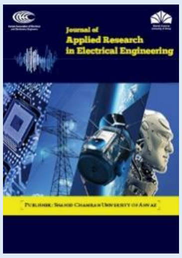
Shahid Chamran University of Ahvaz

Iranian Association of Electrical and Electronics Engineers

Journal of Applied Research in Electrical Engineering

E-ISSN: 2783-2864
P-ISSN: 2717-414X
Homepage: https://jaree.scu.ac.ir/



Research Article

Analysis of the Potential of Different Air Conditioner Brands for Piezoelectric Energy Harvesting

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Abstract: Piezoelectric energy harvesting from air conditioner compressors is a promising technology for generating renewable electricity. This study comprehensively compares the energy harvesting potential derived from mechanical vibrations in compressors across various air conditioner brands, harnessing piezoelectric systems. Initially, a data collection system rooted in Internet of Things (IoT) technology is employed to capture vibration signals from different branded air conditioner compressors. The acquired data undergoes pre-processing and is subsequently analyzed in MATLAB Simulink to gauge its energy harvesting potential through a piezoelectric framework. Notably, the maximum voltage harvested demonstrated strong positive correlations with both the compressor vibrational frequency (0.7892) and velocity (0.7855), emphasizing their role in determining available mechanical energy for conversion to electrical power. Furthermore, a moderate positive correlation (0.0659) was observed between the harvested voltage and the compressor's rated power, indicating its influence on energy conversion. An additional positive correlation (0.2839) between temperature and harvested voltage was attributed to the increased electrical conductivity of compressor materials at higher temperatures. Conclusively, the compressor's frequency and velocity emerged as primary determinants of the maximum voltage harnessed, with rated power having a less pronounced yet contributory effect. This research provides valuable insights for optimizing energy harvesting from air conditioner compressors, highlighting the pivotal role of operational parameters.

Keywords: Piezoelectric energy harvesting, air conditioners, simscape

Article history
Received 22 November 2023; Revised 25 May 2024; Accepted 26 May 2024; Published online October 9, 2024.

How to cite this article
D. Kwegyir ,F. B. Effah, D. Opoku, P. Asigri, Y. Hayford, E. O. Boateng, K. Kessey-Antwi, N. M. Abdul-Bassit Munagah, and K. W. Tamakloe, "Analysis of the Potential of Different Air Conditioner Brands for Piezoelectric Energy Harvesting," *J. Appl. Res. Electr. Eng.*, Vol. 3, No. 1, pp. 40-50, 2024. DOI: 10.22055/jaree.2024.45352.1089

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1. Introduction

While reliable, conventional electricity generation methodologies, like hydroelectric and thermal power stations, pose significant environmental challenges. These include the depletion of natural resources, emission of greenhouse gases, and contribution to air pollution [1]. In pursuit of more eco-friendly alternatives, nations globally are turning to renewable energy sources, including solar, wind, and nuclear fusion. Although these renewables offer reduced environmental footprints, their reliability can be compromised by unpredictable environmental conditions, such as fluctuating sunlight and wind patterns [2].

Recently, piezo energy harvesting has emerged as a promising avenue for energy generation. This technique captures renewable, environmentally friendly electricity from mechanical vibrations, movements, and pressure, positioning it as a sustainable energy alternative [3]. Many mechanical devices in daily use, for instance, air conditioners, dispense several joules of mechanical energy as vibrations. This energy, primarily overlooked and wasted, holds the potential for conversion into usable power. Consequently, piezoelectric energy harvesting has attracted considerable research interest recently [4], as evidenced by numerous studies and publications.

Y. Li et al. [5] introduced a hybrid energy harvester that combines electromagnetic, piezoelectric, and triboelectric mechanisms to harness ocean wave energy. Their approach utilised a shaking energy harvesting mechanism, encompassing gear and pendulum components, supplemented by piezoelectric and electromagnetic generators. While the system could power at least 90 LEDs and environmental sensors, its effectiveness was constrained by the low frequency of ocean waves. W.M. Jayarathne et al. [6] presented a piezoelectric vibration energy harvester tailored for vehicular energy extraction. The model employed lead zirconate titanate as the piezoelectric medium and resonant frequency analysis within a cantilever configuration. Despite Finite Element Analysis (FEA) projecting an output of 5.99V, real-world motorcycle tests produced only 3.56V. Such discrepancies underscored the influence of dynamic road conditions and material inconsistencies. In their work, Abishek Ray et al. [7] explored the applicability of a modified cantilever design for vibration energy harvesting using piezoelectric sensors. They incorporated unique structural features, including a stair-shaped sidewall and a beam-integrated hole, to modulate the resonant frequency. The subsequent Finite Element Analysis, employing unimorph PZT-5H piezoelectric material, suggested promising outcomes, though structural modifications did pose challenges to the system's mechanical integrity. V.J. Caetano et al. [8] embarked on an experimental journey to engineer versatile piezoelectric devices that accommodate varied environmental excitation frequencies. Their innovative designs, especially the pizza-shaped prototype, were contrasted against conventional beam structures. The results favored the novel designs, especially when subjected to harmonic excitations. Corina et al. [9] ventured into optimizing a dual-stage piezoelectric energy harvesting circuit tailored for the SMD10T2R111WL transducer's SPICE model. Although their approach, encompassing synchronous buck configuration, showcased improved efficiency, specific results stemming from the piezoelectric transducer appeared unfeasible. Delving into the domain of human-centric energy harnessing, S. Mariem et al. [10] investigated the potential of converting human breathing patterns into electricity via piezoelectric systems. Their simulations underscored the impact of cantilever dimensions on energy optimization, revealing some insightful correlations. Z. Wang et al. [11] showcased a piezoelectric energy harvester leveraging rotational magnetic excitation. Despite the promising voltage outcomes, the generated power remained suboptimal due to the resonance frequency constraints inherent to their design.

Contrasting conventional piezoelectric structures, R. Newton et al. [12] championed the efficacy of an E-shaped design. Their comparative analysis, rooted in simulation, posited the superiority of the E-shaped model, though it necessitated further efficiency refinements. Lastly, N. Burham et al. [4] delved into vehicular energy harvesting using piezoelectric mechanisms. Their empirical assessments highlighted the pronounced influence of vehicle attributes, such as weight and speed, on voltage outputs while underscoring the longevity challenges transducers face in such dynamic environments.

