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Green Steps: A Simulation – Based Approach to Sustainable Power Using Electromechanical Footsteps

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ABSTRACT

The optimization of footstep energy harvesting as an eco-friendly and sustainable alternative source of energy is examined in this paper. Employing piezoelectric technology, the research aims to harness mechanical energy from footstep actions and convert it to electrical power in areas of high pedestrian volume like railway stations and shopping malls. The outlined method combines piezoelectric sensors with high-quality DC-DC converters and energy storage systems to optimize power output. MATLAB/Simulink simulation and mathematical modelling has been used to optimize the electromechanical performance of the piezoelectric harvester, putting special focus on the influence of block design with damping conditions. It has been shown that footstep energy harvesting can be a sustainable means to fulfil low and medium power requirements, providing a portable and highly durable energy solution. By addressing optimization with simulation, this research helps to pave the way for renewable energy technologies towards practical uses.

Keywords: Piezoelectric Energy Harvesting, Footstep Power Generation, MATLAB/Simulink Simulation, Voltage Boost and Storage, Renewable Micro-Energy Systems

1. INTRODUCTION

The increasing need for electricity and the intrinsic limitations of conventional energy sources are the primary reasons for the serious energy crisis of the contemporary world. Fossil fuels, such as coal, oil, and natural gas, have been the major energy source for several decades. Since fossil fuels are non-renewable natural resources, they are available in limited quantities. These resources become highly depleted and ultimately disappear because of uncontrolled and unlimited use. Humans are pushed to seek sustainable and alternative ways of generating electricity because of our use of finite resources and increased worries concerning the impact of global warming [1] [2]. Fossil fuels have a tremendous negative environmental impact as well as cause climate change, and this highlights the fact that there should be a shift in energy generation [3].

Different researchers have suggested various concepts for the production of green and renewable energy [4] [5] [6] [7]. These concepts range from a broad spectrum of technologies with distinct features and uses. The master goal is to utilize the rich natural energy streams available on the planet to supply the earth's energy requirements in a sustainable and economically justifiable way. It is imperative that the world shift to renewable energy to realize a sustainable world, attain energy security, and fight climate change. This evolution incorporates not only the creation of new technologies but also the refinement of current ones in order to improve efficiency, lower costs, and allow wider uses.

The fast-paced advancements in wireless sensors and electronic systems have brought with them a corresponding need for efficient and long-term power solutions [8]. Batteries, used historically to power these devices, though useful, are highly limited. Batteries exhaust themselves quite rapidly, and replacing or recharging them is difficult, particularly where the location is inaccessible or remote [8]. Such a drawback inhibits extensive deployment and constant use of most wireless and electronic systems. In addition, with reducing sizes in circuits as a result of emerging technological advancements, the power needs for these smaller devices also change, requiring more efficient and compact energy supplies [8].

Energy harvesting, the capture of ambient energy from the environment and its conversion to useful electrical power, is an attractive alternative to traditional batteries. It is becoming increasingly prominent due to the promise it holds for offering autonomous power to low-power electronic devices, thus making their operational lifetime longer and maintenance less frequent. Of the different methods of energy harvesting, those involving kinetic energy, like piezoelectricity, have been quite promising. Piezoelectric materials are capable of generating a voltage upon being subjected to mechanical stress or vibration [9]. Although single piezoelectric crystals generate voltages of lower magnitudes, which are appropriate for powering low-powered devices, new methods are being pursued to increase their power supply [9]. For example, pairing multiple piezo crystals in a well-planned design can generate an increased rate of power, allowing them to power more sophisticated applications [9]. When cumulatively used, this technique utilizes the array of piezoelectric elements to generate significantly more power for self-powered sensors and other electronic devices.

Apart from piezoelectric elements, there are other methods as well for harvesting kinetic energy, including systems that can yield human kinetic energy as electricity. A good example of this is a design that uses two square-sized tile structure pavers [10]. This mechanism employs fluid bags in fluidic connection with each other through flow control systems, such as unidirectional valves and mini-hydro generators [10]. With human kinetic energy being transferred to the pavers, fluid movements are generated, which are then utilized by the hydro generators to generate electricity [10]. These types of systems illustrate the possibility of widespread energy harvesting from daily activities, converting public spaces into power generation areas. These developments in energy harvesting are pivotal to the further growth of wireless sensor networks, the Internet of Things (IoT), and other distributed electronic systems because they have the potential to greatly alleviate logistical burdens of battery management and can help create a more sustainable technological environment. This paper aims to delve deeper into these aspects, exploring the feasibility and implications of large-scale implementation of such innovative energy solutions, contributing to the broader discourse on achieving a sustainable and energy-secure future for all.

