Integration of wind energy with a single-ended primary inductor converter and a brushless DC motor for water pumping system

Hassan Abdi Abi, Abdullahi Mohamed Isak, Suleiman Abdullahi Ali, Yakub Hussein Mohamed, Sowdo Mursal Abdi, Abdirisakh Khalif Osman
Department of Electrical Engineering, Faculty of Engineering, Jamhuriya University of Science and Technology, Mogadishu, Somalia

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ABSTRACT

This paper explores a simulation-based study on a renewable energy system that integrates wind energy with a single-ended primary inductor converter (SEPIC) to drive a brushless DC (BLDC) motor for water pumping applications. The proposed system addresses the challenge of regulating the variable output of wind turbines by employing a SEPIC converter to provide a stable direct current (DC) voltage supply to the BLDC motor. The novelty of this work lies in the combined modeling and performance analysis of the wind turbine, SEPIC converter, BLDC motor, and electronic commutation in MATLAB/Simulink, optimized for energy-efficient off-grid pumping. Simulation results demonstrate that the SEPIC converter effectively stabilizes the wind-generated voltage, ensuring reliable motor operation under varying wind conditions. The proposed system exhibits high efficiency, stable dynamic response, and low maintenance requirements, making it a practical solution for water pumping in wind-rich regions where solar irradiance is limited, particularly for off-grid water pumping applications.

Corresponding Author:

Abdullahi Mohamed Isak
Department of Electrical Engineering, Faculty of Engineering
Jamhuriya University of Science and Technology
Mogadishu, Somalia
Email: abdullahi.isak@just.edu.so

1. INTRODUCTION

The integration of wind power with single-ended primary inductor converter (SEPIC) and brushless direct current (BLDC) motors for water pumping remains unexplored. Despite substantial research on individual components, their combined applicability is largely unexplored. About 4% of global electricity comes from wind energy [1]. It is projected to gain significance in the energy landscape in the forthcoming years, with forecasts of achieving a 10% penetration rate and a capacity of $1.9x10^9$ kilowatts by 2030-35 [2].

Because SEPIC converters may step up and down input voltages, they offer the versatility required for applications involving renewable energy. Their capacity to raise voltage also helps to stabilize output voltages, which lessen fluctuations brought on by environmental factors affecting energy sources like wind turbines [3]-[5]. SEPIC converters can mitigate the issues related to buck-boost converters, including pulsating load current and inverted load voltage. Buck-boost converters have lower efficiency compared to SEPIC and Cuk converters [6], [7]. The characteristic features of SEPIC and Zeta are demonstrated to be nearly similar. It is important to note that the capacitor filter employed in the SEPIC converter was 80 μF, whereas the capacitor utilized in the Zeta converter was 120 μF. This indicates that employing a bigger capacitor can enhance the quality of the output voltage in conjunction with a SEPIC converter. The output voltage polarity remains unchanged in the SEPIC converter, which is advantageous compared to its counterparts and positively impacts microprocessor control of the converter.

The integration of SEPIC converters, wind energy, and BLDC motors in water pumping systems is a significant approach. Key topics in this area include enhancements in system efficiency, optimizations of control algorithms, and issues pertaining to wind energy integration, such as power quality and grid compatibility [8]. Systems for converting wind energy into electrical energy are used to harness the available wind energy. For implementing efficient water pumping systems [9], BLDC motors are integrated with SEPIC converters and wind energy. They offer advantages such as quiet operation, reliability, and a good torque-to-power ratio [10]. This study investigates a wind-driven water pumping system integrating a wind turbine, a SEPIC DC–DC converter, and a BLDC motor. MATLAB/Simulink simulations are used to evaluate the interaction between the SEPIC converter and the BLDC motor under variable wind conditions, with the aim of achieving efficient and reliable power conversion for standalone water pumping applications.