This study comprehensively compares the energy harvesting potential derived from mechanical vibrations in compressors across various air conditioner brands, harnessing piezoelectric systems. Initially, a data collection system rooted in Internet of Things (IoT) technology is employed to capture vibration signals from different branded air conditioner compressors. The acquired data undergoes pre-processing and is subsequently analyzed in MATLAB Simulink to gauge its energy harvesting potential through a piezoelectric framework. This paper is outlined as follows: Section 2 introduces the foundational theory of piezoelectric energy harvesting. Section 3 presents the proposed block diagram for the experimental design, detailing each block's component selection and functionalities. Section 4 discusses the experimental approach for data collection, while Section 5 delves into the related simulations. Results are discussed in Section 6, ending with conclusions in Section 7.

2. Piezoelectric Energy Harvesting

Piezoelectricity refers to a unique phenomenon where certain materials, upon experiencing mechanical stress, generate an internal electric charge separation. These materials often possess crystal lattices devoid of central symmetry. When subjected to pressure, the relative movement of their positive and negative ions creates an electric voltage. Even though the material remains electrically neutral, the charge displacement induces an electric field, producing electricity. The resultant piezoelectric voltage exhibits pulsatory characteristics, requiring extensive processing for real-world applications [13].

2.1. Electrical and Mechanical Behaviour of Piezoelectric Material

The electrical and mechanical behaviour of the piezoelectric material can be represented by (1) and (2).

$$S = s^E T + d_t E \tag{1}$$

$$D = d_t T + \varepsilon^T E \tag{2}$$

Equations (1) and (2) contain the following parameters: 'S' represents mechanical strain, *'E'* denotes the electric field, '*T*' signifies the applied mechanical stress, and *'D'* is the electric displacement. Meanwhile, ' s^E ' is the elasticity matrix maintained at a constant electric field, ' ε^T ' stands for the permittivity matrix under consistent mechanical strain, and ' d_t ' is the matrix defining the piezoelectric coefficient.

2.2. Inertia Mass and Resonant Frequency in Vibrational Analysis

The power density of a piezoelectric material is related strongly to the vibration´s frequency and amplitude by (3)

$$P_{res} = 4\pi^3 m f_{res}^{\ 3} y z_{max} \quad (3)$$

Equation (3) includes parameters pivotal to vibrational dynamics for piezoelectric energy harvesting. Here, 'm' stands for the inertia mass, which reflects the resistance of an object to any change in its velocity, including a change in direction. Inertia mass is central to understanding how vibrations will affect the piezoelectric material. The term 'fres' represents the resonant frequency. It is the specific frequency at which a system naturally oscillates with maximum amplitude due to external periodic driving forces. In piezoelectric systems, aligning the resonant frequency with expected external vibrations can substantially optimize energy capture. The parameter 'y' denotes the amplitude of the vibrations, indicating the maximum displacement of a point on the beam from its rest position. In many scenarios, the amplitude correlates directly with the amount of energy that can be harvested: larger amplitudes often mean more significant energy potential. Lastly, 'zmax' is the paramount amplitude of vibrations, signifying the utmost extent to which a point on the beam can deviate from its equilibrium state during oscillation.

From (3), the resonance can significantly amplify the vibrations of the beam, leading to a larger deflection and, in the piezoelectric materials, a higher generated voltage or power. Thus, designing a piezoelectric cantilever beam to have a natural frequency that matches or is close to the frequency of expected vibrations can optimize energy harvesting.

From the Euler-Bernoulli Beam theory, the natural frequency of a cantilever beam can be determined by (4) [14].

$$f_n = \frac{k_n}{2\pi}\sqrt{\frac{El}{l^4}} \quad (4)$$

In equation (4), '*E*' is Young's modulus of elasticity, provides a measure of the stiffness of a material. The parameter '*I*', is the area moment of inertia used for determining a beam's resistance to bending and deflection. Also, '*l*' is the length of the beam, and 'kn', a constant, relies on the mode of vibration being analyzed. The value 'kn' is taken as 3.52 for the first mode of vibration (mode 1).

3. Methods and Materials for Experimental Design and Setup

This study adopted a four-phase methodology to guarantee meticulous and thorough investigations. A summary of these phases is presented in Fig. 1. This study randomly selected various air conditioner brands to ensure a representative sample of popular models in Ghana's market. A robust Internet of Things (IoT) system was developed to capture vibrational data from these air conditioners. The system interfaced directly with the compressors, logging vibrational data into an Excel sheet. After data collection, pre-processing techniques were employed to extract essential features. These features were then integrated into a

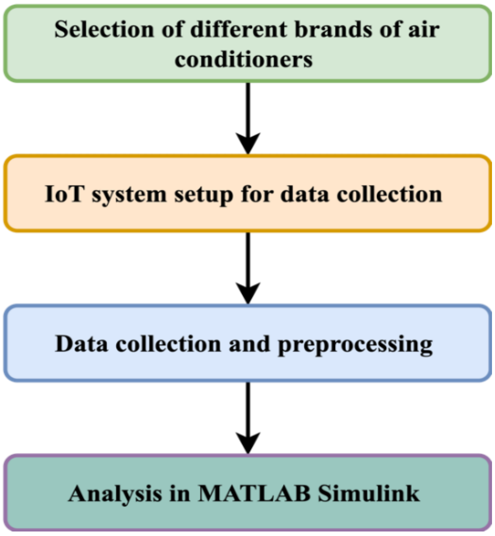

Fig. 1: Block Diagram for experimental Design

piezoelectric energy harvester model in MATLAB Simulink. This methodology enabled the simulation of the vibrational dynamics, offering profound insights into the energy generation capabilities of the examined air conditioner units. Details of each step in the proposed methodology are explained in the sub-sections.

3.1. Selection of different air conditioner brands for experimental setup

This study purposefully selected seven (7) different air conditioner brands to ensure the representation of commonly used air conditioner types in Ghana. This was aimed at diversifying the array of air conditioning systems in the energy harvesting analysis. Each air conditioner unit was installed at different locations, each characterized by unique patterns of operation that could influence the voltage generated over time: Details of the location and usage patterns of each unit is provided in Table 1.

Again, the electrical specifications i.e., rated input power, rated input current of the air conditioners are given in Table 2.

