International Journal on Energy Conversion (I.R.E.CON.), Vol. 12, N. 2
ISSN 2281-5295 *March 2024*

Enhancing Energy Storage System Charging Controller for Smart Grids Stability: a Dragonfly Optimization Approach

Mohammed Qasim Taha[1], Bamba El Heiba[2], Issa Cheikh Elhassene[2]

Abstract – *This study presents a new approach using the Dragonfly Algorithm (DA) optimization to improve the Energy Storage System (ESS) controller in a grid-tied Smart Grid (SG). The main objectives are to improve the voltage stability in the SG while minimizing the battery discharge rate. As a result, this approach improves the performance and lifetime of Battery ESS (BESS) connected to SGs by mitigating the effects of a high charge/discharging process frequency. Connecting BESSs and renewable energy is essential to ensuring energy supply continuity and, hence, robust grid functioning. The proposed method achieves a 30% reduction in battery discharge rate (from 80% to 50%), maintains grid voltage stability within a 4 V deviation, and keeps the energy price constant at 30 cents/kWh. This paper presents an optimization of SG operation control by improving BESS charging performance during fluctuations in energy supply and demand. The model simulation of SG connected to a 5 kV medium distribution system shows that the DA-optimized controller provides grid voltage stability with less depth of discharge in BESS at the same energy cost.* ***Copyright © 2024 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords: *Battery Lifetime Enhancement, Dragonfly Optimization, Energy Storage, Smart Grid*

Nomenclature

A_i	Alignment of dragonflies
BESS	Battery Energy Storage System
C	Cost
COE	Cost of Energy
DA	Dragonfly Algorithm
ESS	Energy Storage System
$Lévy(x)$	Lévy flight mechanism
LOLE	Loss of Load Expectation
N	Number of individuals
PCC	Point of Common Coupling
$P_{grid}(t)$	Simultaneous active power
$P_{setpoint}$	The desired active power setpoint
PV	Photovoltaic systems
$Q_{grid}(t)$	The simultaneous reactive power
$Q_{setpoint}$	The desired reactive power setpoint
RES	Renewable Energy Sources
SG	Smart Grid
$SoC(t)$	The simultaneous state of charge
THD	Total Harmonic Distortion
$V_{grid}(t)$	Simultaneous voltage
V_j	Velocity of j^{th} individual
$V_{setpoint}$	Desired SG voltage setpoint
X	Dragonfly spatial position
$X-$	External threats position
$X+$	The food source position
X_j	Position of j^{th} individual
β, σ	Cooperative behavior constants

I. Introduction

Controlling power flow in a smart grid is a challenging task, ensuring the stability of the system. Therefore, ESS is very effective in the control of SG in either island mode or grid-connected operation as a stand-by supply in all grid circumstances [1]. The control of ESS requires communication with the central SG controller and load meter. Thus, this control can be poor if there is a lack of communication between the containment of the ESS and the main grid. The ESS charging control plays a role in controlling and fine-tuning SG voltage and frequency [2].

The voltage and frequency stability are indications of the supply and demand control effectiveness [3]. The integration of BESS into SG architecture can play a necessary role in balancing supply and demand, enabling the use of Renewable Energy Sources (RESs), and ensuring consistently reliable power quality [4]. However, it poses more difficulties and costs due to the complex infrastructure and maintenance. Therefore, to reach the full potential of SG systems, they need to be more efficient and cost-effective [5]. Thus, improving BESS charging efficiency is essential to extending the life of storage units and maintaining grid voltage stability. Therefore, the cost of BESS replacement and maintenance is reduced. Also, several proposals have been made to improve SG, as shown in Fig. 1, to enhance BESS management, hence adapting the use of various RESs [6]. Due to the complexity and instability of SGs, the efficiency of conventional ESS controllers can be compromised, thus the reliance on battery discharge increases, resulting in poor BESS performance and life-degrading [7].