An examination of the current literature review indicates, based on to the best our knowledge, no prior work has systematically analyzed the transient and steady-state behavior of a wind–SEPIC–BLDC water pumping system under realistic environmental changes. Although certain studies have investigated analogous components, the majority concentrate on solar photovoltaic (PV) systems as the primary energy source [11]-[14]. Moreover, while studies related to wind energy and SEPIC converters are available [15], [8], [16]-[19], they generally do not focus on water pumping applications employing BLDC motors. Importantly, this study is particularly relevant for remote and wind-rich regions with limited solar irradiance, where conventional PV-powered systems may be less effective.

Rakshith *et al.* [20] modeled a wind energy conversion system in MATLAB/Simulink using a SEPIC DC–DC converter and an incremental conductance (In Cond) based maximum power point tracking (MPPT) strategy to maximize power extraction. Simulation results under varying wind speeds demonstrated effective peak power tracking and a total power output of 10 kW, confirming the suitability of the approach for efficient wind energy utilization. Researchers in [21]-[23] made a comparative analysis of DC–DC converter topologies for wind energy applications using MATLAB/Simulink, with emphasis on efficiency, power extraction, and total harmonic distortion. The SEPIC converter, operated with a perturb-and-observe MPPT strategy, demonstrated superior performance compared to buck, boost, buck–boost, and CUK converters, offering fast dynamic response, bidirectional voltage regulation, and reduced electrical stress.

Preview study [5] a hybrid solar–wind energy system employing CUK and SEPIC converters was modeled and evaluated using PSIM to ensure continuous and regulated power delivery. The system demonstrated effective source coordination, producing a 50 Hz, 220 V RMS inverter output with low harmonic distortion and high efficiency, confirming the suitability of CUK and SEPIC converters for hybrid renewable energy applications. Preview study [9], a SEPIC-based solar photovoltaic water pumping system driving a BLDC motor, was analyzed using MATLAB/Simulink, with emphasis on reliability and performance. An incremental conductance MPPT strategy was employed to improve starting behavior and regulate power delivery, and both dynamic and steady-state results confirmed the suitability of the SEPIC–BLDC configuration for photovoltaic water pumping applications.

Preview study [24] and [25], SEPIC converter operating in continuous conduction mode, were designed for a small-scale wind energy conversion system with digital MPPT control. A DSP-based controller was used to adapt the SEPIC parameters under varying wind conditions, and experimental results confirmed effective MPPT integration and improved energy conversion efficiency. Preview study [26], a hybrid wind–PV water pumping system driving a high-voltage BLDC motor was modeled in MATLAB/Simulink using incremental conductance MPPT and inverter-based electronic commutation, demonstrating stable operation and efficient power utilization under varying renewable conditions.

This study presents a simulation-based wind-driven water pumping framework integrating a variable-speed wind turbine, a SEPIC DC–DC converter, and a BLDC motor. A perturb and observe (P&O)-based MPPT controller is implemented to track maximum wind power, while the SEPIC stage is designed and regulated to stabilize the wind-derived DC-link voltage for reliable BLDC motor operation. The system's dynamic and steady-state performance is evaluated under wind speed variations from 12 m/s to 8 m/s using MATLAB/Simulink. In addition, preliminary stability and sensitivity analyses assess the impact of duty-cycle variation, wind-speed fluctuations, and load-torque changes on converter and motor performance.

The subsequent sections of this work are structured as follows: i) Section 2 presents the system methodology, system specification, design of the wind turbine, and design of the SEPIC converter; ii) Section 3 presents results and discussion, performance of wind speed, the wind turbine's voltage and current performance, SEPIC converter output power performance, SEPIC converter voltage and current performance, BLDC motor performance, efficiency metrics, and total harmonic distortion (THD) evaluation; and iv) Section 4 concludes the study and suggests future research directions.

2. METHOD

The methodology is based on MATLAB/Simulink modeling of the proposed wind–SEPIC–BLDC system, including SEPIC converter design, wind source integration, and control strategy implementation. Simulation results are used to assess system feasibility and performance for off-grid water pumping applications.