3.2. IoT System Set-up for Data Collection

In this study, we developed an Internet of Things (IoT) framework to acquire and document vibrational data from multiple air conditioner models. The system incorporates numerous pivotal elements and methodologies, ensuring precise and trustworthy data gathering. The setup consists of a sensor, microcontroller, and computer with Arduino IDE and Microsoft Excel installed. This setup was integral to the experiment process, enabling the subsequent analysis of energy generation potential based on the recorded vibrations. Fig. 2 depicts the aforementioned setup, and details of the data collection processes are elaborated below.

A critical component of the IoT setup is the selection of an appropriate sensor capable of accurately detecting and measuring mechanical vibrations. For this purpose, an MPU-6050 GYRO+ACCELEROMETER sensor was selected due to its dual-axis accelerometer and gyroscope, which enabled comprehensive measurement of linear accelerations and rotational movements, aligning with the experiment's objective of capturing air conditioner vibrations in detail [15]. This sensor is connected physically and interfaced between the air conditioner compressor and an Arduino Uno microcontroller to sense vibrations. Also, to ensure precise and consistent measurements, a calibration process is carried out on the MPU-6050 to adjust its sensitivity and offset parameters to eliminate any potential biases or inaccuracies in the collected data. The Arduino UNO is a central processing unit responsible for data acquisition and communication with the sensor. It is programmed to read the sensor data from the AC compressor continuously and sends it to a connected computer for storage in Excel and further analysis. The connection of MPU-6050 GYRO+ACCELEROMETER sensor to the Arduino Uno microcontroller is shown in Fig. 3. The physical setup of the IoT system which involves connection to AC compressor and laptop is shown in Fig. 4.

Table 1: Description of AC brands

AC Brand	Location	Usage pattern
Chigo	Lecture's office	Operates intermittently aligned with lecturer's office hours
Nasco	Lecturer's office	Operates intermittently aligned with lecturer's office hours
LG	Lecturer's office	Operates intermittently aligned with lecturer's office hours
Beko	Student´s room on university campus	Operates based on student´s daily routine but remained operational throughout the evenings.
Frigidaire	Installed in a laboratory	Operates throughout the daytime during lab hours and remain off in the evening.
TCL	Lecturer's office	Operates when the room is needed for activities
Hisense	Office of teaching assistants	Operates throughout the daytime during office hours

Table 2: Ratings of selected air conditioners

Air Conditioner Type	Rated Input Power (W)	Rated Input Current (A)	Year of Installation
TCL	3430	12	>10 years
Beko	1800	9.5	>10 years
Hisense	1010	4.5	< 3years
LG	5000	8.5	> 5 years
Frigidaire	2122	9.46	>10 years
Nasco	1561	8.5	> 5 years
Chigo	1730	7.9	> 10 years

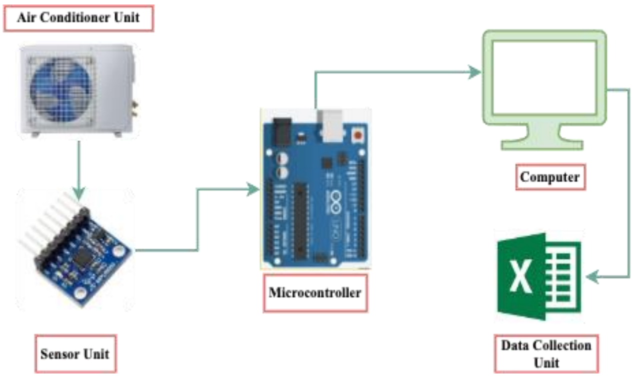

Fig. 2: IoT setup for data collection

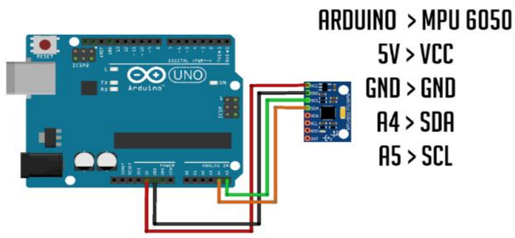

Fig. 3: Arduino Uno connected to MPU6050 GYRO+ Accelerometer

Fig. 4: Physical set of IoT system for data collection

3.3. Data collection and pre-processing

Vibration data was gathered at temperatures of 16℃, 20℃, and 24℃ specifically for TCL, Beko, and Hisense while maintaining a steady 17℃ for other units. Every data entry in the Excel file was marked with a timestamp of 0.01s to ensure accurate alignment with the air conditioner units' respective operational states and usage patterns. This data was securely stored in a designated Excel file, allowing further analysis and processing. The data underwent a fast Fourier transform (FFT) treatment during the pre-processing phase. This involved importing the data into MATLAB and executing an FFT through custom code. The output of this transformation was a complex dataset, capturing the signal in its frequency, phase and acceleration spectrum. This FFT outcome was subsequently recorded in the Excel file. Sample outputs of vibration data analysis from the AC brands are shown in Figs. 5-7.

Tables 3 and 4 provide information about the different air conditioner types, the operating temperatures at which the vibrational data was collected, the frequency of the dominant vibration and its velocity from the Fourier analysis. The maximum frequency and velocity are fed into the piezoelectric model in Simulink to harness the energy for further analysis.

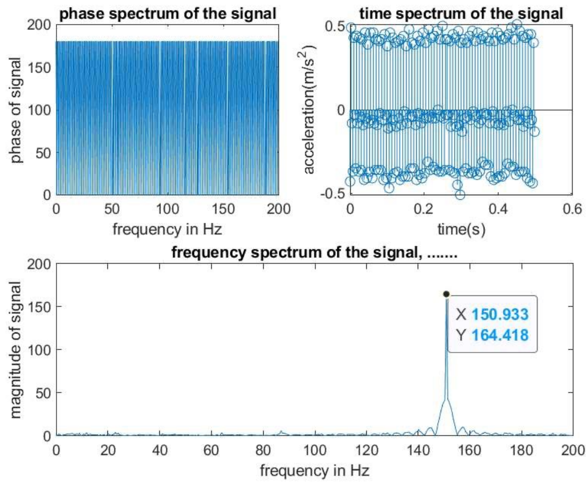

Fig. 5: Frequency, phase and time spectrum of Hisense vibrational data at an operating temperature of 24ºC

