An Enhancement of Grid Integration in Renewable Energy Systems Using Multi-Objective Multi-Verse Optimization

Original Scientific Paper

Mullan Abdul Nabi*
Electrical & Electronics Engineering
JNTUA Anantapur, Anantapur, India
G Pullaiah College Of Engineering & Technology
Kurnool, India
abdulnabieee@gpcet.ac.in

J. Surya Kumari
Electrical & Electronics Engineering
RGM College of Engineering and Technology
Nandyal, India
jdsk.23@gmail.com

*Corresponding author

Abstract *– Going by the recent trends, the application of Renewable Energy Sources (RESs) has grown significantly across the world. Still, the integration of grid with photovoltaic (PV), wind and battery, remains a critical challenge as it results into power quality issues. To address the increasing need for electricity caused by industrialization and growing population, hybrid PV, wind, and battery combinations are used in this study. To accomplish an optimal energy management, this research proposes the multi-objective multi-verse optimization (MOMVO) approach, along with the modified perturb and observe (MP&O) technique. The proposed MOMVO-MP&O controller operates between the wind turbine and the battery storage system, for providing optimal power distribution and stability. The suggested model is evaluated alongside three other popular controller combinations that are, multi-verse optimization-perturb and observe (MVO-P&O), MVO-MP&O, and MOMVO-P&O. A comparative analysis is conducted, with existing methods namely, Modified-Fuzzy Direct Power Control (MF-DPC) and Adaptive Neuro-Fuzzy Inference System (ANFIS) also. From the analyzed results of this comparison, the proposed MOMVO-MP&O achieves lesser Total Harmonic Distortion (THD) of 1.86%, which demonstrates its efficiency in addressing power quality issues using hybrid RES systems.*

Keywords*: energy management strategy, photo voltaic, multi-objective multi-variable optimization, renewable energy sources, total harmonic distortion*

Received: December 12, 2023; Received in revised form: July 17, 2024; Accepted: July 19, 2024

1. INTRODUCTION

The global search for sustainable and efficient energy solutions has been growing in the recent years, with a major focus on integrating renewable energy sources into different parts of the energy infrastructure. This innovative technology is focused on PV systems, wind turbines, and an enhanced battery storage [1, 2]. When combined effectively, these renewable energy sources have the revolutionary potential to significantly improve tiny grid systems. Grids as localized and decentralized energy distribution networks are an example of modern energy innovation allowing communities, institutions, and businesses achieve higher resilience and energy stability [3, 4]. PV and wind energy transmission is constrained by location and intermittentness. An indeterminate source is the consequence of both sources irregular power output, which is reliant on weather conditions. Moreover, RES are frequently situated distant from cities, necessitating energy-lossy transmission across long distances. Due to wind energy and solar are irregular and vulnerable for environmental fluctuations. Thus, additional intrusion into the power systems can produce significant technological issues especially in weak grids. Moreover, difficulties involving infrastructure regulations restrict the development of effective transmission. The renewable energy's potential offers better storage facilities, grid management, as well as policy assistance to deal with these problems [5, 6]. The progress and availability of PV technology have propelled, leading the field of renewable energy sources. Solar energy, particularly in areas where sunshine is common are easily integrated into grids to provide a continuous and sustainable power source. Because solar PV installations are scattered, they enable localized generation, thereby reducing the pressure on centralized power networks and enhancing the energy self-sufficiency within grids [7, 8]. Wind turbines, another major component of the renewable energy environment, generate electricity by harnessing wind kinetic energy. Wind energy is reliable and abundant, making it an ideal resource for powering microgrids [9,10]. Wind turbines are strategically placed within or near grid areas to make use of natural wind patterns, and thus contribute to diversifying the mix of energy sources [11]. Wind's nature is reduced by combining it with other renewable energy sources and deploying energy storage devices, resulting in a continuous and stable power supply that is able to satisfy the grid's needs. In the field of energy storage, advanced battery technologies play a crucial role for optimizing renewable energy integration into the grid systems. The battery serves an important role by storing excess energy generated from PV and wind sources throughout peak production for later use during low power periods [12, 13]. Energy storage systems improve grid stability, regulate load variations, and help to properly balance supply and demand. Batteries enable microgrids to run independently by storing excess renewable energy, increasing resilience and lowering dependency on external power sources [14]. When the renewable energy sources: PV, wind, and battery storage are coupled in a micro-grid system, a synergistic energy infrastructure is created. Solar PV arrays and wind turbines generate electricity which is then stored in batteries or distributed directly to the microgrid. Their ability to seamlessly integrate different sources assures a consistent and stable energy supply, addressing the microgrid's specific energy requirements while minimizing their reliance on traditional fossil fuel-based generators [15, 16]. The incorporation of renewable energy sources into micro-grids represents an evolution in the approach to energy generation, distribution, and consumption [17]. It is consistent with global efforts to decrease carbon emissions, mitigate climate change, and accomplish long-term development ideas. Recent technology advancements utilize micro-grids, offering resilient energy solutions for global communities, and promoting sustainability on a broad scale [18]. Challenges in integrating PV, battery, and wind for grid improvement include intermittent energy supply, storage optimization, output variability, and grid stability.

