Hybridization of Photovoltaic and Thermoelectric Energy Harvesting Systems at Seismic Nodes

Abstract
Seismic data is one of the most important data for analysis and interpretation of subsurface, but remote seismic node fails frequently. This is one of the main constraints that limits seismic network to acquire continuous seismic data and near real-time prediction of seismicity of an area. There are several ambient energy sources at the remote seismic nodes. Optimization of their energy transducers and DC-DC converters is inevitable. In this study, solar and thermal sources are utilized with maximum power point tracking (MPPT) algorithm. The algorithm is based on the Neural Network model to supply the duty cycle across the converter optimally. Historical data were generated from Perturb and Observe algorithm in PSIM for the Neural Network Model to train the data and predict the duty cycles for both within and outside the data. The proposed system delivered an over 75% conversion rate of the Photovoltaic module's power. The system was modeled in Simulink under the ideal conditions of its components. It could face few constraints during prototype implementation due to the unusual characteristics of the thermoelectric elements. However, certain additional electrical energy was achieved for a low duty power load, such as a remote seismic node. The significant contributions are to identify operating constraints and design optimal hybrid energy harvesting systems at a remote seismic node.

Keywords: Converter, Energy, MPPT, Photovoltaic, Thermoelectric.

I. INTRODUCTION
The continuous and reliable geophysical database provides appreciated and meaningful details about the interior of the earth [1]. Seismic data is one of the most important data for analysis and interpretation of subsurface [2]. A remote seismic node is an embedded system that could be a permanent or temporary node. It detects, measures, and stores earth vibration in an electrical signal manner. It usually consists of sensing, processing, and storing units, while the Global Positioning System (GPS) and telecommunication backbone could be optional. Energy harvesting systems extract available ambient energy, which could be solar, thermal, radio-frequency, or vibration sources, and convert them into usable electrical power.

The performance of a solar energy harvesting system depends strongly on the temperature and irradiance of the ambient environment. For delivering reliable and continuous electrical energy at the remote seismic nodes, the above considerations are investigated. The optimization of these considerations enables the delivery of steady and continuous power supply to remote sensor deployment like seismic node [3]. Apparently, in thermoelectric technique, any thermal gradient results in electricity generation, and it is relatively reliable as well as quiet in nature. It has no moving parts, unlike other resonant generated energy transducers. It is capable of converting the wasted thermal gradient created by the photovoltaic(PV) transducer into electrical energy [4]. The thermal gradient across the thermoelectric transducer and the application of the Seebeck effect is the essential factors that cause the transitioning of charge carriers to its output as a terminal voltage [5]. Thermal heat is permanently available [6], and the small thermal gradient is usually experienced [7]. The thermoelectric elements could be cascaded in series to deliver usable voltage for remote nodes [8]. Hence, the solution is suitable for seismic deployments.

A layout of the energy harvesting system at a case study is shown in Fig. 1, which comprises a PV module and lead-acid battery as the only source of energy without any form of optimization. Linear mode regulation is used, which is characterized by low efficiency. Broadband seismometers are
active electronic feedback sensors, and they require reliable, steady, and continuous power to function optimally [9]. Linear mode regulator also takes a lot of life from a conventional battery. Fig. 2 is a diagram of the proposed energy harvesting system that intends to deliver a continuous and sustainable electrical energy.

This paper intends to identify and demonstrate the constraints of PV and thermoelectric techniques in a hybrid energy harvesting system. Maximum Power Point Tracking (MPPT) and a buck converter at seismic nodes are simulated in the Simulink environment. The two main contributions of this study are (1) identification of operating constraints to enable a continuous and affordable supply of the seismic system, and (2) designing a hybrid energy harvesting system at the remote seismic node.

The remainder of the paper is organized as follows; Section 2 discusses related works to the study. Section 3 investigates materials and methods in PV, thermoelectric energy transducers, and buck converter with its MPPT. In Section 4, we provide the findings, simulated results, and discussions of the design. Section 5 covers the conclusion of the study.

II. RELATED WORK

Several approaches to energize remote nodes by energy harvesting systems have been reported in the literature. However, each remote node requires different considerations of energy transducers and energy conversion for a particular remote node. Most of the approaches are deployed for a relatively short period and need no optimizing of their subsystems, and unsuitable for a seismic node, which operates endlessly. A continuous and sustainable energy harvesting system requires logical optimization at the conversion stage of the design and implementation [10] [11].