https://doi.org/10.15866/irecon.v12i2.25020

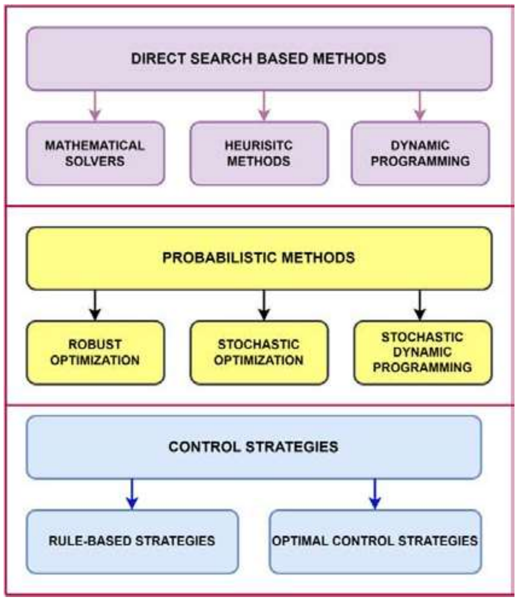

Fig. 1. Charge management approaches of BESS

Thus, there is a need to formulate new intelligent SGs and ESS control strategies that can effectively deal with the unpredictability of RESs, demand variability, and grid complexity, as shown in Fig. 1. The main objective of this research is to use the Dragonfly Algorithm (DA) to improve ESS charging controllers. DA is a nature-inspired algorithm that uses a mechanism similar to dragonflies to solve multi-objective problems. Therefore, it is nominated to be a fast search algorithm to optimize BESS performance [8]. We choose DA for its superior balance of exploration and exploitation, fast convergence, and adaptability to dynamic environments. These features are critical for optimizing complex, multi-objective problems like ESS control in smart grids.

In the next sections, modeling will be introduced and DA optimization for the model will be presented. Then, the objective functions to optimize the BESS is introduced. The method is presented its results are discussed.

II. Smart Grid Modelling

The grid-tied SG model in Figure 2, integrates conventional PV systems with ESSs, and consumer loads. The network configuration highlights the role of the proposed optimized controller to maintain stable voltage within the accepted range during the operation of the power system [9]. This grid-connected SG model contains BESS, PV system, and consumer loads. These units are connected to the SG at the Point of Common Coupling (PCC) which connects the SG to the main grid. The SG is connected to the 5 kV medium voltage distribution system [10]. In this model, the power from PV and grid line are included to cover the base-load power. BESS is used to lower peak loads by supplying energy at times of intermittent renewable energy or demand surges.

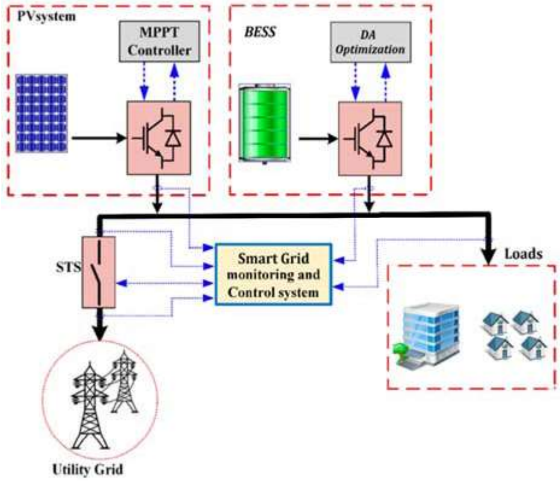

Fig. 2. Smart grid model architecture

Hence balancing the supply-demand in the smart grid [11]. ESS performance factors include battery efficiency, long-term deterioration, and increased charge/discharge cycles. Optimizing ESS charging and discharging decreases grid voltage stability [19]. SG power flow dynamics follow daily consumer demand swings. Thus, demand response allows supply adjustments while maintaining energy price stability in the model. Enhancing ESS performance will solve several grid issues that rely on RESs [20].

More RESs integrated into SG can reduce grid transmission and distribution components and infrastructure such as transformers, substations, and transmission cables [21], Reducing line losses, voltage dips, and grid control of power flows to load centers are also considered. To improve SGs, advanced metering infrastructure is integrated into the central control to gather and process data from all grid points and input the charge controller supply-demand dynamics [12]. This technology allows real-time grid monitoring for demand response and power dispatch optimization. [13]. This model is implemented using the Simulink/MATLAB environment to create more dynamics to examine optimized SG's performance in diverse settings. Imposing a high penetration of PV RESs in this model is used to show how the optimized charger can fight the grid disturbances caused by variable energy supply.

III. Dragonfly Algorithm Optimization

Based on dragonflies' complicated traits, the natural dragonfly's behavior of swarming is common among +3000 species, DA is inspired by cooperative dynamics arrangements to navigate and congregate in smaller cohorts for hunting. This complicated algorithm is expected to the performance of the ESS charge controller [14]. Energy efficiency is improved by optimizing the battery charge/discharge cycles, reducing energy losses, and maintaining higher battery SoC, which minimizes degradation and enhances overall system performance.