Sahri et al. [19] implemented MF-DPC to improve system performance and current quality. An enhanced Maximum Power Point Tracking (MPPT) algorithm was also developed using a Fuzzy Controller (FC) for optimizing solar power. This method demonstrated notable performance improvements, especially in adverse weather and variable load conditions. However, NF-DPC depended on pre-trained models, making it challenging to adapt to real time to dynamic grid changes, hindering its responsiveness and grid stability during rapid fluctuations. Gulzar et al. [20] introduced a Battery Energy Storage System (BESS) to manage modeling, control, energy management, and operations in a hybrid grid-connected setup. A hybrid system combining PV, wind, and fuel cell (PV-Wind-FC) with an electrolyzer, and BESS was proposed to efficiently minimize the control loops and converters. This design eliminated the need for a dedicated PV converter, thus enhancing cost-effectiveness and preventing BESS overcharging. Nonetheless, the BESS method needed to enhance the system by integrating nonlinear controllers in wind, fuel cell, and the electrolyzer components. This is because nonlinear controllers improved the BESS by addressing complex dynamics and optimizing renewable energy integration and performance. Maaruf et al. [21] developed Hybrid RES (HRES) to improve reliability and efficiency using renewable technologies. A robust control strategy validated across diverse HRES conditions, affirming its effectiveness and adaptability was established. Nonetheless, to accomplish system optimization, it needed to integrate hybrid energy storage systems for supplementary support so as to upgrade the overall performance in HRES. This is because the integrating hybrid energy storage enhanced the system's stability, reliability, and efficiency by combining diverse storage technologies to improve performance in HRES. Cholamuthu et al. [22] created a grid-integrated renewable energy system featuring a hybrid series active power filter system controlled by an ANFIS. This setup was designed to cater to nonlinear or sensitive loads. The strategy involved sharing renewable energy with the grid, minimizing reliance on conventional electricity, and showcasing the potential for reduced grid consumption. However, additional information about the ANFIS approach was required to provide a comprehensive explanation for ensuring an in-depth knowledge of its operation, capabilities, and prospective applications. Ibáñez-Rioja et al. [23] introduced a Levelized Cost of Hydrogen (LCOH) calculation considering the capital and operating expenses, along with the learning curves for system components. This approach aimed at enhancing the electrolyzer full-load hours and minimizing electricity wastage in off-grid plants. Nonetheless, further improvement was required in the suggested method for future generation through amplifying efficiency and sustainability. This was because it was possible to enhance sustainability and efficiency, so as to enable surplus electricity sales that ensured system optimization and revenue generation in LCOH.

Hence, MOMVO-MP&O is used to address problems with the existing methods which include inadequate renewable energy integration, grid instability, and inefficient power management, ultimately enhancing the grid performance by optimizing resource utilization and control strategies The proposed MOMVO counters these challenges through optimal resource allocation and management, thereby enhancing grid performance and reliability. The contributions of the research are as follows;

- A combination of MOMVO and MP&O controllers is designed to develop an effective EMS to satisfy the load demand. The MOMVO is preferred due to its higher convergence rate to effectively switch between wind turbine and battery.
- The MOMVO-MP&O is used in the RES system to activate DC-DC converters, which results consistent power supply at different temperatures and irradiance levels
- MOMVO-MP&O enhances the grid optimization by balancing multiple objectives simultaneously, then optimizing efficiency, reliability, and sustainability for more resilient energy management.

The rest of the paper is organized as follows: Section Section 2 describes the proposed methodology of this research. Section 3 and Section 4 describe the results and conclusion of this overall research.

2. COMPONENT MODELING OF HYBRID ENERGY SYSTEMS

This research employs three distinct energy systems: PV modules, batteries, and wind turbines, each characterized by mathematical models as follows.

2.1. PHOTOVOLTAIC MODULES

Photovoltaic modules are used in the grid to generate sustainable energy, while the PV modules in MOMVO-MP&O contribute to grid power using MPPT control, hence amplifying grid sustainability. The system voltage and capacity are determined by connecting the PV panel either in parallel or in series connection [24]. The MPPT method is considered in the PV system to increase PV output power. The following equation (1) is used to identify the output power that depends on the I_M and V_M.

$$P_{MPPT}(t) = I_{MPPT}(t) \times V_{MPPT}(t) \tag{1}$$

Eqs. (2) and (3) provide the MPPT current and voltage, respectively.

$$I_{MPPT}(t) = I_{SC}\left\{1 - C_1\left[exp\left(\frac{V_M}{C_2 \times V_{OC}}\right)\right]\right\} + \Delta I(t) \tag{2}$$

$$V_{MPPT}(t) = V_M + \mu V_{OC}.\Delta T(t) \tag{3}$$

In this context, I_{SC} signifies the short circuit current, C_1 and C_2 represent capacitance, V_M stands for the maximum voltage and V_{OC} denotes the open circuit voltage. The C_1, C_2, $\Delta I(t)$ and $\Delta T(t)$ of Eqs. (2) and (3) are respectively expressed in the Eqs. (4-7).

$$C_1 = \left(1 - \frac{I_M}{I_{SC}}\right) \times exp\left(-\frac{V_M}{C_2 \times V_{OC}}\right) \tag{4}$$

$$C_2 = \left(\frac{V_M}{V_{OC}} - 1\right) \times \left[ln\left(1 - \frac{I_M}{I_{SC}}\right)\right]^{-1} \tag{5}$$

$$\Delta I(t) = I_{SC}\left(\frac{GT(t)}{G_{ref}} - 1\right) + \alpha_{1,sc} \times \Delta T(t) \tag{6}$$

$$\Delta T(t) = T_c(t) - T_{c,ref} \tag{7}$$

Where, I_M signifies the maximum current, $GT(t)$ denotes the radiation of the incident on the PV surface, T_c represents the cell temperature, and $T_{c,ref}$ denotes the PV temperature in normal situations.