Hybrid Energy Harvesting System aims at capturing more than one source of ambient energy, process, and store them in a usable manner. Integrating energy sources improves continuity in seismic data acquisition. However, optimizing their constraints is challenging. A hybrid energy harvesting system could be a combination of PV, radio frequency (RF), vibration, or thermal sources. Table I shows the different sources of energy and their respective peripherals.

| S/No. | Combination | Conversion Type | Type of Converter | Type of MPPT | Expected Efficiency | Application /Topology | Remarks | Reference |
|-------|-------------|-----------------|-------------------|--------------|---------------------|-----------------------|---------|-----------|
| 1     | Thermoelectric | Temperature gradient | MOSFET is driven by PWM and control by a micro-controller | MPPT Tracking efficiency of 99.85% | 99.85% Theoretical tracking | Buck or Boost converters for Remote, Space, and Automobile | The Thermoelectric transducer, MPPT, and SMPS were utilized, but battery alone and low-cost Microcontroller | [12] |
| 2     | Thermoelectric | Temperature gradient | DC-DC switch is driven and modulated by PWM | Open-circuit Algorithm MPPT | Not Available | Boost Converter | Open Circuit Algorithm is the simplest MPPT to developed, but parameters are difficult to determine | [14] |
| 3     | Thermoelectric | Temperature Gradient | MOSFET Switch based on Burst mode to control the output voltage and reduce wastage of energy for maximum power to be | Fractional open circuit voltage MPPT | Functional overall efficiency 81% | Boost and buck | With reduced power losses, the overall efficiency is improved | [15] |
| S/No. | Combination                        | Conversion Type         | Type of Converter | Type of MPPT | Expected Efficiency | Application /Topology | Remarks                                                                 | Reference |
|-------|-----------------------------------|-------------------------|-------------------|--------------|--------------------|-----------------------|--------------------------------------------------------------------------|-----------|
| 4     | Thermoelectric Temperature Gradient | SMPS                    | Perturb Observe MPPT Algorithm | Not Available | Boost converter     | P&O MPPT tracked fast under sudden changes in temperature and irradiances. | [16]      |
| 5     | Thermoelectric Temperature Gradient | MOSFET driven by a micro-controller | Open Circuit MPPT Algorithm Track 99% power | Not Available | Remote, military, space, medical Buck Switched Mode Power Supply (SMPS) | Open Circuit MPPT is easy to implement since there is no need to measure current | [17]      |
| 6     | Thermoelectric Temperature Gradient | Bipolar DC-DC Converter | Open Circuit MPPT Algorithm | 70% efficiency | Buck/Boost          | Not Available |                                                                          | [18]      |
| 7     | PV and Thermoelectric Photocurrent and Thermocouple | Not Available | Not Available | Not Available | Not Available | The PV installed alone has an efficiency of 14%. The wasted thermal heat generated 100-140Wm² To increase the efficiency of PV transducer should be relatively decreased | [19] [20] [21] |
| 8     | PV and Thermoelectric Photocurrent and Thermocouple | Not Available | Not Available | Not Available | Not Available | Thermoelectric was able to contribute 7% of the output power where MPPT and SMPS were employed | [22]      |
| 9     | PV and Thermoelectric Photocurrent and Thermocouple | Not Available | Not Available | Not Available | Not Available | Efficiency was increased by 3,6% without optimization | [23]      |
| 10    | PV and Thermoelectric Photocurrent and Thermocouple | Not Available | Not Available | Not Available | Not Available | Hybrid enhanced output power 2-20%. The efficiency of the photovoltaic increase up to 3.37% | [24]      |
| 11    | PV and Thermoelectric Photocurrent and Thermocouple | Not Available | Not Available | Not Available | Not Available | From 25°C to 100°C reduced by 25%; Hybrid at 83°C, the efficiency increased by 10% without optimization of MPPT and SMPS | [25]      |
| 12    | PV and Thermal Photocurrent and Thermal Difference | MOSFET as a switch driven Microcontroller and modulated by PWM | MPPT employed | 80% | Boost SMPS | Hybrid improved efficiency | [26]      |

In a thermoelectric energy harvesting system, the converter includes an inductor that has an accurate conversion rate. However, the high value of the inductor is needed to improve efficiency [27]. The author in [28] used a voltage multiplier based on a charge pump in the design, and low voltage levels of thermoelectric transducers were converted to usable forms.

