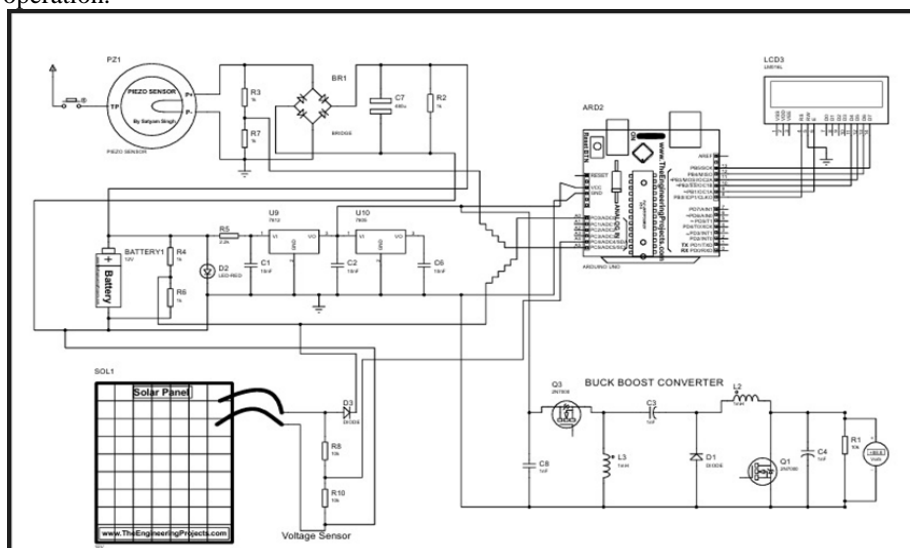


Figure 1: Circuit diagram of the hybrid solar-piezoelectric energy harvesting system with MPPT and buck-boost control

Power Management and Control Strategy:

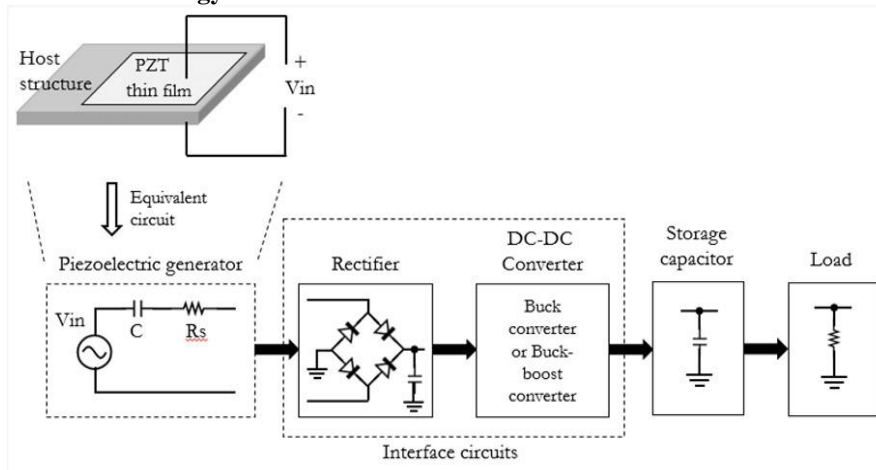


Figure 2: Workflow of system

The power management and control strategy of the proposed hybrid energy harvesting system is designed to ensure efficient energy utilization, stable voltage regulation, and safe battery operation under varying environmental conditions. The strategy coordinates power flow between the solar photovoltaic (PV) module, piezoelectric energy harvester, energy storage unit, and load. The solar PV subsystem is controlled using a Maximum Power Point Tracking (MPPT) algorithm. The controller continuously senses the PV voltage and current and adjusts the duty cycle of the DC-DC converter to operate the PV module at its maximum power point, thereby improving energy extraction efficiency under fluctuating irradiance and temperature conditions.

The piezoelectric energy harvester generates an alternating electrical output from ambient mechanical vibrations. This output is rectified using a full-wave rectifier and filtered to obtain a DC signal. The rectified piezoelectric energy is treated as a supplementary input and is combined with the solar PV output on the DC bus. A buck-boost DC-DC converter is employed as the main power conditioning stage. The converter regulates the combined input voltage by stepping up or stepping down the voltage as required to maintain a stable DC output. Pulse-width modulation (PWM) signals generated by a microcontroller or Digital Signal Processor (DSP) control the switching operation of the converter.