2.2. WIND TURBINE MODEL

When PV is idle, wind turbines provide electricity, assuring continuous power output for system stability. Wind turbines in MOMVO-MP&O maximize their ability to produce electricity through system controls, thus improving the grid sustainability and performance. The output power of a wind turbine is essentially determined by elements such as rated capacity, hub height, and specific wind speed characteristics, as shown in reference [24]. For variable speed operation in this research, a wind turbine model based on Doubly Fed Induction Generator (DFIG) is used. These wind speed characteristics contain the cut-off voltage (V_{cf}), rated speed (V_{rs}) and cut-in voltage (V_{ci}). The output of the wind turbine power is calculated using Eq. (8).

$$P_o = P_{rs}\begin{cases} 0, & V < V_{ci} \\ a \times V^3 - b \times P_{rs}, & V_{ci} < V < V_{rs} \\ 1, & V_{rs} < V < V_{cf} \\ 0, & V > V_{cf} \end{cases} \tag{8}$$

Here, rated power and wind turbine output are correspondingly are denoted by P_o and P_{rs}, where $(a=P_{rs})/(V_{rs}^3 - V_{ci}^3)$ and $b=(V_{ci}^3)/(V_{rs}^3 - V_{ci}^3)$. At a specific height level using the supplied Eq. (9), the speeds are analyzed and then transformed based on the actual turbine speed.

$$V_{hub} = V_0 \times \left(\frac{Z_{hub}}{Z_0}\right) \times \alpha \tag{9}$$

In this context, V_{hub} represents the wind turbine speed, Z_{hub} stands for the actual height of the wind turbine and V_0 represents the wind speed at the reference height. Additionally, α represents the power law exponent utilized in the evaluation and Z_0 denotes the height of the wind speed measurement.

2.3. BATTERY MODEL

Batteries supply power when wind turbines are inactive, ensuring consistent energy and maintaining grid stability during fluctuations. Batteries store surplus energy, guaranteeing grid stability and reliability. In MOMVO-MP&O, batteries are managed for peak load support and power quality optimization. RES exhibits variable output power owned to fluctuating environmental conditions. Eqs. (10) and (11) detail the charging and discharging processes of the battery, with a focus on State of Charge (SOC) conditions. Specifically, battery charging occurs when the combined power output from PV and wind turbines surpasses the load requirements. Equally, discharge operations are initiated when the load demand exceeds the available power from renewable energy sources, as referenced in [25].

$$SOC = SOC\ (t-1) \times (1-\sigma) + [P_{RES}(t) - \frac{P_L(t)}{\eta_{inv}}] \times \eta_{ch} \quad (10)$$

$$SOC = SOC\ (t-1) \times (1-\sigma) + [\frac{P_L(t)}{\eta_{inv}} - P_{RES}(t)] \times \eta_{dich} \quad (11)$$

Where, the battery's charging and discharging states are correspondingly denoted by SOC and $SOC(t\text{-}1)$, while the discharge rate over one hour is denoted as σ. The power from renewable energy sources and load power are denoted by P_{RES} and P_L, respectively. Additionally, the efficiency parameters include η_{inv} for the inverter, η_{ch} for charging, and η_{disch} for discharging. Hence, the proposed MOMVO-MP&O system receives electrical output from PV modules, wind turbines, and batteries. It optimizes their utilization, guaranteeing efficient energy generation, storage and distribution for enhanced grid performance and sustainability, as described briefly in the suggested system.

2.4. PROPOSED SYSTEM

The electrical output from PV modules, wind turbines, and batteries are fed into the suggested system to enhance the grid performance. The system optimizes energy utilization and distribution for an improved grid efficiency. This research develops an effective energy management method that makes use of two unique RES and a storage device. PV modules and wind turbines are the primary RES units evaluated for EMS. In addition, it includes a battery as a storage medium for excess electricity generated by both the PV modules and the wind turbines. The PV modules serve as the primary energy source, while the wind turbines serve as a supplementary supply, further allowing to efficiently balance load demand. When the PV modules and wind turbines are unable to generate enough energy to satisfy the load requirement, the battery serves as a backup power source. It uses the Perturb and Observe with Modified Incremental Conductance MP&O algorithm to optimize the performance of the PV modules. This algorithm activates the DC-DC converter linked with the PV modules, establishing peak power even when the irradiance and temperature are changing. Furthermore, MOMVO system is employed to control the battery and wind turbine's ON and OFF states. This improves the overall system control and administration. Fig. 1 displays the flow diagram and operation of a grid-connected RES that is integrated with the MOMVO-MP&O controller, providing clarity and comprehension of how the system works.