1.1 Software Implementation in Research Gaps and Proposed Work

To concentrate research gaps and proposed work on software implementation with MATLAB / Simulink, the following points can be incorporated:

1.1.1 Detailed Electromechanical Modelling: Although electromechanical models have been developed in Simulink and validated against theoretical and equivalent electrical models, there is a constant need to improve these models in order to accurately predict the behaviour, responsiveness, and output of piezoelectric harvesters over a broad range of parameters [1] [2] [3]. There is a gap in the development of strongly adaptable Simulink models that can easily integrate different material properties and critical damping effects, which play a major role in harvester output [4].

1.1.2 Integration of Optimization Strategies: While mathematical modelling of piezoelectric modules within MATLAB/Simulink has been done, and appropriate optimization strategies are suggested to enhance system performance, there exists a gap in complete integration and demonstration of these optimization strategies exclusively in the Simulink environment [5]. This involves investigating how various optimization algorithms can be tested and implemented in Simulink in order to maximize energy harvesting efficiency.

1.2 Proposed Work

1.2.1 Advanced Simulink Model Development: The work proposed in this paper will include the development of advanced electromechanical piezoelectric energy harvesting system models using MATLAB/Simulink only. The models developed will be made such that dynamic parameter changes, including input vibration magnitudes and piezoelectric materials, can be directly implemented in Simulink blocks [6]. The hope is to have a realistic piezoelectric harvesting case where different material properties can be considered [2] [4].

1.2.2 Simulation and Verification: In Simulink, extensive mechanical and electrical system simulations will be performed with a large number of simulation steps to validate extensive analysis [7]. The theoretical and simulation outputs of the electromechanical model developed in Simulink will be validated, and their conclusions compared with current equivalent electrical models [1].

1.2.3 Optimization and Performance Enhancement: The present work aims to design and simulate optimization techniques in the MATLAB/Simulink environment to model the performance of the piezoelectric energy harvesting system [5]. This involves mimicking the behaviour of piezoelectric harvesters, and study their responsiveness and output at different vibration frequencies and amplitudes directly by Simulink simulation [3]. By this approach, this study can utilize the strength of MATLAB/Simulink in thorough modelling, simulation, and optimization of piezoelectric energy harvesting systems in order to create a simulatory mechanism before actual implementation.

2. PROPOSED METHODOLOGY

This research addresses these challenges by proposing a software-based experimental framework that models, simulates, and analyzes a piezoelectric energy harvesting system using MATLAB / Simulink. By leveraging simulation tools, it becomes feasible to conduct systematic evaluations of system performance under varied conditions without requiring physical hardware. The core idea is to model the entire signal flow from footstep force generation to energy capture, power conditioning, and storage, and to analyze the behavior of each subsystem within a flexible and cost-effective virtual environment. This enables informed design decisions and establishes the conceptual platform for researchers and developers before physical implementation. The framework is divided into five major simulation stages:

2.1 Footstep Force Modeling

A simulated mechanical input representing the impact of human footsteps is created using a Pulse Generator block in Simulink. The pulse amplitude and frequency are tuned to mimic realistic human walking behavior, typically ranging from 600 to 1000 Newtons per step at approximately 1–2 Hz. This signal serves as the dynamic force input applied to the piezoelectric model.

2.2 Piezoelectric Transducer Modeling

The piezoelectric element is modeled as a voltage source in series with a capacitor and a high internal resistance, representing the electromechanical energy conversion behavior. Simscape Electrical components are used to simulate the electrical response of the piezoelectric material to varying mechanical loads. This step translates mechanical energy into AC voltage output.

2.3 Power Conditioning Circuit Simulation

The raw AC voltage from the piezoelectric transducer undergoes rectification and voltage boosting by a full-bridge rectifier (comprising ideal diode blocks) converts AC to DC and a DC-DC boost converter is modeled using Simulink components (inductor, capacitor, diode, and controlled switch). Pulse-width modulation (PWM) is applied to control the duty cycle of the boost converter for optimal energy transfer.