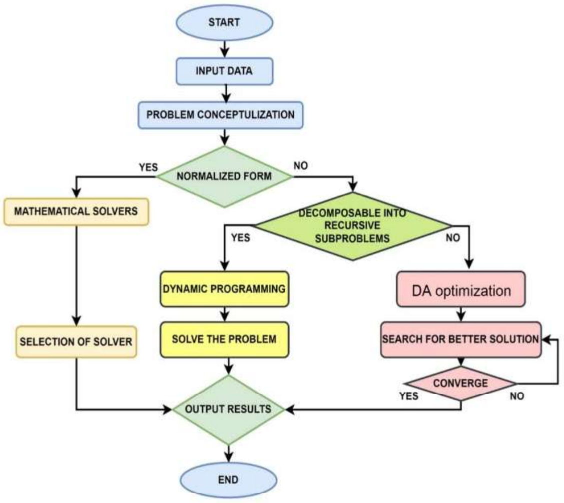

Fig. 3. DA optimization flowchart

Figure 3 illustrates the DA flowchart optimization process and describes the path of the control strategy used to improve the operational control for reliability and efficiency of the power system operation. It details the interactions between cohesion, alignment, and separation behaviors for optimal ESS control. This paper aims to achieve energy efficiency, grid stability, and cost-effective benefits of implementing BESS, using DA optimal BESS control strategy.

DA offers a superior balance between exploration and exploitation, faster convergence, and better adaptability to dynamic conditions compared to algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). These attributes make DA particularly effective for optimizing complex, multi-objective problems in smart grid applications.

The following equations show how swarms coordinate: cohesion and alignment, hazard response, food attraction, and collision avoidance [15]. Heuristic links and algorithmic frameworks extend DA's versatility and durability, making it a powerful tool for optimization problems across disciplines. To improve stability and transient response, the synchronous generator needs better voltage regulation [16]. Equation (1) depicts swarm coordination, where entities align with surrounding units to ensure synchronized movement. The difference in spatial coordinates between the seen subject and its surroundings is calculated.

$$S_i = -\sum_{j=1}^{N} X - X_j \tag{1}$$

where X represents the spatial position of the individual currently under examination. X_j corresponds to the position of the j^{th} individual within its immediate vicinity, N denoting the total number of neighboring individuals [17]. The estimation of alignment in the behavior of the dragonfly is expressed as:

$$A_i = \frac{\sum_{j=1}^{N} V_j}{N} \tag{2}$$

where V_j represents the velocity of the j^{th} neighboring individual, Equation (3) delineates the computation of cohesion, capturing the tendency of swarm members to converge towards the center of mass of their immediate vicinity.

$$C_i = \frac{\sum_{j=1}^{N} X_j}{N} - X \tag{3}$$

Subsequently, Equation (4) explains the estimation of attraction towards a designated food source, and the food source position denoted as $X+$. Furthermore, Equation (5) is provided to illustrate the computation of the response to external threats position is represented as $X-$:

$$F_i = X^{+} - X \tag{4}$$

$$E_i = X^{-} - X \tag{5}$$

These factors are combined by DA to define the behavior of artificial dragonflies in the optimization of BESS [18]. Equation (6) outlines these factors, which include cohesiveness, separation, attraction to food sources, alignment, and response to dangers.

Through this algorithm, step ΔX_t and position X agents are generated to update their positions within the search space of DA optimization is made possible via both exploitation and exploration while the agent position update process is governed by Equation (7):

$$\Delta X_{t+1} = (sS_i + aA_i + cC_{i+} fF_{i+} eE_i) + w\Delta X_t \tag{6}$$

$$X_{t+1} = X_t + \Delta X_{t+1} \tag{7}$$

There are different exploratory and exploitative behaviors of optimization in DA [19] by changing things like alignment, separation, food, cohesiveness, and enemy, introduced by (s, a, c, f, w, and e) variables.