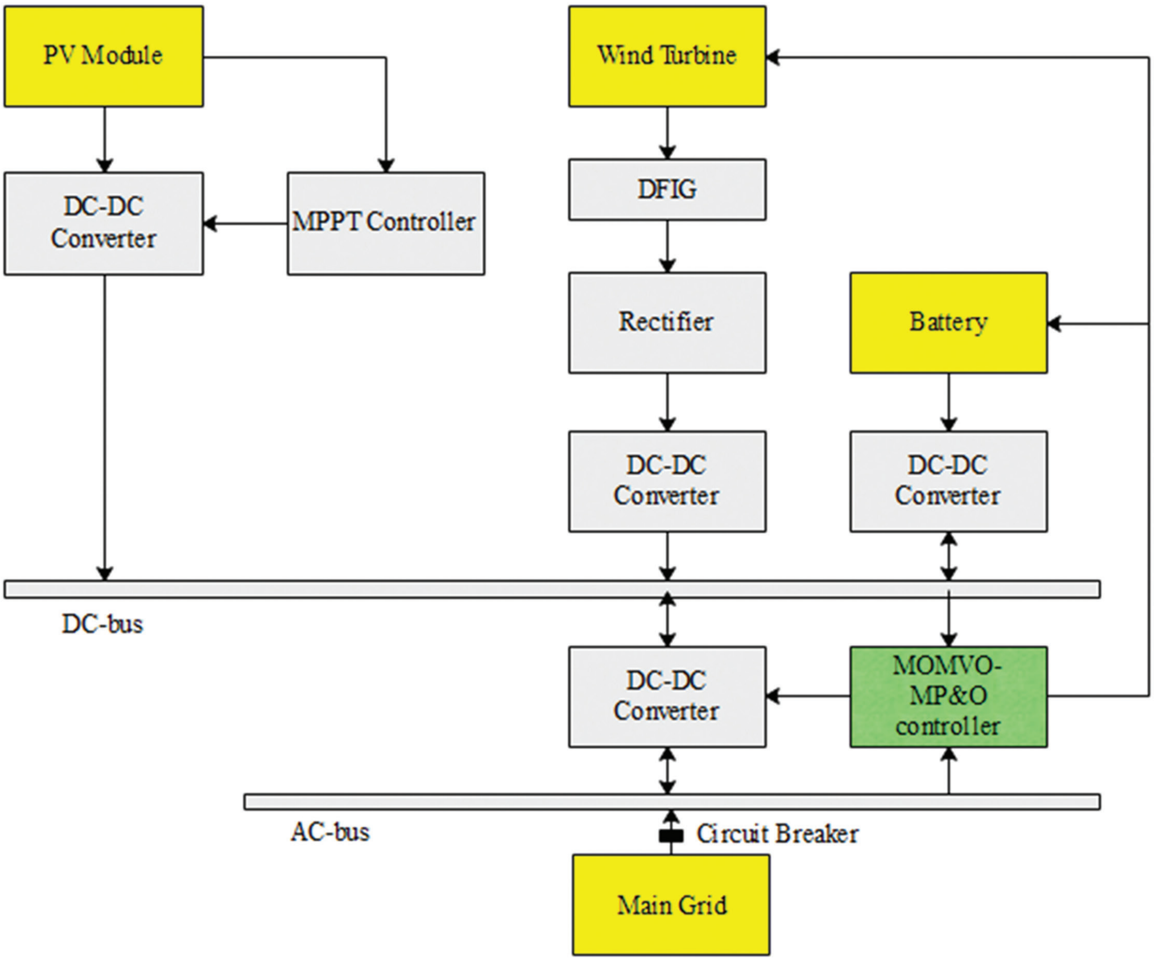

Fig. 1. Flow diagram of RES with the proposed MOMVO-MP&O controller

2.4.1. Multi Verse Optimization (MVO)

In this research, an innovative approach is introduced to improve the grid performance through the utilization of the MOMVO. MVO is used to improve grid performance using PV solar panels, wind turbines, and energy storage technologies such as batteries. The fundamental goal is to create a more efficient, stable, and long-lasting grid infrastructure. The problem with these diverse energy sources is optimizing their complicated interactions. During optimization, the following Eqs. (12-13) are applied to the universes of MVO.

$$U = \begin{bmatrix} x_1^1 & x_1^2 \ldots\ldots x_1^d \\ x_2^1 & x_2^2 \ldots\ldots x_2^d \\ x_n^1 & x_n^2 \ldots\ldots x_n^d \end{bmatrix} \tag{12}$$

Where, n is the number of universes (candidate solutions) and d is the number of parameters (variables).

$$x_i^j = \begin{Bmatrix} x_k^j \;\; r^1 < N1\,(Ui) \\ x_i^j \;\; r^1 < N1\,(Ui) \end{Bmatrix} \tag{13}$$

The j_{th} universe N1 (Ui) is normalized inflation rate is connected with parameters, which are represented by x_i^j. Furthermore, k_{th} universe's parameters, x_k^j, are selected through a roulette wheel method that uses a random integer r^1. Assume that wormhole tunnels continuously connect each universe with the best universe developed at this point to boost local alterations and raise the possibility of improving inflation rates. The mechanism is organized in the Equation (14).

$$x_i^j = \left\{ \begin{Bmatrix} X_j + TDR \times \left((ub_j - lb_j) \times r4 + lb_j\right) \;\; r3 < 0.5 \;\; r2 < WEP \\ X_j - TDR \times \left((ub_j - lb_j) \times r4 + lb_j\right) \;\; r3 \geq 0.5 \;\; r2 \geq WEP \\ x_i^j \end{Bmatrix} \right. \tag{14}$$

The mechanism is performed by the best universe j_{th} parameter, represented by X_j. The j_{th} variable's lower and upper limits are represented by lb_j and ub_j, respectively, whereas TDR and WEP are used as coefficients. Additional random numbers that contribute to the process are $r2$, $r3$, and $r4$, all of which fall within the interval [0, 1]. Furthermore, WEP, TDR is gradually increased between iterations to provide a more precise local search around the optimal universe. Eqs. (15–16) illustrates the formula for updating both coefficients.