The control unit continuously monitors system parameters such as source voltages, converter output voltage, and battery state-of-charge. Based on these measurements, it manages energy flow between the harvesting sources and the battery. A Battery Management System (BMS) ensures safe charging and discharging by enforcing voltage, current, and temperature limits. During periods of low energy harvesting, the battery supplies power to the load, ensuring uninterrupted operation.

Energy Storage and Battery Management:

Energy storage plays a critical role in the proposed hybrid energy harvesting system by ensuring continuous power availability during periods of low or no energy generation. A lithium-ion battery is employed as the primary energy storage element due to its high energy density, long cycle life, and suitability for low-power autonomous applications. The harvested and regulated energy from the solar photovoltaic and piezoelectric subsystems is directed to the battery through a Battery Management System (BMS). The BMS continuously monitors key battery parameters, including terminal voltage, charging and discharging current, temperature, and state-of-charge (SOC). Based on these measurements, the BMS enforces protection mechanisms to prevent overcharging, deep discharge, over current, and thermal instability, thereby enhancing battery safety and longevity.

During periods of sufficient energy harvesting, the battery operates in charging mode, where controlled current and voltage limits are maintained to ensure safe operation. When harvested energy is insufficient, the battery supplies power to the load in discharging mode, maintaining stable output voltage through the regulated DC bus. The control unit coordinates battery operation with the power conditioning stage to ensure smooth transition between charging and discharging states. This energy storage and battery management strategy enables reliable power buffering, improves system stability, and ensures uninterrupted operation of IoT and embedded loads under dynamic environmental conditions.

Software Implementation:

The proposed hybrid energy harvesting system is implemented and validated using MATLAB/Simulink, which provides an efficient environment for modeling, simulation, and analysis of power electronic systems and control algorithms. The software implementation focuses on verifying system functionality, power flow coordination, and battery charging-discharging behavior under varying operating conditions. The solar photovoltaic (PV) subsystem is modeled using standard PV block models with irradiance and temperature as input parameters. An MPPT control algorithm is implemented to dynamically adjust the duty cycle of the DC-DC converter to ensure maximum power extraction from the PV module. The piezoelectric energy harvester is modeled as an AC voltage source, followed by a full-wave rectifier and filtering stage to obtain a usable DC output.

The buck-boost DC-DC converter is implemented using switching devices, inductors, and capacitors, with pulse-width modulation (PWM) control generated through a control logic block. The control algorithm regulates the converter output voltage and coordinates power flow from the hybrid sources to the battery. A lithium-ion battery model is used to simulate energy storage behavior, including charging and discharging characteristics, while a Battery Management System (BMS) logic monitors voltage and state-of-charge limits. Simulation results are obtained for different operating modes, including battery charging, discharging, and voltage regulation. The software implementation validates stable system operation, effective energy integration from multiple sources, and reliable power delivery to the load, demonstrating the feasibility of the proposed architecture for autonomous IoT applications.