2.4 Energy Storage Simulation

The conditioned DC output is connected to a battery model to simulate energy storage. Parameters such as state of charge, internal resistance, and charging efficiency are incorporated to monitor battery behavior. This storage system is evaluated under various step frequencies and force amplitudes.

2.5 Performance Analysis and Optimization

Simulink scopes and data logging tools are employed to capture time-domain signals, measure output voltage, and calculate harvested energy. Various configurations—such as piezo arrays, different converter parameters, and step frequencies—are tested. Efficiency metrics and system response are plotted to identify optimal design conditions. This software-only simulation platform offers a low-cost, flexible, and insightful approach to developing and optimizing piezoelectric energy harvesting systems, paving the way for real-world deployment in smart floors, transport hubs, and other high-footfall public spaces.

A flowchart is given in Fig. 1 to understand the processflow of the adopted methodology which is implemented using MATLAB / Simulink.

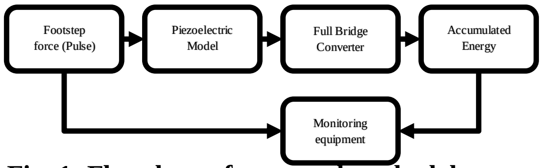

Fig. 1: Flowchart of proposed methodology

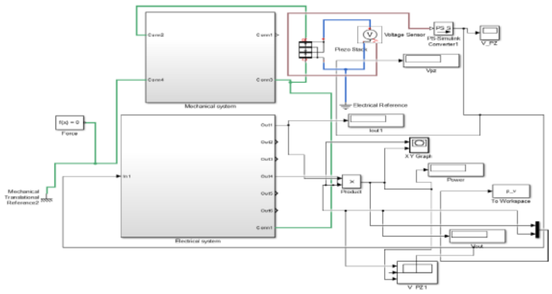

Fig. 2: Model of Simulink

3. TESTING & RESULTS

3.1 Testing Procedure

As shown in Fig. 2, to validate the performance of the proposed piezoelectric energy harvesting system in a software-based experimental environment, a full simulation model was developed and executed using MATLAB/Simulink. The simulation was designed to replicate the electromechanical response of a piezoelectric device under cyclic mechanical loading, along with the corresponding electrical signal conditioning and energy storage stages. This method allows for rapid prototyping and performance evaluation without relying on physical hardware.

The simulation begins by emulating human footsteps using a Pulse Generator block. This block produces a periodic pulse signal with a defined amplitude of 1, a period of 1 second, and a 20% duty cycle to reflect the intermittent nature of human walking. A Gain block is then used to scale the signal to a realistic force magnitude of approximately 700 Newtons, which represents the average vertical force exerted by an adult human during a walking step. Although a physical piezoelectric transducer converts mechanical pressure into AC voltage, this functionality is simulated using a Sine Wave block to mimic the oscillatory nature of voltage output generated by real piezoelectric materials under dynamic pressure. This output is then directed through a simplified rectifier stage, represented in this software model using an Absolute Value (Abs) block, which transforms the alternating waveform into a unidirectional (pulsating DC) signal suitable for energy storage.

Next, the conditioned voltage is processed through a simulated DC-DC boost converter using another Gain block with a gain factor of 2. This abstraction models the increase in voltage level typically required in practical systems to raise the low-voltage output of piezoelectric generators to a usable level (e.g., 3.3V or 5V). The boosted signal is then input into an Integrator block, used here as a surrogate for a rechargeable battery. The integrator captures the cumulative voltage or charge over time, simulating how harvested energy is stored in a real-world energy storage system.

The initial and final outputs are observed using a Scope block, which captures the voltage waveform at each critical point in the system, particularly at the output of the storage stage. The simulation was run over a 10-second period to evaluate the behavior of the system under repeated footstep excitation.

3.2 Discussion on Results

A complete multi-stage simulation graph illustrating the energy harvesting process from footstep input to energy storage is given in Fig. 3. It shows the following:

1. Simulated Footstep Force: Periodic force spikes at ~700N representing human steps.
2. Piezoelectric AC Output: Oscillatory voltage generated under dynamic force (ideal sine wave).
3. Rectified Voltage Output: Absolute value of piezo voltage, mimicking full-wave rectification.
4. Boosted Voltage Output: Amplified signal simulating DC-DC boost conversion.
5. Accumulated Storage Voltage: Cumulative energy stored over time in a simulated battery.