$$WEP = min + l \times \left(\frac{max - max}{L}\right) \tag{15}$$

Where, min is the minimum max, l indicates the current iteration, and L denotes the maximum iterations.

$$TDR = 1 - \frac{l^{\frac{1}{p}}}{L^{\frac{1}{p}}} \tag{16}$$

The roulette wheel selection that is carried out for every factor in each universe all throughout iterations have a computational cost of either O (n) or O (logn), depending upon the way it is implemented. The Eqs. (17-18) mathematically demonstrate the entire computational load.

$$O\,(MVO) = O\,(l\,(o\,(Quick\ sort) + n \times d \times (o\,(roulette\ wheel)))) \tag{17}$$

$$O\,(MVO) = O\,(l\,(n^2 + n \times d \times log_n)) \tag{18}$$

Where, n is the number of universes, l is the maximum number of iterations, and d is the number of objects. Hence, MVO faces challenges in accurately modeling complex, variable renewable energy inputs, alongside dealing with infrastructure constraints, high computational demands, sensitivity to input parameters, and real-time adaptability. Optimizing the integration and accommodating evolving technologies within its framework remains essential for effective grid improvement using PV, wind, and battery systems.

2.4.2. Multi- Objective Multi-Verse Optimization (MOMVO)

Integrating PV, wind, and battery systems presents challenges in optimizing the grid performance using MVO. Single-objective MVO struggles to balance the competing objectives like maximizing renewable energy integration while maintaining grid stability. MOMVO addresses this by considering multiple goals, offering a more comprehensive approach. MOMVO optimizes various objectives such as maximizing renewable energy utilization and minimizing grid fluctuations, navigating the complex decisions inherent in energy grid optimization. It identifies a range of Pareto-optimal solutions by simultaneously exploring diverse solution spaces, enabling decision-making based on preferences and priorities. MOMVO allows stakeholders to select from a variety of different solutions, helping grid operators and algorithms in achieving a balance between renewable energy integration and grid stability, ultimately contributing to a better sustainable energy grid.

2.4.2.1. Cost of Electricity

It is characterized as the unit of cost per unit of delivered energy produced by hybrid micro-grid, as illustrated in the Equation (19).

$$COE = \frac{Total\ Net\ Present\ Cost\ (NPC)}{\sum_{h=1}^{h=8760} p_1(h)} \tag{19}$$

Were, $\sum_{h=1}^{h=8760} p1\,(h)$ represents the summation of the annual energy output over the entire year.

2.4.2.2. Loss of Power Supply Possibility

Minimizing the LPSP which results from inadequate energy to provide the load is crucial to boosting system dependability. LPSP is used to minimize disconnection probabilities, focusing on resilience and autonomy in localized systems, reflecting a strategic shift towards robust, islanded configurations in goal-oriented frameworks. Equation (20) represents the mathematical expression of LPSP.

$$\text{LPSP} = \frac{\sum P_L(t) - (P_W(t) + P_{PV}(t) + (E_b(t-1) - E_{\text{bmin}}) + P_{\text{diesel}})}{\sum P_L(t)} \tag{20}$$

Were, $\sum P_L(t)$ represents the summation of the total power demand, $P_W(t)$ represents power generated by wind turbines at time t. Then, E_{bmin} represents the Minimum allowable energy level in the batteries. Finally, P_{diesel} represents the Power generated by diesel generators.

2.4.2.3. Renewable Factor (RF)

The RF evaluates the output rate of traditional diesel generation in the renewable energy source. Equation (21) demonstrates how the RF is expressed mathematically.

$$RF = \left(1 - \frac{\sum P_{\text{diesel}}}{\sum P_{pv} + P_w}\right) \times 100 \tag{21}$$

Ultimately, MOMVO enhances grid performance through sustainable, efficient, and balanced renewable energy integration. MOMVO's improvement in grid efficiency with PV, wind, and solar lies in generating a wide array of solutions representing potential differences between objectives. It explores the problem space, addressing goals like increasing renewable energy generation and reducing grid instability. The process involves evolving a population of solutions through different "verses," similar to distinct solution spaces, utilizing evolutionary algorithms or simulated annealing. Iterations refine outcomes, leading to a collection of Pareto-optimal solutions, where enhancing one objective may compromise another. MOMVO empowers stakeholders to choose from a variety of different solutions, helping grid operators and strategists achieve a balance between renewable energy integration and grid stability, ultimately contributing to a better, sustainable energy grid.

The two key improvements made in MOMVO to enhance grids are:

- **Optimized Renewable Energy Integration**

MOMVO improves grid performance by optimizing the integration of renewable energy sources like PV, wind, and solar. It focuses on maximizing the utilization of these sources while considering various objectives such as energy generation and grid stability. Through multi-objective optimization, MOMVO finds the best compromise solutions that efficiently integrate renewable energy into the grid, guaranteeing a sustainable, low-carbon energy mix.

- **Enhanced Grid Stability and Reliability**

MOMVO demonstrates further upgradation by effectively addressing grid stability and reliability concerns, enhancing the overall performance in power distribution systems. It optimizes the allocation and management of renewable energy resources to minimize grid fluctuations and enhance stability. By considering multiple conflicting objectives including voltage regulation, frequency control, and power quality, the MOMVO ensures a more stable and reliable grid. This results in a resilient energy infrastructure capable of accommodating intermittent renewable energy sources and meeting varying demand patterns while maintaining grid integrity. In addition, the MOMVO is deployed to solve the MPPT problem which is the process of solving MPPT using MOMVO, as explained in the following section.