Dragonfly neighborhoods highlight their proximity to nearby objects. By adaptively modifying weight inertia and swarming characteristics, exploitation and exploring are balanced. Also, $Lévy(x)$ is the Lévy flight mechanism, detailed in (8) and (9), to introduce randomness in the optimization, and promote exploratory behavior in DA optimization [20]:

$$X_{t+1} = X_t + Lévy(d)\Delta X_t \tag{8}$$

$$X_{t+1} = Lévy(x) = 0.01 \times \frac{r_1 \sigma}{|r_2|^{1/\beta}} \tag{9}$$

The variables r_1 and r_2 introduce random numbers within 0 to 1 interval. At the same time, β and σ constants are directly related and used to impose a cooperative behavior of the dragonflies.

IV. Objective Functions

Optimization objective functions are used to ensure that the optimizer considers that the energy at the consumers' side must meet certain standards such as stable voltage, and frequency, and contain fewer harmonics. Also, ensuring that the quality of energy is cost-effective minimizes energy price, and improves average system efficiency [21].

IV.1. Power Quality

The optimal power quality reduces the probability of voltage and frequency fluctuations, minimizing disruptions to electrical equipment. Stable voltage and frequency ranges contribute to stepped-forward efficiency in energy consumption and system operation. Power quality requires advanced monitoring and analytics to constantly verify energy parameters using voltage regulators, static VAR compensators, and filters to mitigate power exceptional problems such as voltage deviation. These deviations from desired voltage and frequency setpoints and Total Harmonic Distortion (THD) are the typical targets of power quality [22]. This objective is achieved by DA optimized controller by achieving the minimal value of the equation below:

$$\begin{aligned} f_1(t) = {} & \left[V_{grid}(t) - V_{setpoint}\right] \\ & + \left[P_{grid}(t) - P_{setpoint}\right] \\ & + \left[SoC_{ESS}(t) - SoC_{Target}\right] \\ & + \left[Q_{grid}(t) - Q_{setpoint}\right] \end{aligned} \tag{10}$$

where $V_{\text{grid}}(t)$ is the simultaneous grid voltage at time t, V_{setpoint} is the desired SG voltage setpoint, $P_{\text{grid}}(t)$ is the simultaneous load active power, P_{setpoint} is the desired load active power setpoint, $Q_{\text{grid}}(t)$ is the simultaneous load reactive power, Q_{setpoint} is the desired load reactive power setpoint, $\text{SoC}_{\text{ESS}}(t)$ is the simultaneous state of charge and is the target state of charge.

IV.2. Price of Energy Optimization

Optimal electricity pricing optimization objective leads to reduced energy costs and operational charges. Optimizing the price of energy entails minimizing expenses related to energy consumption and operational constraints [23].

Also, DA optimization decreases prices related to BESS maintenance and operation because of the high frequency of charging/discharging cycles. Also, and at the end minimizes charges related to ESS degradation over time. Ensuring energy quality means maintaining stable voltage and frequency with minimal harmonics, which reduces wear on electrical equipment and energy losses, thereby lowering costs. Average system efficiency refers to the overall effectiveness of energy conversion and utilization in the grid [24].

By minimizing energy costs and maintenance expenses, the usual monetary efficiency of power structures is advanced. Finally, effective management of energy costs contributes to the sustainable operation of SG structures and resources [25]. The price optimization goal is accomplished with the aid of achieving the minimum value of the equation below (C refers to the cost):

$$\begin{gathered} f_2(t) = \sum_{t=0}^{T} \left[V_{\text{grid}}(t) - V_{\text{setpoint}}\right] \\ C_{\text{active}}\left[P_{\text{grid}}(t) - P_{\text{setpoint}}\right] + \\ C_{\text{reactive}}\left[Q_{\text{grid}}(t) - Q_{\text{setpoint}}\right] + \\ C_{\text{SoC}}\left[\text{SoC}_{\text{ESS}}(t) - \text{SoC}_{\text{Target}}\right] \end{gathered} \tag{11}$$

Multi-objective optimization techniques are required to solve multi-objective optimization problems involving objectives (10) and (11):

$$\begin{cases} f(x) = \left(f_1(t), f_2(t)\right) \\ t_1 \le t_i \le t_n, \ \ i = 1,2,\dots,n \end{cases} \tag{12}$$

V. Methodology

In this optimization, DA is used to optimize the K_i and K_P control gains of the PI controller in the BESS charge controller, see Figure 4. Finding the best solution by achieving high SoC and stabilizing the grid voltage hence the frequency.