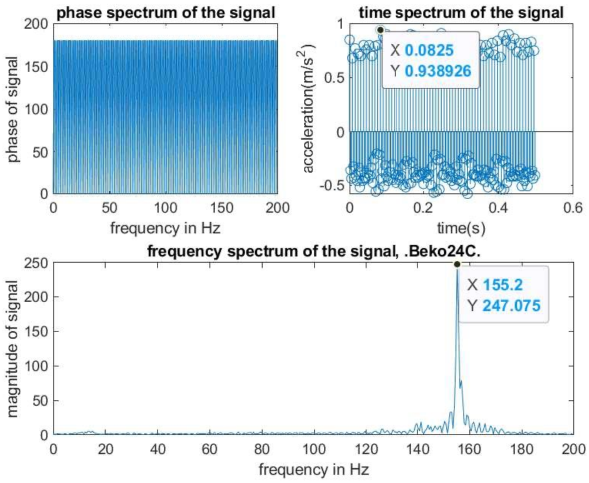

Fig. 6: Frequency, phase and time spectrum of Beko vibrational data at an operating temperature of 24ºC

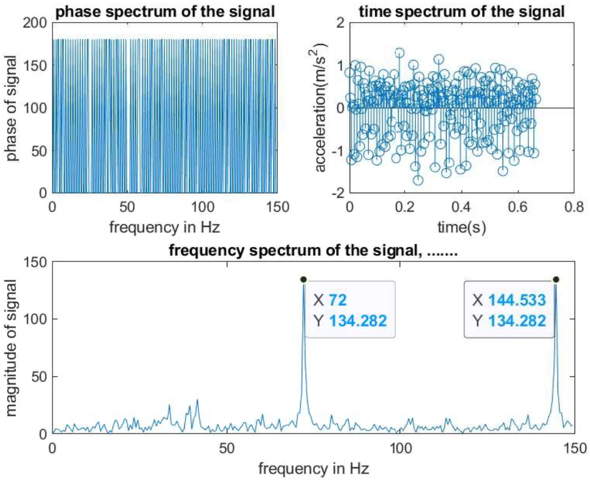

Fig. 7: Frequency, phase and time spectrum of TCL vibrational data at an operating temperature of 24ºC

3.4. Simulation and analysis in MATLAB Simulink

The block diagram in Fig. 8 is employed to model the piezoelectric energy harvester in MATLAB Simulink software.

3.5. Description of each block

Air conditioner vibration data and piezoelectric transducer: this serves as the source of vibrational data for energy harvesting. The vibration energy in a piezoelectric harvesting system consists of two parts, which are the mechanical and electrical parts. The mechanical part provides energy from the surrounding environment, which in this work represents the air conditioner compressor. This is transferred into the piezo device or transducer to vibrate its input and harvest energy. The vibrational source is modelled as a sinusoidal signal used to represent engines that rotate at a constant speed which is the case of an air conditioner compressor when set at a certain temperature shown in Fig.9.

The process of harvesting the vibrations from the air conditioner compressor is further modelled as a piezo bender connected to a vibration system within the energy harvesting system, as illustrated in Fig. 10. The piezo bender block shows a piezoelectric bimorph cantilever beam device, with its parameters used for the simulation detailed in Table 3. This device is modelled to vibrate and generate electrical potential by harnessing vibrational energy. Furthermore, the piezo bender has a tip mass and an unencumbered rotational free end on its right side. Including the tip mass serves multiple purposes, including the modulation of the system's resonance frequency, thereby optimizing its performance. Additionally, it enhances the mechanical responsiveness of the system, particularly during low-amplitude vibrations, thereby augmenting the overall output power. Applying an external force induces mass displacement, leading to deformation in the interconnected piezo element. These deformations yield a charge accumulation and voltage differential across the electrical terminals of the piezo bender, which are efficiently harvested as electrical power.

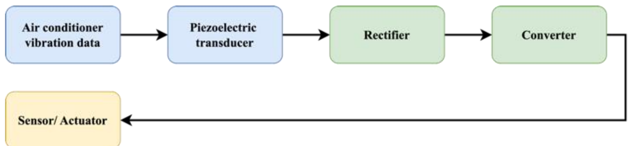

Fig. 8: Block diagram of piezoelectric energy harvester

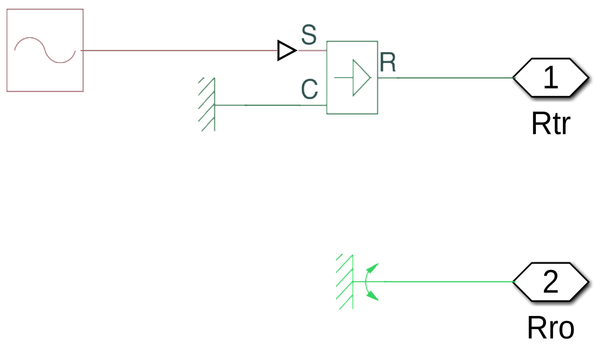

Fig. 9: Sinusoidal vibration source subsystem

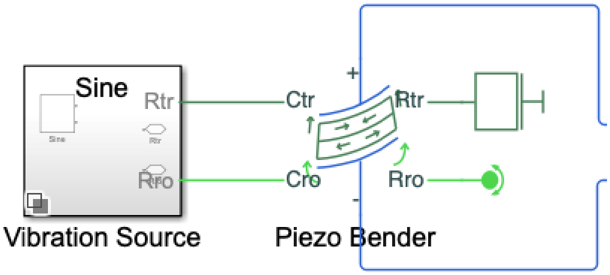

Fig. 10: Piezo bender connected to a vibrational source in Simulink

Again, in this work, the vibration data collected form the different brands of air conditioners are used. Specifically, the dominant frequency component of the vibration and its velocity are set to the sinusoidal subsystem in Simulink shown in Fig. 11 to simulate the production of mechanical vibrations from the AC compressor.

Rectifier: In this research, a full-wave bridge rectifier is employed in conjunction with a piezo bender to facilitate the conversion of alternating current or voltage (AC) generated during the bending of the piezo device into direct current (DC). The rectification process transforms the sinusoidally varying AC input generated by the piezo bender into a pulsating DC voltage. The rectifier assembly comprises four diodes and a capacitor, serving as a filtering component to attenuate voltage ripple, as illustrated in Fig. 12. The resultant pulsating DC output voltage from the rectifier subsequently undergoes further refinement through a low pass filter, effectively reducing distortions and ensuring a smoother output.