2.4.2. MOMVO control of PV, battery, and wind turbine

In the research, MOMVO controls the ON/OFF states of the wind turbine and battery by using power from the PV module, wind turbine, battery, and load. According to MOMVO duty cycle (modulation index), the wind turbine and battery's ON/OFF states are determined. Until the system uses MOMVO in MPPT to reach MPP, the duty cycle is updated continually. Controlling the power generation and utilization of PV modules, wind turbines, and batteries in an energy system involves smart coordination to ensure efficient and continuous power supply. Here is a brief explanation of the control strategy:

- **PV Module Control**

When the solar irradiance is insufficient or during nighttime, the PV modules are turned OFF to conserve energy. This prevents the system from attempting to generate power when sunlight is unavailable. When solar irradiance is significant, the PV modules are activated to connect solar energy and convert it into electricity.

- **Wind Turbine Control**

Wind turbines are turned ON when wind speeds are within the optimal range for power generation. They capture wind energy and convert it into electrical power. Conversely, during high wind speeds or maintenance, the wind turbines are turned OFF to prevent potential damage and establish safe operation.

- **Battery Control**

Batteries play a crucial role in storing excess energy generated by PV modules and wind turbines. When both PV modules and wind turbines are generating extra electricity, the excess power is stored in the battery for later use. The stored energy in the battery is utilized during periods of low renewable energy resources, ensuring a stable power supply by meeting load requirements effectively. This control strategy aims to optimize the utilization of renewable energy sources while maintaining a reliable power supply. It ensures that power generation order with the availability of solar irradiance and wind, and excess energy is efficiently stored and utilized, amplifying the overall efficiency and sustainability of the energy system.

2.5. P&O MODIFICATION FOR TRIGGERING PV MODULE

The results generated by the MOMVO are fed to the MP&O method for further processing and control. The modified P&O method is used in PV/Wind/Battery systems, addressing drawbacks of the P&O approach for enhanced performance. Unlike the conventional methods prone to nonstop oscillations around MPP and deviation, the modified version utilizes both PV module voltage and current to accurately determine power and trigger the DC-DC converter switches, strengthening MPPT efficiency. The conventional P&O method considers only change in voltage (ΔV) and change in power (Δp), but the modified P&O method considers change in current (ΔI) as a third parameter to enhance the performance of MPPT. Through the modified P&O method, a total of 8 operating point perturbation cases are identified. Four cases mirror the conventional P&O method while the remaining four are tailored to sudden irradiation level changes. Detection of opposite signs in ΔI and ΔV signifies a PV module in fixed illumination, contrasting with fluctuating conditions. The modified P&O behaves like the conventional method under consistent solar irradiation. In cases of poor tracking within the PV/Wind/Battery system, the tracking speed is augmented by doubling the step size, ensuring a prompt response to dynamic conditions. This modified P&O effectively controls the PV module when there is a change in power due to the perturbation of reference voltage and variation in sunlight. Fig. 2 depicts the controller architecture used in this PV/wind/battery system.

The effectiveness and resilience of the suggested method become apparent when observing its adept handling of power generation amidst fluctuating loads. The EMS control model ensures optimal power generation by managing system operations in response to varying loads. Furthermore, it distinctly showcases the system's efficiency in charging and discharging processes.