Voltage stability control and price are the two goals that are the objective function of this approach. The voltage deviations and SoC penalties over a given time T are used to calculate the objective function. Maintaining the best SoC is given priority when determining the penalty based on user-defined parameters [26]. The BESS converter performance indicators including voltage stability, SoC management, and standard grid performance are used to assess the proposed control approach performance [27].

DA constantly adjusts the BESS converter's control settings to maximize the fitness function depending on the objective functions.

This model is tested under many scenarios such as variations in PV generation, variations in load, and disturbances to the system, to imitate real-time situations [28].

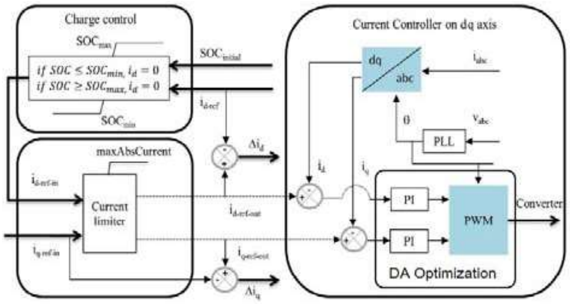

Fig. 4. The block diagram of BESS charge control optimization

VI. Results and Discussions

Figures 5 and 6 depict the voltage and price optimization under a minimum BESS discharge rate to provide a visible representation of this and highlight how BESS-optimized control is superior compared to traditional management.

The results in Figure 5 are derived from simulations using a conventional ESS control method [29]. This comparison demonstrates the improvements achieved with the DA-optimized controller presented in Figure 6.

By contrasting these results, the paper highlights the effectiveness of the proposed optimization approach. The reduction of voltage fluctuation improves SG voltage stability. The performance of the DA-optimized control approach in sustaining a higher SoC for the BESS and stable SG voltage is ascertained through the analysis of the simulation.

The DA-optimized controller reduces the SoC of the BESS from 80% with the conventional controller to 50%, while ensuring the stability of the SG medium voltage within a 4V deviation. Furthermore, the price of energy is also kept at the same value of 30 cents per kWh.

The results shed emphasis on the proposed strategy's adaptability and durability in operational SG dynamics [30].