Table 3: Cantilever beam parameters

Parameter	Dimension
Beam Length	31.75mm
Beam Width	12.7mm
Beam thickness	0.5mm
Capacitance	15nF
Rated Drive Voltage, Vrated	180V
Free deflection at Vrated	0.233mm
Blocking Force at Vrated	-0.414N

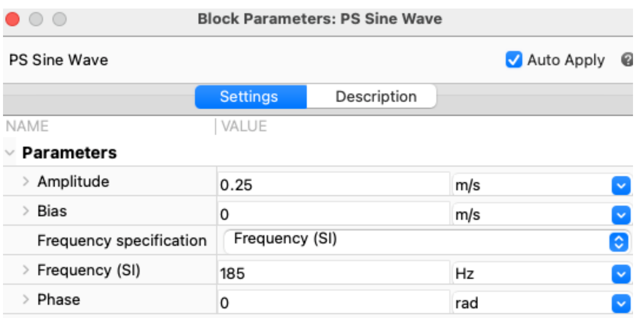

Fig. 11: Sinusoidal vibration source parameters

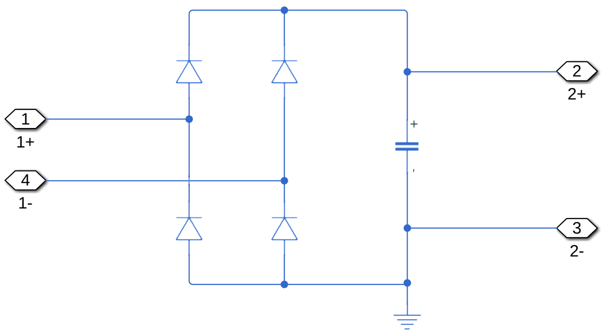

Fig. 12: Full-wave rectifier bridge subsystem with four diodes and one capacitor

Converter: In this study, the DC-DC converter is represented by a buck converter block, as depicted in Fig. 13. The buck converter regulates the voltage to transfer the maximum possible power to the load and ensures that the power transfer is unidirectional. Also, a pulse generator controls the converter in an open loop with a fixed switching frequency and duty cycle.

Actuator/Sensor: The DC voltage generated is applied to power a battery and a load depicted in Fig. 14. Initially, the energy harvester charges a battery. Then, the energy harvester and the battery power up a constant load. The battery cannot hold a charge since its voltage source varies with the amount of charge and resistance connected in series. The source battery's output will be precisely or very close to 3 volts if the internal resistance is adjusted to 2 ohms and the nominal voltage is 3 volts. This is the case since the nominal voltage is also 3 volts.

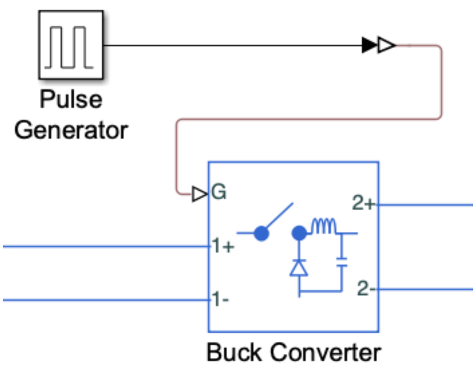

Fig. 13: Simscape buck converter model

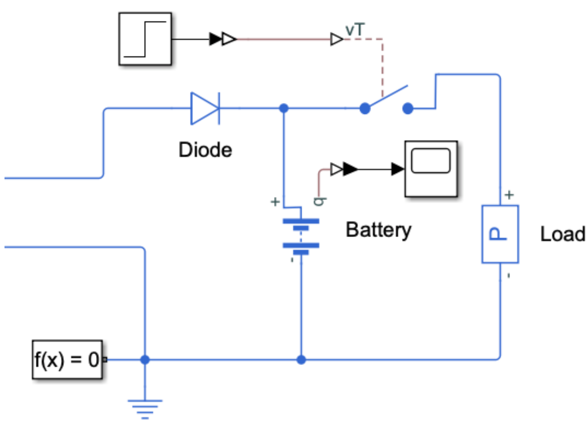

Fig. 14: Actuator circuit of battery and load

4. Simscape Model of Piezoelectric Harvester

The Simscape model in Fig. 15 from the existing literature was utilized to simulate energy harvesting from the air conditioner compressors.

5. Results and Analysis

In this section, a detailed exploration of the maximum DC voltage outputs harvested from air conditioner compressors under varying conditions, encompassing different temperature settings and diverse compressor brands is presented. Again, the findings from the experimentation are analyzed and interpreted. The primary objective of this study was to assess the energy harvesting capabilities of seven prominent air conditioner compressor brands—TCL, Beko, LG, NASCO, Frigidaire, Chigo and Hisense on the Ghanaian market—while subjecting them to different operating temperatures. As energy harvesting from air conditioner compressors gains increasing significance in the context of sustainable and energy-efficient technologies, understanding the variables that influence their performance becomes paramount. The results presented in the preceding sub-sections summarize the intricate relationship between temperature and these compressors' maximum DC voltage output that can be harvested with a piezoelectric harvester. Additionally, these findings shed light on the disparities in energy harvesting potential across the assessed brands, serving as a valuable guide for decision-making in various applications reliant on air-conditioner compressor energy output.

5.1. Comparison of the output voltages of TCL, Beko and Hisense at an operating temperature of 16ºC

The results in Table 4 present the maximum DC voltage harvested from the air conditioner units of three brands (TCL, Beko and Hisense) operating at a temperature of 16°C, 20oC and 24oC. This data is crucial in understanding how various factors such as vibration frequency, signal velocity, rated power, and the year of installation of the ACs influence their energy harvesting capabilities. Again, Table 4 shows the comparison of the average values of the frequency, velocity and maximum DC voltage harvested from the brands of ACs across all temperatures.