2.1. System specification

As shown in Figure 1, the proposed system, modeled in MATLAB/Simulink, comprises a wind turbine, AC–DC conversion stage, SEPIC converter, a voltage source inverter, BLDC motor with electronic commutation, P&O-based MPPT controller, and a water pump. Wind-generated power is rectified and regulated by the SEPIC converter to supply the BLDC drive, while the MPPT controller maximizes power extraction. This section outlines the modeling of the wind turbine and the SEPIC converter.

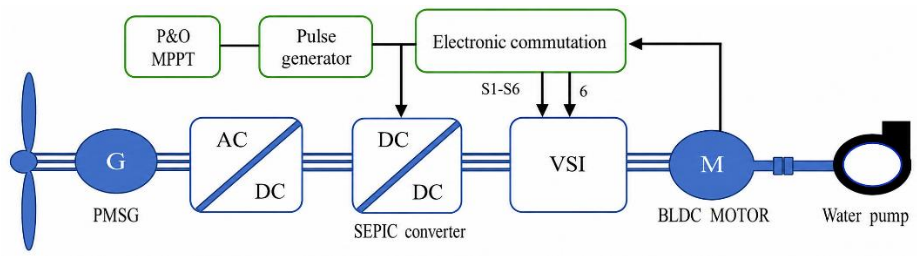


Figure 1. BLDC motor-driven water pumping system with wind-SEPIC feed

2.2. Design of wind turbine

Wind energy systems transform the kinetic energy of moving air into electrical energy. The kinetic energy (Ekin) generated by the motion of an object is represented as (1).

$$\mathrm{E}Kin \;= \frac{1}{2} m\, u^2 \tag{1}$$

The power supplied by the wind (Pv) can be determined by deriving the wind energy [24], [25].

$$Pv = \;½\, \rho aAvu^3 \tag{2}$$

2.3. Design of SEPIC converter

The maximum due to the cycle of the SEPIC converter is as (3).

$$D \;= \frac{Vo+VD}{Vi+Vo+VD} \tag{3}$$

The maximum duty cycle will happen when the input voltage is at its lowest point. Conversely, the minimum duty cycle will occur when the input voltage is at its highest level [27].

– Inductor calculation

$$L1 = L2 = L = \frac{ViD}{\Delta IL + fs} \tag{4}$$

– Capacitor calculation

$$Cs \;= \frac{Io \times \mathrm{D}}{\Delta \mathrm{VCS} \times fs} \tag{5}$$

$$Cout \;= \frac{Io \times \mathrm{D}}{Vripple \times 0.5 \times fs} \tag{6}$$

Where Vo represents the output voltage, Vi denotes the input voltage, and fs is the switching frequency. Io stands for the output current, while IL represents the inductor ripple current. $Vripple$ indicates the voltage ripple, and D represents the duty cycle.

The overall control sequence follows the wind–rectifier–SEPIC–VSI–BLDC chain with P&O-based MPPT and electronic commutation, as implemented in MATLAB/Simulink. The proposed system, simulated in MATLAB environment, is illustrated in Figure 2. The system consists of several essential components, including a wind turbine, SEPIC DC/DC converter, voltage source inverter (VSI), control unit of BLDC motor, BLDC motor, and water pump.