Table I lists several approaches, and each approach observed that all the transducers contribute to the overall energy. Based on Table I and the literature review, a low power duty system such as the seismic PV module can serve as the primary source and assigned to bias an operational amplifier adder. Simultaneously, the thermoelectric module is merely a complement energy source to the PV source by contributing additional electrical energy. Relatively low ripples and high efficiency characterize a buck converter topology, and the neural network MPPT algorithm is employed to improve efficiency.

### III. MATERIALS AND METHODS

#### III.1 System Architecture at a Seismic Node

A typical seismic node consists of an embedded system, seismometer (sensor), data acquisition system, Global Positioning System (GPS) antenna, and its receiver, while telemetry is optional, as shown in Fig. 3. A case study at 06°
52.022N 07°25.045E in Southeast Nigeria, Nsukka Seismic Node on Nigerian National Network of Seismographic Stations (NNNSS) has five subsystems:

1. Broadband Seismometer
2. Data Acquisition System
3. Mobile Router
4. GPS Receiver
5. Power Supply

III.II Energy Transducer

Deploying seismic instrumentation at a quiet node is necessary [29], and suitable installation of PV and thermal transducers which have no moving parts [30] are appropriate for seismic nodes. A thermoelectric transducer has a solid-state conversion, characterized by a very long lifespan and can produce electrical energy even without sunlight [31]. Table II shows the electrical characteristics of a case study at Nsukka Seismic Node. The proposed system employs a PV module as the primary source and thermoelectric as a compliment. The two sources are combined using a non-inverting operational amplifier across the DC-DC converter to power the load and energy storage.

Table II. Electrical Specifications at Nsukka Seismic Node in Nigeria

| Subsystem                  | Nominal Voltage/Current | Mode of Operation |
|----------------------------|-------------------------|-------------------|
| Seismometer                | 12V/200mA               | Always            |
| Digital Acquisition System | 12V/200mA               | Always            |
| GPS Receiver               | 12V/100mA               | Always            |
| Mobile Router              | 12V/300mA               | Hourly            |

III.II.1 Photovoltaic Module

Photovoltaic cell consists of p-n junction diodes that convert solar energy to electrical energy and typically have an efficiency between 6% to 20% [32]. Ambient temperature and irradiance are the significant parameters that affect the outputs of a PV cell, and they are always considered during the design of a solar energy harvesting system. Fig. 4 represents an equivalent circuit of a PV cell and consists of current source $I_{PV}$ connected in parallel to the p-n junction diode. Fig. 5 demonstrates how the cell inputs vary with irradiance and temperature. The circuit and plot define the relationships between current and voltage levels by Kirchoff's law. The generated current at the load, $I_L$, is based on the circuit, defined by (1) and (2) as well as the curve in Fig. 3 [33]:

$$ I_L = \frac{V - I_O R_S}{R_{SH}} $$

Fig. 3: Proposed Architecture of Optimized Energy Harvesting System with Seismic Instrumentation

Fig. 4. Equivalent Solar Cell Circuit

Fig. 5. Simulated I-V Relationship of a Solar Cell
The open-circuit voltage, $V_{OC}$ being one of the key parameters of a PV cell, is the maximum voltage available for the load when the current flow does not exist, as shown in Fig. 5 earlier. Fig. 7 demonstrates the linear relationship between temperature effects and the $V_{OC}$, and its highest value was measured at the lowest temperature of 0°C at 0.56V:

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_s}{I_o} + 1\right) \text{ at } I = 0 \quad (3)$$