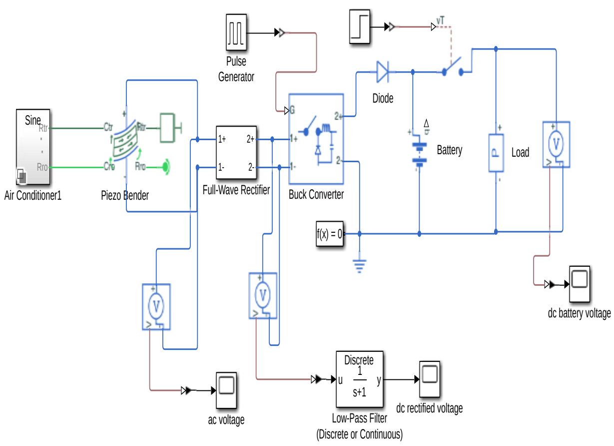

Fig. 15: Simscape model of piezoelectric harvester

Table 4: Maximum voltage harnessed from different brands of air conditioners

Air conditioner type	Temperature (ºC)	Maximum Frequency (Hz)	Velocity of Signal (m/s)	Maximum DC Voltage Harvested (V)
TCL	16	140.80	0.60	5.03
Beko	20	141.11	0.90	6.52
Hisense	24	144.53	0.70	6.01
Beko	16	152.53	0.84	8.61
Frigidaire	20	154.13	0.74	8.29
Nasco	24	155.20	0.90	10.01
Hisense	16	125.33	0.50	3.24

TCL: At 16°C, the maximum frequency is 140.80 Hz, the velocity of the signal is 0.60 m/s, and the maximum DC voltage harvested is 5.03 V. As the temperature rises to 20°C, there is a slight increase in frequency to 141.11 Hz, a rise in signal velocity to 0.90 m/s, and an increase in harvested voltage to 6.52 V. At 24°C, the frequency further increases to 144.53 Hz, the velocity drops slightly to 0.70 m/s, while the harvested voltage drops marginally to 6.01 V.

Beko: Starting at 16°C, the maximum frequency is 152.53 Hz with a signal velocity of 0.84 m/s, and the harvested voltage is 8.61 V. At 20°C, the frequency slightly increases to 154.13 Hz, the signal velocity decreases to 0.74 m/s, but the harvested voltage decreases slightly to 8.29 V. By 24°C, the frequency has increased to 155.20 Hz, the signal velocity rises to 0.90 m/s, and the harvested voltage notably jumps to 10.01 V.

Hisense: At 16°C, Hisense shows the lowest frequency of 125.33 Hz compared to the other two brands, with a signal velocity of 0.50 m/s and harvested voltage of 3.24 V. At 20°C, there is a significant jump in frequency to 149.87 Hz, but the signal velocity remains the same at 0.50 m/s, leading to a harvested voltage of 5.74 V. At 24°C, the frequency slightly rises to 150.93 Hz, the velocity decreases to 0.40 m/s, and the voltage drops to 5.02 V.

Among the three brands, Beko consistently demonstrates the highest maximum frequency and harvested voltage across all temperatures. The high vibration velocity and frequency in the Beko and TCL air conditioners leading to higher voltage outputs can also be due to the wear and tear in some AC components, such as the fan, motor or compressor since they were installed about ten years ago. The low vibration velocity and frequency in the case of Hisense AC may be due to how new it is. Technological advancements have led to the developing of quieter and more efficient air conditioning units such as the Hisense brand. Again, modern air conditioners often incorporate features that minimize vibrations, such as better insulation, improved motor designs, and advanced compressor technologies. Clearly, the efficiency and capability of air conditioners to harness voltage vary based on the brand, year of installation and temperature. This information could be crucial for users or industries aiming to optimize energy harnessing from air conditioners. The output voltage of the rectifier at temperatures of 16°C, 20°C and 24°C for TCL, Beko and Hisense are shown in Figs. 16-18.

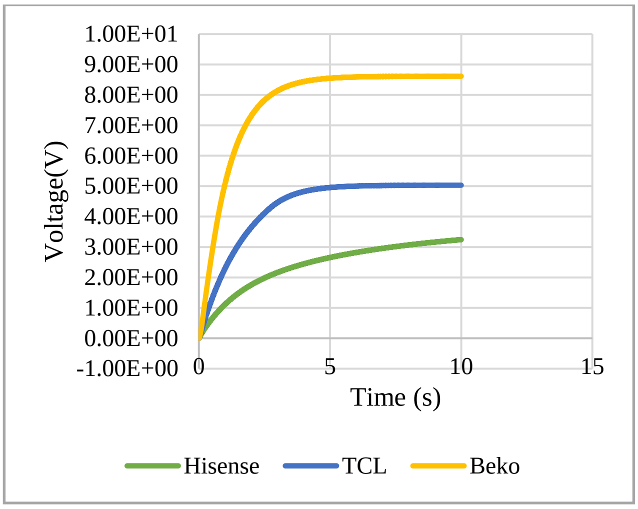

Fig. 16: Rectified voltage at 16ºC

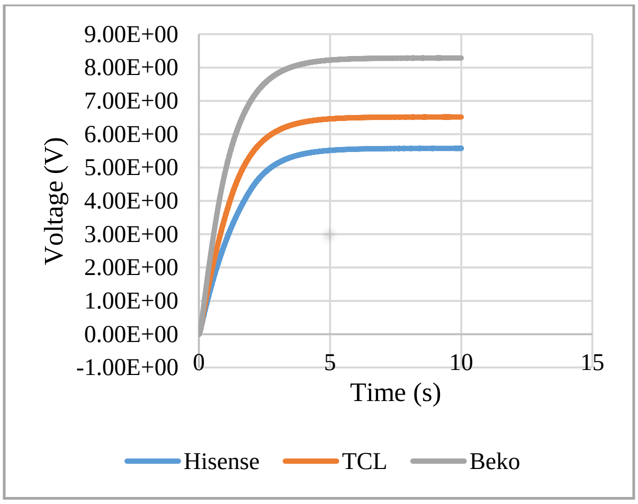

Fig. 17: Rectified voltage at 20°C

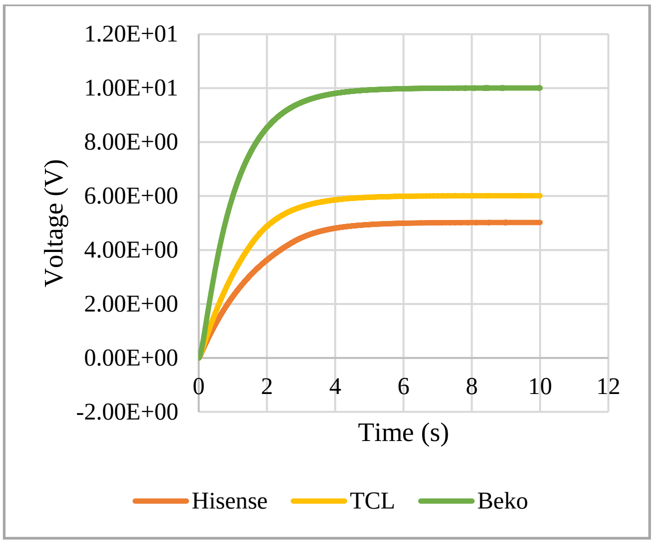

Fig. 18: Rectified voltage at 24°C

5.2. Comparison of output voltage harnessed from LG, NASCO, Frigidaire and ChIGO air conditioners at different operating temperature

Table 5 shows the maximum DC voltage harnessed from LG, NASCO, Frigidaire, and ChIGO air conditioner vibrations at a constant temperature of 17°C. The results show that the maximum voltage harnessed increases with frequency and velocity. A more detailed discussion is given below.