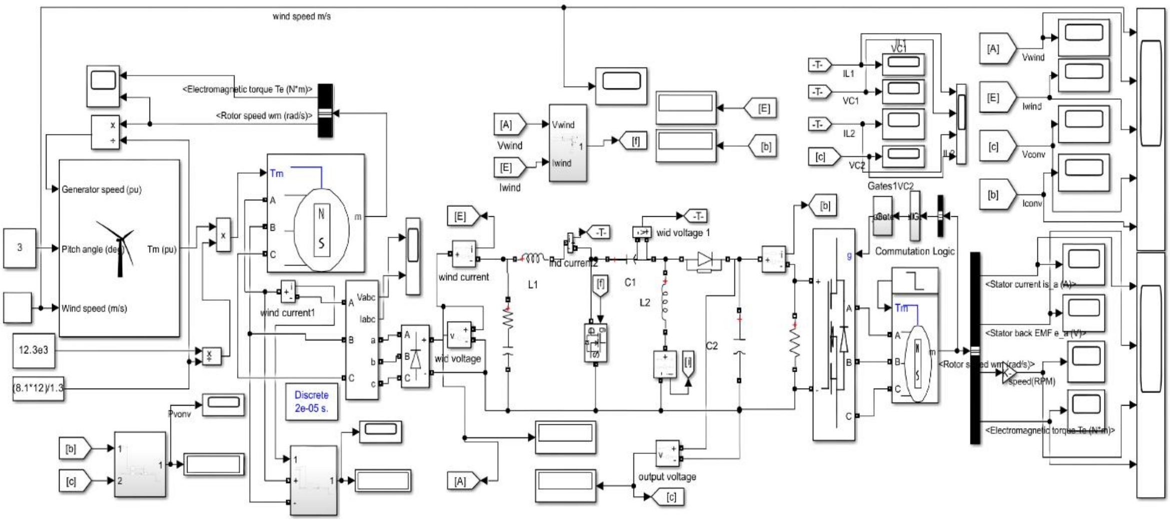


Figure 2. MATLAB/Simulink of the proposed WPS

3. RESULTS AND DISCUSSION

This section evaluates the steady-state performance of the BLDC-driven water pumping system under wind speed variations from 12 m/s to 8 m/s. Key electrical and mechanical responses of the wind source, SEPIC converter, and BLDC motor are analyzed to characterize overall system behavior.

3.1. Performance of wind speed

Figure 3 shows the wind speed profile, which remains constant at 12 m/s from 0 to 0.4 s and then decreases to 8 m/s at 0.4 s, maintaining this value until 0.8 s. This step change is introduced to evaluate the dynamic response of the proposed system under sudden variations in wind conditions. It enables the assessment of the SEPIC converter’s capability to regulate the output voltage while ensuring stable operation of the BLDC motor during transient conditions. Furthermore, the selected wind speed levels represent realistic operating scenarios in wind energy applications, allowing for a practical evaluation of overall system performance.

3.2. The wind turbine's voltage and current performance

Figure 4 shows the wind turbine responses, where Figure 4(a) illustrates the voltage and Figure 4(b) the current. Before the wind speed changes, the turbine produces approximately 150 V and 55 A. After the wind speed drops at 0.4 s, the voltage decreases to about 100 V and the current to around 35 A, reflecting the direct influence of wind speed variation on the electrical output.

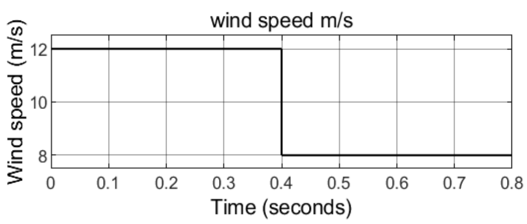
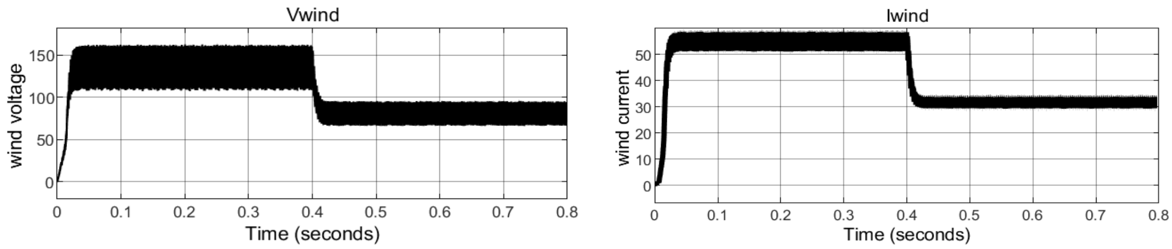