The temperature effects on $V_{OC}$ is given by (3), while the recombination of the carriers in the PV cell depends on $I_o$ as well as the irradiance. The thermal voltage, $V_T$ caused inefficiency of the PV cell, and the expression is as shown in (4). The saturated current, $I_o$ is a fraction of the reverse current in the diode, which estimates the characteristics of the diode, as shown in (2). Then (4) equally implies the thermal voltage is directly proportional to temperature $T$. The behaviours of (2) and (4) indicate the voltage is mostly affected by temperature negatively, and it influences the terminal voltage swiftly:

$$V_T = \frac{kT}{q} \quad (4)$$

Fig. 5 shows the graphical representation of the short circuit current, $I_{SC}$, showing the highest value of PV cell current against voltage as zero, assuming the series resistance $R_s$ is neglected in (2) to obtain (5). In Fig. 6, $I_{SC}$ slightly changed when compared to $V_{OC}$ behaviour with temperature variations. The highest measurement was at 0.71196A at a temperature of 60°C and the lowest at 0.69816 at 0°C:

$$I_{SC} = I_{PV} \quad (5)$$

Fig. 7 clearly shows the direct dependence of $P_{MAX}$ on the ambient temperature. It demonstrated the performance of the PV cell measurements from Table III, decreasing from 0.281315W to 0.169977W as the temperature levels increased from 0°C to 60°C. Hence, efficiency is directly affected by temperature shown in Fig. 8 to Fig. 10.

### Table III. Simulated Measurements of PV cell at fixed Ambient Irradiance

| Temperature | $I_{MAX}$ (Amps) | $V_{MAX}$ (Volts) | $P_{MAX}$ (Watts) |
|-------------|------------------|-------------------|-------------------|
| 0           | 0.69816          | 0.56              | 0.28              |
| 10          | 0.70046          | 0.53              | 0.261817          |
| 20          | 0.70276          | 0.5               | 0.24346           |
| 30          | 0.70506          | 0.48              | 0.224837          |
| 40          | 0.70736          | 0.45              | 0.206325          |
| 50          | 0.70966          | 0.42              | 0.187845          |
| 60          | 0.71196          | 0.39              | 0.169977          |
Fig 8. A Plot of Temperature effects on $I_{SC}$ with fixed Ambient Irradiance

Fig 9. A Plot of Temperature effects on $V_{OC}$ with fixed Ambient Irradiance

Fig 10. A Plot of Generated Power with varying temperature

III.II.II Thermoelectric Transducer

A thermoelectric transducer converts thermal heat to electrical energy due to the thermal gradient between two junctions, utilizing Seebeck effects [34]. The equivalent circuit of its element is modelled with a voltage source in series with internal resistance $R_{TH}$, as shown in Fig. 10 [35]. The source voltage, $V_{TH}$ is calculated as open-circuit voltage $V_{OC}$, which is directly proportional to the thermal gradient, as exhibited in Fig. 11(a) with linear characteristics. The voltage across the terminal of the two junctions is defined as:

$$V_{TH} = \alpha_{p-n} \Delta T \frac{R_{O}}{R_{O} + R_{th}}$$  \hspace{1cm} (6)

$P_{O} = \left(\frac{\alpha_{p-n} \Delta T}{R_{O} + R_{th}}\right)^2 \times R_{O}$  \hspace{1cm} (7)

Where;

$\alpha_{p-n} = \text{Seebeck Coefficient between p-type and n-type materials}$

$R_{TH} = \text{Internal Resistance}$

$R_{O} = \text{Load Impedance}$

$\Delta T = \text{Thermal Gradient between the two junctions}$

$P_{O} = \text{Generated power at the load}$

Most frequently, modeling of a thermoelectric transducer is performed under constant thermal gradient $\Delta T$ [36]. The effects of internal resistance $R_{TH}$ of the transducer are ignored, and it is modelled with a fixed voltage source connected in series to internal resistance and implement (6) and generate power as (7) [35].

Fig. 11(b) and Table IV have simply demonstrated the voltage magnitude being linearly dependent on the thermal gradient and varies with the ambient temperature. Based on the results, the $V_{MPQ}$ is almost half of the $V_{OC}$ simply because of the linear characteristics of the plots. The linearity implies tracking MPP will be less tricky than PV cell.
### Table IV. Performance of the various Thermal Gradient

| Thermal Gradient, ΔT | VMPP (V) | P_{MPP} (W) |
|----------------------|----------|-------------|
| 30°C                 | 0.05     | 8           |
| 60°C                 | 0.07     | 15          |
| 90°C                 | 0.088    | 20          |
| 120°C                | 0.118    | 28          |

III.III Hybrid Energy Transducer

The proposed design intends to use the phenomena of a photovoltaic and thermoelectric system. Their outputs are DC source, and the nominal voltage of a remote seismic node is 12VDC. In the proposed design, since the output voltage of the thermoelectric transducer is low, less than 1VDC, and hardly exceeding 1.5VDC for remote environments [37]. Hybrid circuit of non-inverting Op-Amp adder, as shown in Fig. 12, the output of the PV module is employed to bias the amplifier as the primary energy source, and the thermoelectric module is applied to the non-inverting terminal.