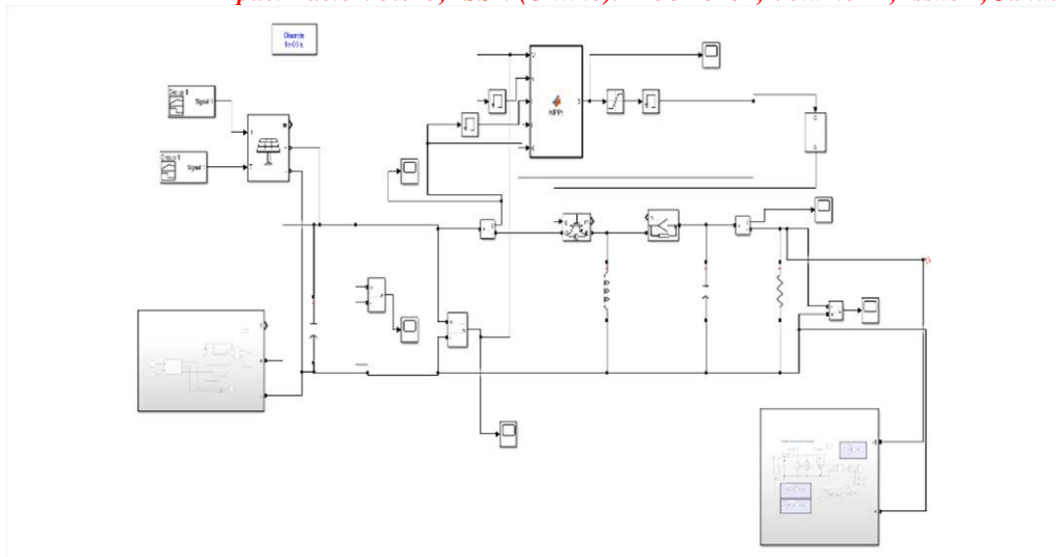


Figure 3: Simulation circuit diagram

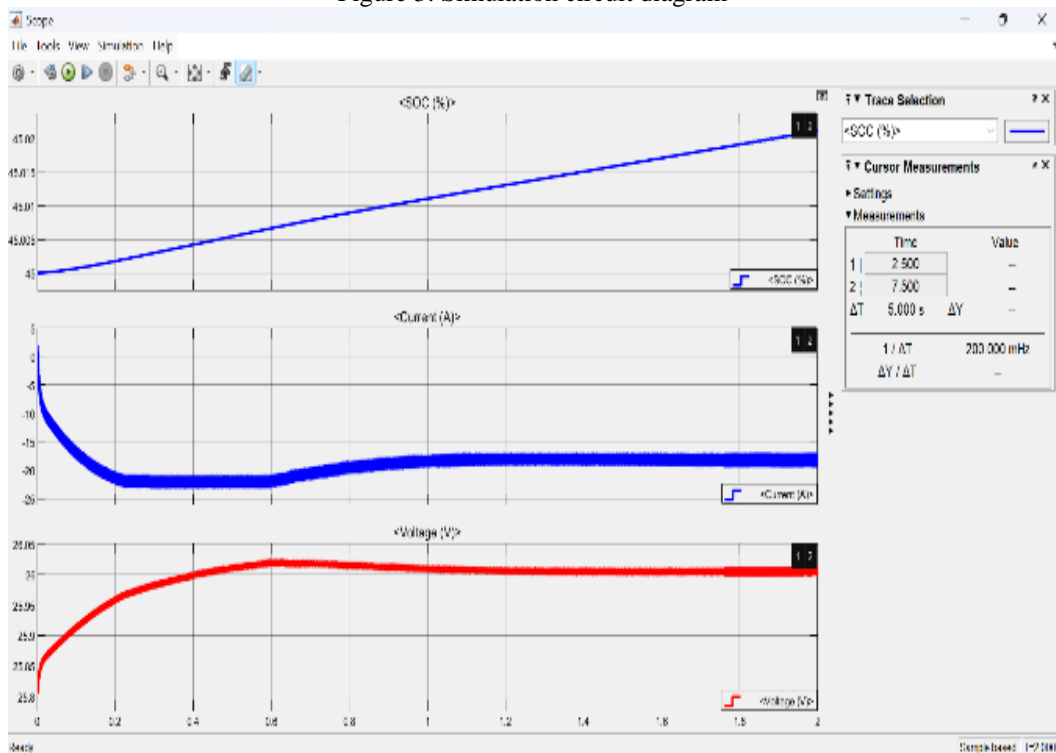


Figure 4: Charging mode

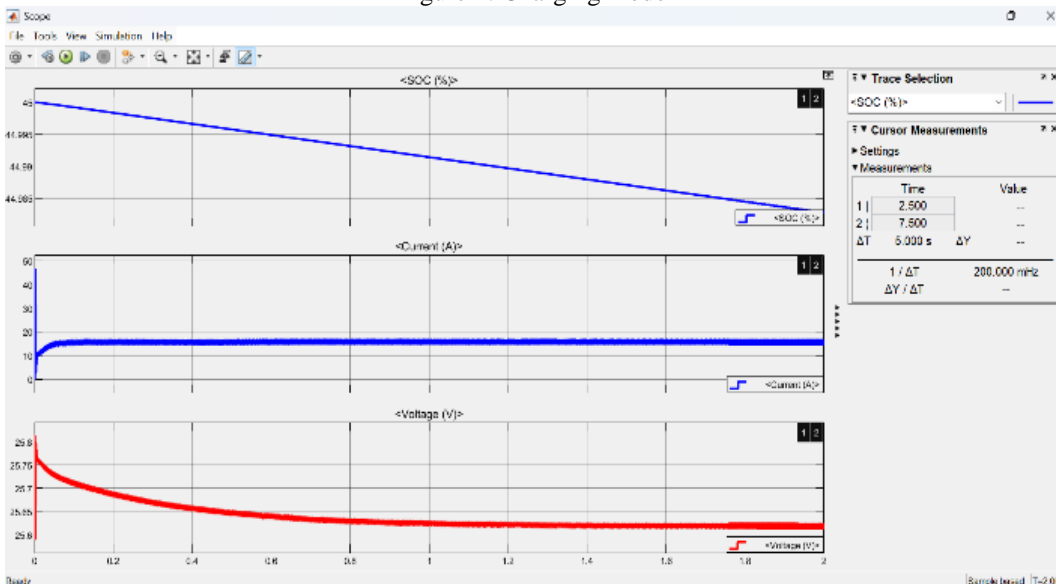


Figure 5: Discharging mode

Applications:

The proposed hybrid energy harvesting system is applicable to low-power autonomous systems requiring continuous operation under variable environmental conditions. It is well suited for Internet of Things (IoT) sensor nodes used in environmental monitoring, smart agriculture, and infrastructure health monitoring, where maintenance-free operation is essential. The system can be deployed in wireless sensor networks (WSNs) and remote monitoring units such as weather stations, industrial condition monitoring, and surveillance systems operating in off-grid locations. The hybrid energy approach improves power reliability compared to single-source systems. Additionally, the architecture is suitable for portable and embedded electronics, including wearable devices and smart instrumentation, where compact size and efficient energy utilization are required. The modular design also enables integration into smart infrastructure and micro-power applications, supporting sustainable and autonomous operation.

Future Scope:

The proposed hybrid solar-piezoelectric autonomous power system establishes a strong foundation for several promising future developments. One of the most impactful directions is the integration of Artificial Intelligence and Machine Learning-based adaptive MPPT control, where predictive models can forecast solar irradiance and vibration patterns in advance, replacing fixed algorithms like Perturb & Observe with intelligent real-time optimization for significantly higher energy yield.

The current dual-source architecture can be further extended by incorporating additional renewable sources such as micro-wind turbines or thermoelectric generators (TEG), creating a tri-source or quad-source hybrid system that ensures reliable power generation across a wider range of environmental conditions. Alongside this, the system can be enhanced with IoT-based real-time remote monitoring using ESP32 or Raspberry Pi integrated with cloud platforms like Microsoft Azure IoT, enabling live tracking of SOC, voltage, current, and power parameters through a mobile dashboard with predictive maintenance capabilities.