Figure 3. Wind speed over time



(a) (b)

Figure 4. Wind voltage (Vwind) and current (Iwind) performance graphs: (a) wind voltage (Vwind) performance and (b) wind current (Iwind) performance

3.3. SEPIC converter power performance

As shown in Figure 5, the output power initially exhibits a startup transient with a sharp spike above 20 kW. The response then reaches a steady state at approximately 10 kW from about 0.05 s to 0.4 s, indicating stable energy transfer from the SEPIC converter to the BLDC pumping load. At 0.4 s, the power drops from ~10 kW to just above 5 kW and then reaches a new steady state, stabilizing again from 0.7 s to 0.8 s. The steady-state efficiency of the SEPIC converter is estimated as the ratio of output power to rectified input power; at 12 m/s, the converter operates with an efficiency of approximately 93%.

3.4. SEPIC convertor voltage and current performance

Figure 6 illustrates the SEPIC converter output, where Figure 6(a) shows the voltage and Figure 6(b) the current. Initially, the converter regulates the output at approximately 175 V and 30 A. Following the reduction in wind speed, the output voltage decreases to about 125 V and the current to around 20 A, demonstrating the converter's ability to maintain regulated power delivery under varying input conditions, which is essential for stable BLDC motor operation.

3.5. BLDC motor performance

Figures 7–10 compare the BLDC motor performance under varying wind speeds. As shown in Figure 7, the phase-a back electromotive force increases with wind speed due to higher rotor speed. Correspondingly, Figure 8 shows that the phase-a stator current rises as the motor draws more power to match the available wind energy. The motor speed in Figure 9 follows the wind speed variation, indicating adaptive and stable operation. Figure 10 further shows that electromagnetic torque increases with wind speed, demonstrating the motor's ability to meet changing load demands effectively.

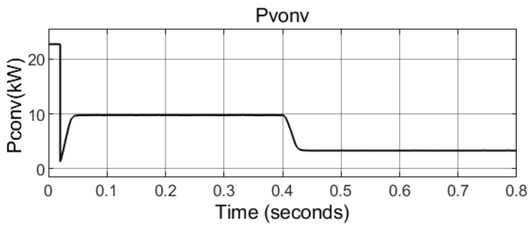
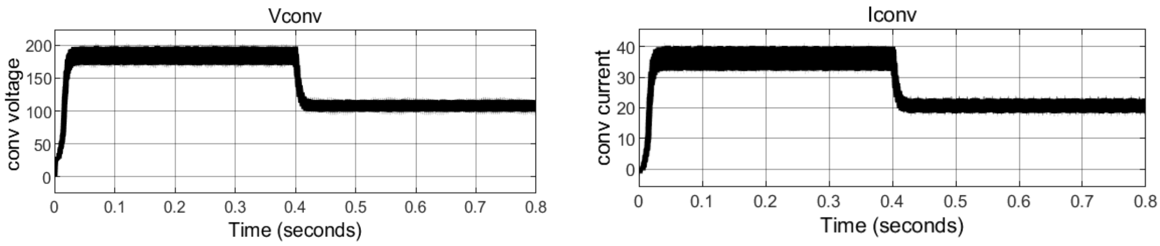


Figure 5. Power output (Pconv) in kilowatts (kW) of a SEPIC converter



(a) (b)

Figure 6. SEPIC converter outputs: (a) voltage (Vconv) and (b) current (Iconv)