From Table 5, there is notable variations in vibrational frequency and velocity among the four brands of AC producing significant variation in the voltage harnessed. Frigidaire, with the highest frequency of 252.27 Hz and velocity of 0.70m/s, demonstrates the highest maximum DC voltage harvested, measuring 6.72 V. With the next highest frequency of 145.60 Hz and a velocity of 0.6m/s, LG generates a maximum DC voltage of 5.60 V, showcasing a similar trend of higher frequency resulting in higher voltage output. Chicago, with a frequency of 133.87 Hz and velocity of 0.70m/s, and NASCO, at 128.00 Hz and a velocity of 0.50m/s, yield lower DC voltage outputs of 4.78 V and 3.53 V, respectively, further supporting the correlation between frequency and harvested voltage. It is clear that the amount of electricity that can be generated is limited by the frequency and velocity of the vibration, as well as the year of installation of the air conditioner. The output voltage of the rectifier is shown in Fig. 19.

Table 5: Maximum voltage harnessed from vibrations of different air conditioners at a constant temperature

Air conditioner type	Temperature(oC)	Maximum Frequency (Hz)	Velocity of Signal (m/s)	Maximum DC Voltage Harvested (V)
LG	17	145.60	0.60	5.60
NASCO	17	128.00	0.50	3.53
Frigidaire	17	252.27	0.70	6.72
ChIGO	17	133.87	0.70	4.78

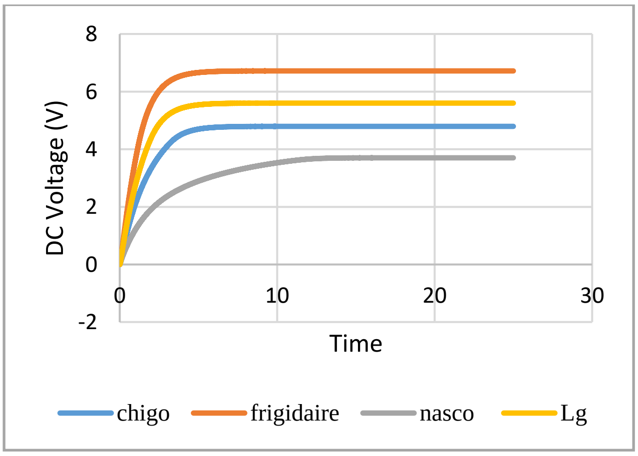

Fig. 19: Rectified output voltage at 17°C

5.3. Correlation between maximum DC voltage harnessed and temperature, power rating, frequency and velocity

The correlation table to study the impact of operating temperature (T), power rating (P), frequency (F) and velocity (S) of vibration signal on the amount of voltage (M) harvested from the ACs is shown in Table 6.

The results from Table 6 shows a strong positive correlation of 0.7892 and 0.7855 between the maximum voltage harnessed and the frequency and velocity respectively of the air conditioner compressor signal. This is because the frequency and velocity of the compressor determine the amount of mechanical energy available to be converted into electrical energy. The higher the frequency and velocity, the more mechanical energy is available and the higher the maximum voltage harnessed. There is also a positive correlation of 0.0659 between the maximum voltage harnessed and the rated power of the air conditioner compressor. This is because the rated power of the compressor is a measure of the amount of mechanical power it consumes. The higher the rated power, the more mechanical power can be converted into electrical energy. However, the correlation between the maximum voltage harnessed and the rated power is less intense than the correlation between the maximum voltage harnessed and the frequency and velocity of the compressor. Again, there is a positive correlation of 0.2839 between temperature and maximum voltage harvested, which can be explained by the fact that the electrical conductivity of the materials used in the compressor increases with temperature. This means more electrons can flow through the circuit, producing higher voltage output. The Table shows that the compressor's frequency and velocity primarily determine the maximum voltage harnessed from an air conditioner compressor. The rated power of the compressor also has a positive effect on the maximum voltage harnessed, but the effect is not more substantial.

6. Conclusion

The energy harvesting potential of various air conditioner brands on the Ghanaian market has been explored. The study unveiled significant insights into the eco-friendly energy-harnessing landscape through systematic experimentation and analysis. It was evident that different air conditioner brands, each with unique design and operational characteristics, exhibit varying energy harvesting capabilities. The study established a strong positive correlation between the frequency and velocity of air conditioner compressor vibrations and the maximum voltage harnessed.

Table 6: Correlation matrix

	T	P	F	S	M
T	1.0000				
P	0.0000	1.0000			
F	0.4893	-0.1187	1.0000		
S	0.0466	0.4898	0.3218	1.0000	
M	0.2839	0.0659	0.7892	0.7855	1.0000

This correlation underlines the significance of mechanical energy, available in vibrations, in influencing the electrical energy output. Moreover, factors like the rated power of the compressor and the operating temperature also correlate with the amount of voltage harnessed. The rated power, indicative of the compressor's mechanical power consumption, revealed a less intense yet positive correlation with the harvested voltage. Simultaneously, the positive correlation between temperature and harvested voltage points towards the increased electrical conductivity of compressor materials at higher temperatures. Again, the year of installation also manifested as a significant determinant of energy harvesting efficiency.

Furthermore, brand-specific analyses showcased brands like Beko consistently outperforming others, emphasizing the brand-to-brand variability in energy-harnessing capabilities. The technological strides made in recent years, with brands focusing on quieter and more efficient units, were also evident in the research findings. This research is paramount in light of the growing global emphasis on sustainable energy solutions. The detailed insights from the study can guide consumers and industries in optimizing energy harnessing from everyday appliances like air conditioners. Moreover, the findings can spur further innovations in piezoelectric energy harvesting, pushing the boundaries of eco-friendly energy generation. In essence, this research not only underscores the untapped potential of mechanical vibrations in energy generation but also paves the way for more comprehensive studies and technological advancements in this domain.