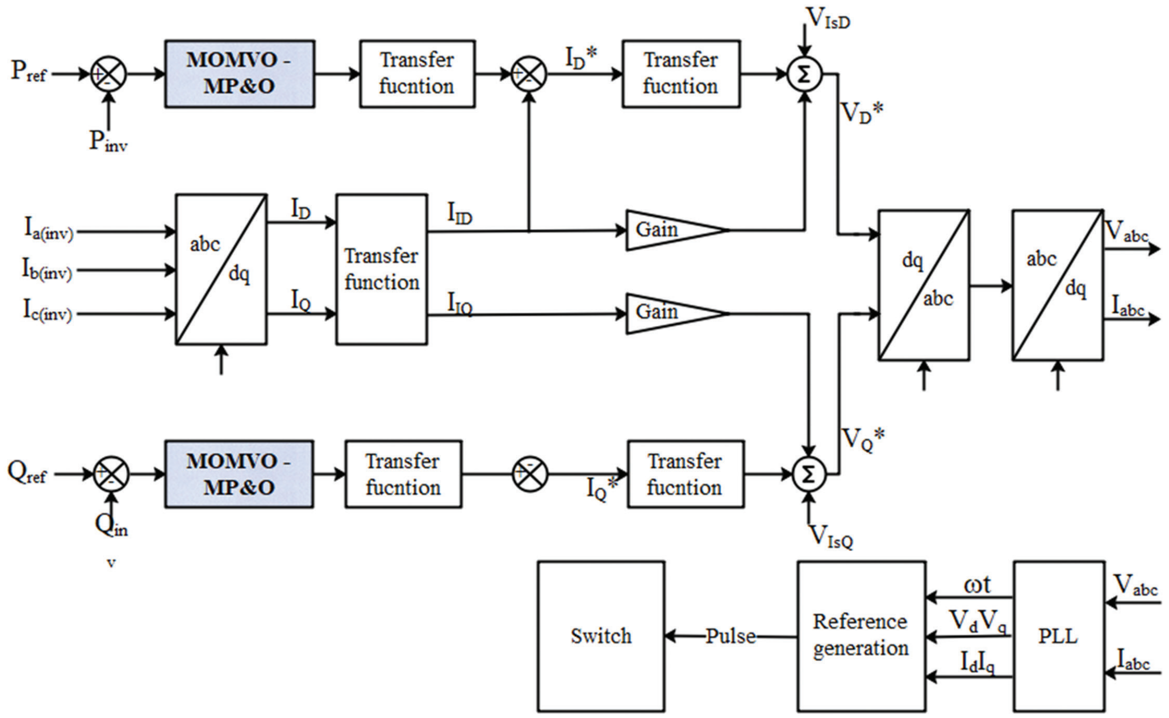

Fig. 2. Architecture of MOMVA-MP&O controller design

3. EXPERIMENTAL SETUP AND RESULTS

Many experiments are conducted to validate the effectiveness of the proposed Multiple-Objective Multi-Variable Optimization (MOMVO) for the 3S configuration, encompassing the patterns of 1, 2, and 3. This evaluation is performed under dynamic insolation levels as depicted in Tables 1, 2 and 3. Hence, the existing methods such as MultiVerse Optimization Perturb Observe (MVO-P&O), Multi-Verse Optimization – Modified Perturb Observe (MVO-MP&O) and Multi-Objective Multi-Verse Optimization – Perturb Observe (MVO-MP&O) are analyzed based on the performance analysis of power rating, extracted power, time tracking, number of iterations and maximum efficiency. Additionally, the specifications of PV, wind and battery systems are illustrated in Table 1. The simulation diagram of the proposed method is illustrated in Fig. 3.

Table 1. Specifications of PV, Wind and solar

Power systems	Specifications	Values
PV	STC power rating	150 W
	Open circuit voltage (V_oc)	23.3V
	Minimum power circuit (I_mp)	7.87 A
	Minimum power Voltage (V_mp)	17.8V
Wind systems	Type	Espanda
	Cut off wind speed	3 m/s
	Cut in wind speed	25 m/s
	No. of blader	2
Battery	Type	GFM-100
	Rated voltage	2V
	Rated capacity	100Ah
	Hourly self-discharge rate	0.0001