The initial input pulse generation is shown in Fig. 4 and the final energy accumulation is shown in Fig. 5. The results of the simulation confirm the theoretical operation of a piezoelectric energy harvesting system. The pulse generator output successfully mimics discrete footsteps, and the scaled output force creates a periodic signal that feeds into the piezoelectric model. The sine wave abstraction produces an alternating waveform that aligns well with expected piezoelectric voltage patterns. Upon rectification, the waveform is converted to a unidirectional pulse, validating the energy conversion stage. The boost stage effectively increases the voltage magnitude, simulating the function of a real boost converter used in hardware implementations. The integrator output displays a steadily rising voltage profile, indicating successful energy accumulation over time. This supports the potential for real-world applications, such as powering wireless sensors or microcontrollers in smart environments.

4. CONCLUSION

This work has presented a MATLAB/Simulink-based framework, which effectively demonstrates the fundamental behavior and performance of a piezoelectric energy harvesting system, offering a cost-effective and flexible tool for evaluation, academic research, and very importantly, a prerequisite for hardware system design. By modeling footstep induced force, piezoelectric voltage generation, rectification, voltage boosting, and energy storage, the system successfully emulates real-world energy harvesting behavior. The simulation confirms that low frequency mechanical input can be converted into usable electrical energy for low power applications. This framework provides a cost-effective, scalable platform for simulatory analysis and optimization prior to physical implementation, and lays the groundwork for future integration with realistic Simscape components and advanced control strategies.

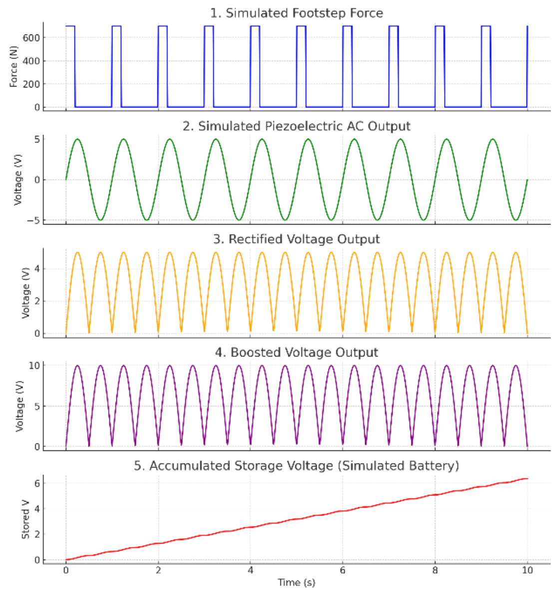

Fig. 3. Output graphs from every step

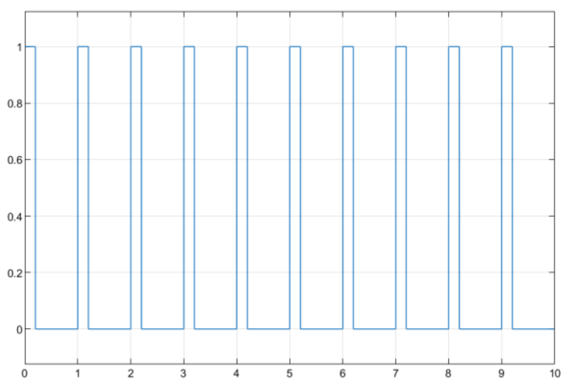

Fig. 4. Pulse Generator (I/P signal)

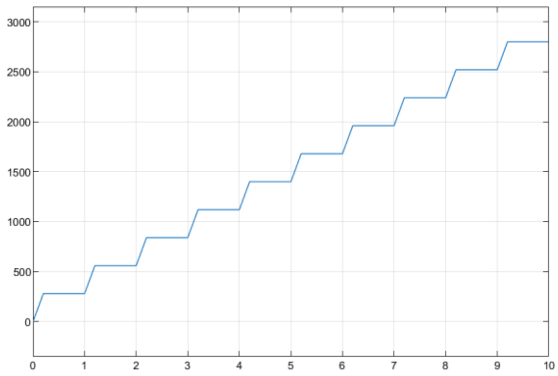

Fig. 5. Output energy accumulation over time

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