7. Further Research

While this study analyzed selected brands of air conditioners available in the Ghanaian market, further research should encompass a broader range of local and international brands. This would provide a more comprehensive understanding of the energy harvesting potential across different manufacturing and design philosophies. Long-term studies on air conditioner units should be conducted to understand the wear and tear effects on energy harvesting capabilities over extended periods. This would provide insights into the longevity and sustainability of such energy harvesting methods.

Declaration of Competing Interest

We declare that we have no conflict of interest.

Credit Authorship Contribution Statement

Daniel Kwegyir: Conceptualization, Formal analysis, Project administration. **Francis Boafo Effah**: Investigation, Validation. **Daniel Opoku**: Resources, Supervision. **Peter Asigri:** Funding acquisition, Roles/Writing - original draft. **Yoosi Hayford:** Data curation, Roles/Writing - original draft. **Eliezer Owusu Boateng:** Conceptualization, Software. **Kwaku Kessey-Antwi:** Conceptualization. **Nana Maryam Abdul-Bassit Munagah:** Conceptualization, Methodology. **Kelvin Worlanyo Tamakloe:** Conceptualization, Methodology.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

REFERENCES

[1] I. D. Ibrahim et al., "A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study," Energy Strategy Reviews, vol. 38. Elsevier Ltd, Nov. 01, 2021. doi: 10.1016/j.esr.2021.100740.

[2] W. Strielkowski, E. Tarkhanova, M. Tvaronaviˇ, and Y. Petrenko, "Renewable Energy in the Sustainable Development of Electrical," pp. 1–24, 2021.

[3] N. Sezer and M. Koç, "A comprehensive review on the state-of-the-art of piezoelectric energy harvesting," Nano Energy, vol. 80, no. August 2020, p. 105567, 2021.

[4] N. Burham et al., "Development of iezoelectric nergy arvesting via ehicle ovements."

[5] Y. Li et al., "An Electromagnetic-Piezoelectric-Triboelectric Hybridized Energy Harvester towards Blue Energy∗∗Resrach supported by ABC Foundation.," in Proceedings of the 16th Annual IEEE International Conference on Nano/Micro Engineered and Molecular Systems, NEMS 2021, Institute of Electrical and Electronics Engineers Inc., Apr. 2021, pp. 1070–1073. doi: 10.1109/NEMS51815.2021.9451366.

[6] S. L. University of Moratuwa, Institute of Electrical and Electronics Engineers. University of Moratuwa Student Branch, S. L. E. R. U. University of Moratuwa, Institute of Electrical and Electronics Engineers, and IEEE Sri Lanka Section, "MERCon 2018 : 4th International Multidisciplinary Engineering Research Conference : May 30-June 1, 2018, Civil Engineering Complex, University of Moratuwa, Sri Lanka," in 2018 3rd International Conference on Information Technology Research (ICITR), 2018, pp. 1–6.

[7] A. Ray, V. Butram, N. Gupta, and A. Naugarhiya, "Non-conventional cantilever for piezoelectric energy harvesting at ultra low resonant frequency," IEMECON 2019 - 9th Annu. Inf. Technol. Electromechanical Eng. Microelectron. Conf., pp. 90–93, 2019.

[8] V. J. Caetano and M. A. Savi, "Multimodal pizza-shaped piezoelectric vibration-based energy harvesters," J. Intell. Mater. Syst. Struct., vol. 32, no. 20, pp. 2505–2528, Dec. 2021.

[9] C. Covaci and A. Gontean, "Two-Stage Converter for Piezoelectric Energy Harvesting using Buck Configuration," in 2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging, SIITME 2020 - Conference Proceedings, Institute of Electrical and Electronics Engineers Inc., Oct. 2020, pp. 408–411.

[10] M. Saida, G. Zaibi, M. Samet, and A. Kachouri, "Design and study of piezoelectric energy harvesting cantilever from human body," 2018 15th Int. Multi-Conference Syst. Signals Devices, SSD 2018, vol. 2018-Janua, no. 1, pp. 164–168, 2018.

[11] Z. Wang, L. He, Z. Zhang, Z. Zhou, J. Zhou, and G. Cheng, "Research on a Piezoelectric Energy Harvester with Rotating Magnetic Excitation," J. Electron. Mater., vol. 50, no. 6, pp. 3228–3240, Jun. 2021.

[12] N. Rai, M. J. Nagaraj, A. M. Morey, and V. Shantha, "Construction and Simulation of Various Structures of Unimorph Piezoelectric Cantilever for Energy Harvest," in Proceedings of the 4th International Conference on Communication and Electronics Systems, ICCES 2019, 2019, pp. 651–655.

[13] C. Team, "Piezoelectric Effect Discovery of Piezoelectric Effect," pp. 1–6, 2023.

[14] G. C. Mekalke and A. V. Sutar, "Modal Analysis of Cantilever Beam for Various Cases and its Analytical and FEA Analysis," Int. J. Eng. Technol. Manag. Appl. Sci., vol. 4, no. 2, pp. 60–66, 2016.

[15] C. I. Nwakanma, F. B. Islam, M. P. Maharani, D. S. Kim, and J. M. Lee, "IoT-Based Vibration Sensor Data Collection and Emergency Detection Classification using Long Short Term Memory (LSTM)," 3rd Int. Conf. Artif. Intell. Inf. Commun. ICAIIC 2021, pp. 273–278, 2021.

[16] J. A. B. Gripp and D. A. Rade, "Vibration and noise control using shunted piezoelectric transducers: A review," Mech. Syst. Signal Process., vol. 112, pp. 359–383, 2018.

[17] S. Sivakumar, M. J. Sathik, P. S. Manoj, and G. Sundararajan, "An assessment on performance of DC-DC converters for renewable energy applications," Renew. Sustain. Energy Rev., vol. 58, pp. 1475–1485, 2016.

[18] A. Zablocki, "Energy Storage | Energy Storage," Pulsed power Syst. Princ. Appl., vol. 2040, no. February, pp. 1–8, 2019, [Online].

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