From an energy storage perspective, the existing Li-ion battery setup can be upgraded by introducing a super capacitor-battery hybrid storage unit, where super capacitors handle rapid charge-discharge bursts from piezoelectric transients efficiently, thereby reducing stress on the battery and extending its overall lifecycle. At a larger scale, the system holds strong potential for Electric Vehicle auxiliary charging applications, where piezoelectric road tiles harvest vibrations from vehicular traffic alongside rooftop solar panels to feed an EV charging management system.

On the implementation side, transitioning from the current MATLAB/Simulink simulation environment to a real hardware prototype using STM32 or Arduino-based embedded controllers with actual PZT or PVDF piezoelectric patches and PV panels will validate simulation results under real-world physical conditions. Further, the standalone system can be scaled for integration into rural microgrids and smart city infrastructure, where decentralized hybrid harvesters contribute to a shared community energy network through grid-tie inverters.

Looking at miniaturization, the use of flexible PVDF-based piezoelectric films embedded in clothing, footwear, or structural surfaces opens the possibility of self-powered IoT wearables that harvest energy from human body motion combined with thin-film solar cells. In parallel, developing a digital twin of the hybrid system using platforms such as Azure Digital Twins or MATLAB Digital Twin Toolbox will enable virtual performance simulation, fault prediction, and system optimization without physical risk. Finally, in a networked microgrid deployment, the integration of blockchain-based green energy metering can provide transparent and tamper-proof recording of energy generation and consumption data, enabling future green energy credit trading for prosumers and promoting a fully decentralized sustainable energy ecosystem.

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