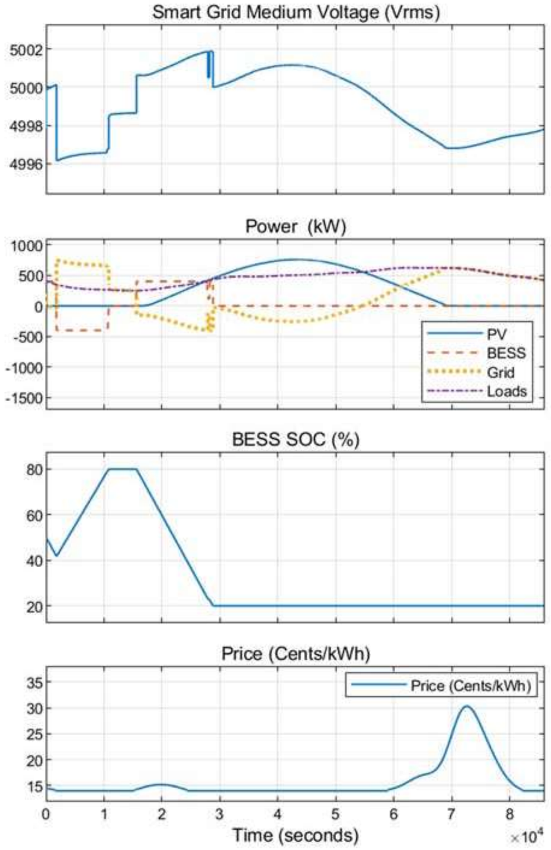

Fig. 5. Performance of conventional control of SG BESS charge controller

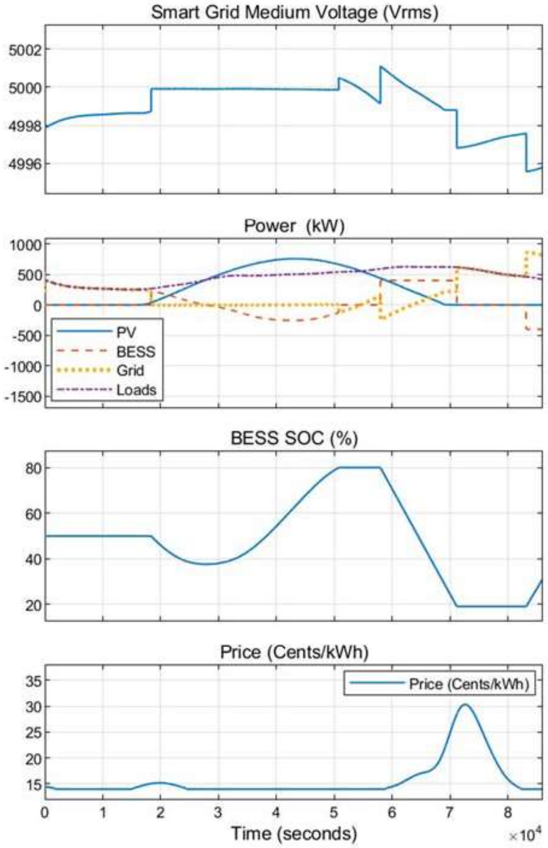

Fig. 6. Performance of optimized BESS distributed control of SG

This paper proved the effectiveness of DA optimization under common uncertainties to assess its robustness and reliability. The improvement in COE efficiency, depicted as consistent in both Figures 5 and 6, results from DA optimizing BESS control strategy. Despite maintaining a steady COE value, the DA-optimized approach achieves superior grid stability and battery performance compared to the conventional method shown in Figure 5. This improvement reduces operational costs associated with energy losses and maintenance, enhancing overall system efficiency and reliability [31].

The integration of PVs with BESS control systems improves RES dependability by reducing fluctuations in voltage and frequency due to changes in solar irradiation [32], [33]. Additionally, it enables SG stability during transient disturbances during grid-connected mode operations. This control approach offers a fast response and improved SG voltage stability. BESS controller optimization has shown superior performance compared with conventional control. Table I compares key performance metrics between the proposed DA optimization method and the genetic sorting algorithm employed to optimize objectives for pollution emission, COE, and Loss of Load Expectation (LOLE) [33]. Metrics include voltage stability, battery performance, energy cost, and overall system efficiency to evaluate effectiveness in smart grid applications.

TABLE I
COMPARISON OF PERFORMANCE METRICS WITH OTHER METHODS

Performance Metrics	Proposed Optimization	[34]
Voltage Deviation	4 V	6 V
SoC	(50-80) %	(25-35) %
COE	0.3 $/kW	1.29 $/kW
Overall Efficiency	95%	85%

VII. Conclusion

This study focused on enhancing BESS charging controllers in SG using the Dragonfly Algorithm optimization to improve voltage stability and minimize the battery discharge rate within the SG. The proposed DA-optimized controller demonstrated significant improvements in both the performance and lifespan of BESS connected to SGs. Key findings include a 30% reduction in battery discharge rate, maintenance of grid voltage stability within a 4V deviation, and stabilization of the energy price at 30 cents/kWh. The scope of this research encompassed the implementation of an optimized control for BESS within a medium voltage grid-tied smart grid environment to enhance the voltage stability of the smart grid, reduce the frequency and extent of battery discharge cycles, and ensure cost-effectiveness by maintaining consistent energy prices. Important future research directions include further exploration of advanced optimization algorithms to enhance the integration of optimized BESS charging with diverse RESs to assess performance in low inertia complex environments, investigating scalability and real-time implementation, conducting economic analyses to evaluate long-term benefits, and exploring the impact on overall SG resilience.

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Authors’ information

[1]College of Applied Sciences-Hit, University of Anbar, Iraq.

[2]Applied Research Unity to Renewable Energies (URA3E), University of Nouakchott, Mauritania.

Mohammed Qasim Taha is full-time Lecturer at the University of Anbar, Iraq. He is highly interested in microgrids and smart grids control, renewable energy resources, solar tracker systems, wind turbines, electrical power systems, power distribution systems, electromagnetic waves, and digital signal processing (DSP). He has published many papers regarding his interests.

Bamba El Heiba is a research lecturer in the physics department of the University of Nouakchott, Mauritania, since 2019. Since 2018, he works at Applied Research Unity to Renewable Energies 'URA3E’, University of Nouakchott, Mauritania. He is interested in renewable energy resources and has published many papers regarding his research fields.

Issa Cheikh Elhassene is a researcher at Applied Research Unity to Renewable Energies 'URA3E’, University of Nouakchott, He is highly interested in renewable energy resources, electrical power systems and Energy Efficiency, power distribution systems, and automatic control. He has published many papers regarding his research fields.