Fig 12. Hybrid Transducer with Inputs from PV and Thermoelectric Modules

The aggregate current levels of PV and thermoelectric modules are expressed in (8) to increase the total current generated [38]. The total power harvested of the two transducers is also expressed in (9) [38] as:

\[
I_{\text{hybrid}} = I_{\text{PV}} + I_{\text{TH}} \tag{8}
\]

\[
P_{\text{hybrid}} = P_{\text{PV}} + P_{\text{TH}} \tag{9}
\]

III.III.I Buck DC-DC Converter for the Hybrid Energy Harvesting System

Fig 13 shows a buck DC-DC converter that converts the outputs from the PV module to the desired 12VDC across the remote seismic node. It is used to charge the battery and energize the load simultaneously.

Fig 13. Buck Converter Circuit
IV. RESULTS AND DISCUSSIONS

Reviewing the related work shows abundant studies of energy harvesting system aimed at improving the efficiency and simultaneously adding more electrical energy at remote modes. In the case study, a 120W solar module is installed, and Fig. 14 represents the typical daily generated power. It employs a linear mode of DC regulation, which delivers inefficient, disproportionate, and expensive to run on a long-term basis.

Fig 14. Generated Power by the Case Study with the PV Module

Fig 15 shows a simulated circuit in Simulink utilizing similar electrical characteristics and ambient irradiance and temperature measurements obtained from a weather station operated by Centre for Atmospheric Research, Anyigba, Nigeria. Fig. 16 demonstrated that relatively higher generated power could be delivered in the case study.

Fig 15. Simulated Circuit of the existing Energy Harvesting System at a Remote Seismic Node

Fig 16. Simulated Current, Voltage, and Power supplied to the node
For the optimal duty cycles across the DC-DC converter, the neural network model will be interfaced with the converter to predict duty cycles from the corresponding ambient irradiance and temperature levels. Perturb and Observe (P&O) algorithm was used to generate $V_{\text{MAX}}$ and duty cycle as the output measurements of historical data. The corresponding ambient irradiance and temperature measurements were used as the inputs measurements. The historical data were trained by a neural network model to predict duty cycles across the buck converter each time a set of irradiance and temperature hit the PV module. This model could predict accurately for both trained and untrained data, and it does require no voltage or current sensors to sense both voltage and current measurements. Meanwhile, Fig. 17 shows the P&O MPPT implemented circuit and to produce the $V_{\text{MAX}}$ measurements and the computed duty cycles. Fig. 18 describes the proposed circuit implementing the neural network MPPT in Simulink, and Fig. 19 is the plot showing $V_{\text{MAX}}$ measurements of the circuit. The circuit takes 0.00005s to stabilize to deliver the $V_{\text{MAX}}$ levels, maximum power of 90W, and efficiency of 75%, with ambient irradiance levels from 0 to 683.6. Fig. 20 and Fig. 21 represent the load voltage and current, respectively. They are relatively stable despite the irregularities of the ambient inputs across the PV module. While the generated power without and with MPPT is shown in Fig. 14 and Fig. 22, respectively, obviously indicating, MPPT optimally track the maximum possible power.
V. CONCLUSIONS

The hybrid energy harvesting system based on theoretical studies of the photovoltaic and thermoelectric techniques has been simulated to power remote seismic nodes. The efficiency of 75% was attained with relatively lower ambient irradiance levels. Although the thermoelectric and PV modules have been demonstrated separately but analytically, it is shown that more electrical energy is added when it serves as a compliment, with the PV as the primary source. The PV module measurements at the case study were simulated because it is the primary ambient source, and its output would be used to bias the thermoelectric module. Neural network MPPT and buck converter were executed, and delivered an optimal energy harvesting system. The essence of the study is to develop a simple, sufficient, and affordable energy harvesting system at the remote seismic node for a long-term seismic database without discontinuities.

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