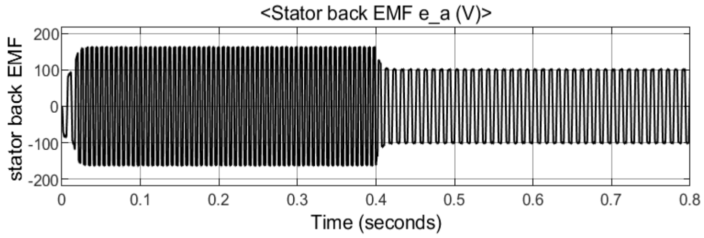


Figure 7. Stator back EMF (e_a) in volts (V)

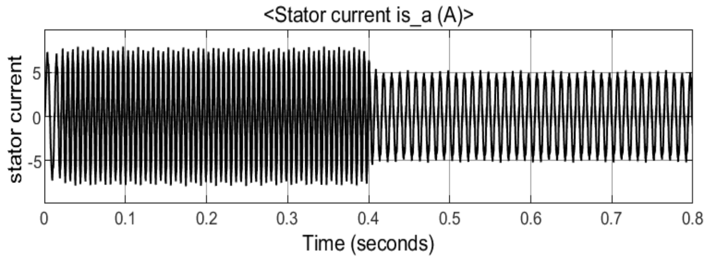


Figure 8. Performance of stator current (is_a) in amperes (A)

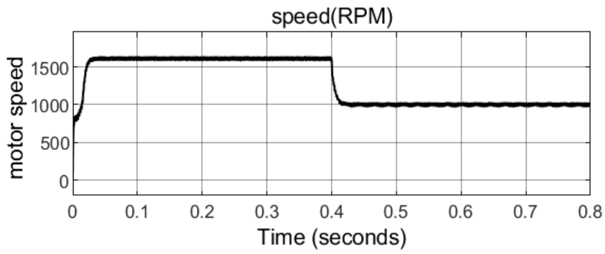


Figure 9. Motor speed in revolutions per minute (RPM)

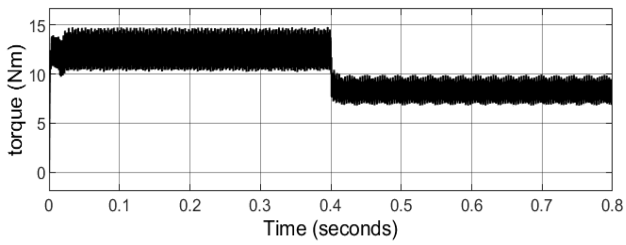


Figure 10. Electromagnetic torque (Te) in Newton-meters (N*m)

System stability is observed from the converter output voltage and motor speed responses under a sudden wind speed change from 12 m/s to 8 m/s. All variables settle to new steady-state values without sustained oscillations, indicating stable closed-loop operation and robustness to wind speed variations. In addition, the total harmonic distortion of the inverter-fed BLDC stator current was evaluated using fast Fourier transform (FFT) analysis in MATLAB/Simulink. As shown in Figure 11, the measured THD is approximately 11.57%, which is acceptable for standalone BLDC drive applications such as off-grid water pumping. According to IEC 61800-3, allowable harmonic levels for adjustable-speed drives depend on installation conditions, and higher current distortion may be tolerated without affecting functional performance.

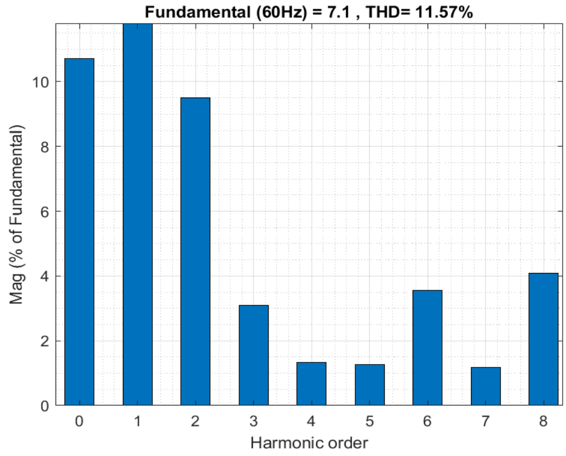


Figure 11. Frequency spectrum of the BLDC stator phase current obtained using FFT analysis, showing a THD of 11.57%

4. CONCLUSION

A wind–SEPIC–BLDC water pumping system was modeled in MATLAB/Simulink and evaluated under wind speed variation from 12 m/s to 8 m/s. The SEPIC stage regulated the DC-link to support stable BLDC operation, with an estimated converter efficiency of 93% at 12 m/s. Dynamic responses settled to new steady states without sustained oscillations, and the inverter-fed BLDC stator current THD was approximately 11.57%. The results confirm the feasibility of the proposed configuration for off-grid pumping in wind-rich regions. Developing a physical prototype for real-world testing and exploring alternative topologies, advanced control strategies, and improved power electronics to enhance system efficiency, performance, and robustness.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Abdullahi Mohamed Isak	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		
Yakub Hussein Mohamed	✓				✓		✓			✓	✓		✓	
Suleiman Abdullahi Ali					✓					✓			✓	
Sowdo Mursal Abdi		✓	✓			✓	✓	✓		✓	✓			
Abdirisakh Khalif Osman		✓	✓			✓		✓		✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest, no competing financial interests or personal relationships that could have influenced the work reported in this paper.

DATA AVAILABILITY

All data and simulation models used in this study are available from the corresponding author upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Hassan Abdi Abi earned a B.Sc. in electrical and electronics engineering, majoring in power and energy, from Jamhuriya University of Science and Technology in 2024. He has worked as a Technical Engineer at Prime Care Diagnostics and Medical Equipment since June 2024, maintaining and repairing medical equipment, and previously served as a Technical Engineer at Binqoje Electric Company from March 2014 to February 2020, focusing on transmission and distribution systems. His expertise includes power electronics, electrical design, solar installation, power systems, and troubleshooting. He can be contacted at email: hassan.abi@just.edu.so.

Abdullahi Mohamed Isak received his M.Sc. degree in electrical and electronics engineering from Necmettin Erbakan University, Konya, Türkiye, in 2021. He is currently a senior lecturer and researcher at Jamhuriya University of Science and Technology and also works with the Ministry of Energy and Water Resources of Somalia. His research interests include renewable energy systems, power generation, solar energy, wind energy, power conversion, energy systems, artificial intelligence applications in energy, and power systems. He can be contacted at email: abdullahi.isak@just.edu.so.

Suleiman Abdullahi Ali received his M.Sc. degree in electrical and electronic engineering from Near East University in 2021. He is the Head of the Electrical Engineering Department and a senior lecturer at Jamhuuriya University of Science and Technology. His research interests include internet of things (IoT), artificial intelligence (AI), wireless communications, renewable energy systems, STEM education, and digital transformation. He can be contacted at email: suleiman@just.edu.so.

Yakub Hussein Mohamed received an M.Eng. degree in electrical power from Universiti Teknologi Malaysia in 2022. He worked as a senior lecturer and researcher at Jamhuriya University of Science and Technology. His research interests include renewable energy systems, power generation, solar power, and wind power. He can be contacted at email: yakub.hussein@just.edu.so.

Sawdo Mursal Abdi earned a B.Sc. degree in electrical and electronics engineering, majoring in telecommunications and networking systems, from Jamhuriya University of Science and Technology in 2024. Her expertise includes telecommunications systems, computer networks, data communication, network design and configuration, and power electronics. She can be contacted at email: mursalsawda@gmail.com.

Abdirizak Khalif Osman earned a B.Sc. degree in electrical and electronics engineering, majoring in telecommunications and networking systems, from Jamhuriya University of Science and Technology in 2024. His expertise includes telecommunications systems, computer networks, data communication, network design and configuration, and power electronics. He can be contacted at email: mohaiyow@gmail.com.