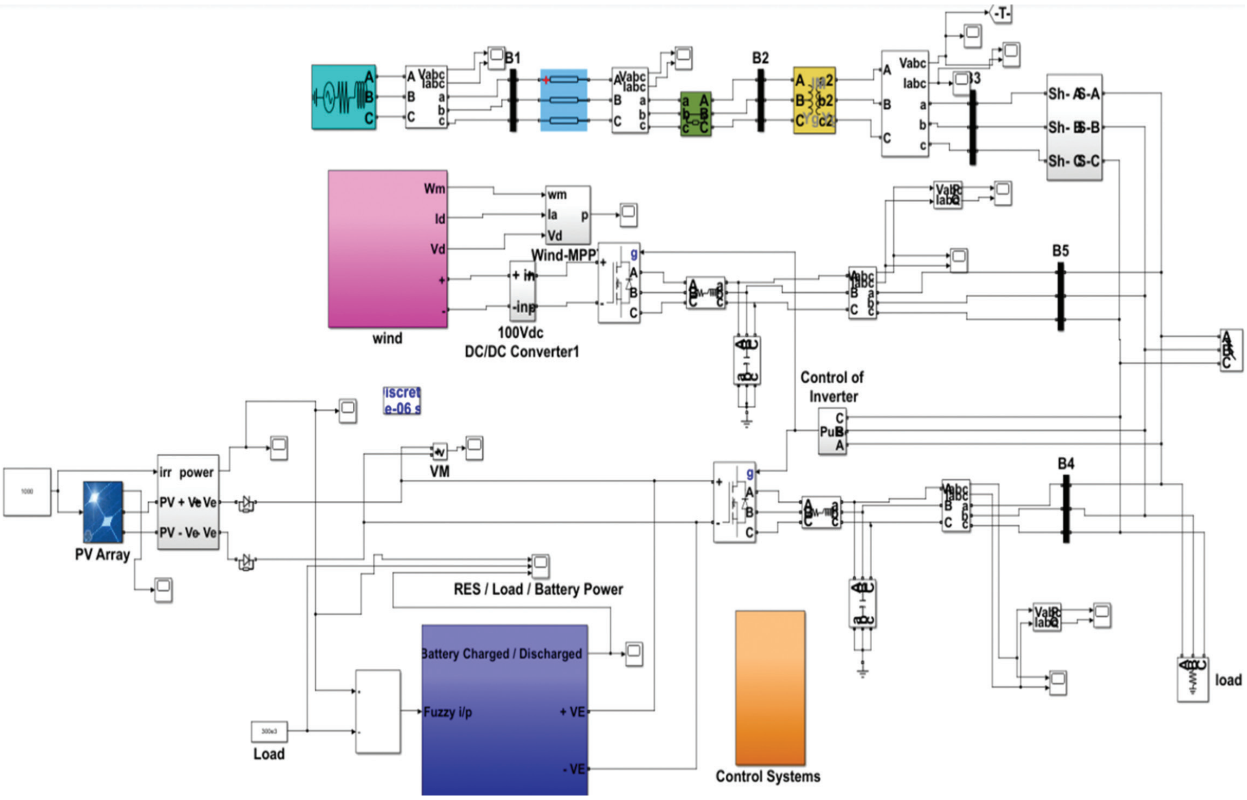

Fig. 3. Simulation diagram of the proposed method

3.1. PATTERN- 1

In this research, a 250 W PV array is subjected to varying irradiance levels in a partial shading scenario, while maintaining a relatively consistent temperature range of $T = 25$ to 25.5 °C. At $t = 0$ s, the MPPT algorithms are sequentially initiated, each corresponding to irradiance levels of $G = 1000$, 300, and 600 W/m^2 on the respective PV. The MPPT algorithms' experimental waveforms are shown in the figure and tables below. The outcomes proved that the suggested method achieves superior performances in terms of power rating, extracted power, time tracking, number of iterations and maximum efficiency. The existing methods such as MVO-P&O, MVO-MP&O, and MOMVO-P&O respectively achieve 91.56%, 93.41%, and 78.74%, in terms of maximum efficiency, whereas the suggested MOMVO-MP&O method achieves a superior maximum efficiency of 98.51%, as illustrated in Table 2 and Fig. 4.

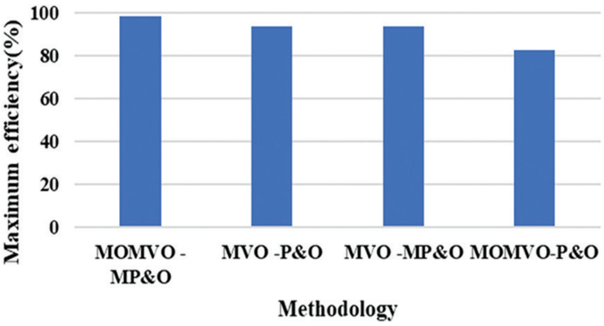

Fig. 4. Graphical representation of the proposed method for Pattern-1

Table 2. Evaluation of the proposed MOMVO with metaheuristic algorithms for pattern-1 performance analysis

Methodology	Power rating (W)	Extracted power (w)	Time Tracking (s)	Number of Iterations	Maximum Efficiency (%)
MOMVO -MP&O	104.50	104.21	0.35	13	98.51
MVO -P&O		103.45	1.50	13	91.56
MVO -MP&O		103.36	1.48	15	93.41
MOMVO-P&O		85.65	0.78	10	78.74

3.2. PATTERN- 2

The MPPT algorithms are sequentially initiated at different irradiance levels: 450, 750, and 650 W/m2 for the first, second, and third PV modules, as described in this research. The experimental waveforms are illustrated in Fig. 4. Table 3 presents the response times of the MPPT algorithms to reach stability near the power point for these conditions with a 123.88 W of global power. By employing the proposed MOMVO process in a PV system, a peak power of 122.88 W is attains within 0.54 seconds and fifteen iterations, showcasing the effectiveness of the MOMVO algorithm in achieving optimal power tracking. The results show that the suggested method attains greater performances in terms of power rating, extracted power, time tracking, number of iterations, and maximum efficiency. The existing methods namely, MVO-P&O, MVO-MP&O and MOMVO-P&O correspondingly achieve 93.52%, 93.74% and 82.80% in terms of maximum efficiency, whereas that of the suggested MOMVO-MP&O method is 98.50%, as illustrated in table 3 and Fig. 5.

Table 3. Evaluation of the proposed MOMVO with metaheuristic techniques for pattern-2 performance analysis

Methodology	Power rating (W)	Extracted power (w)	Time Tracking (s)	Amount of Iterations	Maximum Efficiency (%)
MOMVO -MP&O	123.88	123.12	0.45	13	98.50
MVO -P&O		122.14	1.30	20	93.52
MVO -MP&O		120.48	0.60	16	93.74
MOMVO-P&O		116.12	0.78	15	82.80

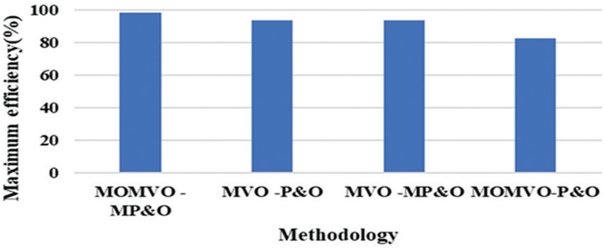

Fig. 5. Graphical representation of the proposed method for Pattern-2

3.3. PATTERN- 3

For pattern 3, the first, second, and third PV modules experience irradiances of 1000, 600, and 600 W/m2, respectively. Analysis of the P-V curve reveals two peaks with the global maximum at the second peak and a local maximum at the leftmost peak. The maximum power output for pattern-3 is measured at 157.95 W. The typical MVO algorithm with a tracking duration of 1.31 s and an MPPT value of 156.67 W produce power waveforms with steady-state oscillations identical to patterns 1 and 2. In addition, the PSO algorithm is used in pattern-3 which achieves MPPT in 15 iterations with a global peak power of 138.66 W, and a tracking time of 1.02 seconds. PSO dominates those obtained by MOMVO in average. By making similar observations for the remaining rows, it attains better performance of MOMVO solutions. The results prove that the suggested method achieves higher performances in terms of Power rating, extracted power, Time tracking, number of iterations, and Maximum Efficiency. The existing methods namely, MVO-P&O, MVO-MP&O, and MOMVO-P&O correspondingly accomplish 90.54%, 94.34% and 93.80% in terms of maximum efficiency, whereas the suggested MOMVO-MP&O method accomplishes a higher performance with 98.80%, as outlined in Table 4 and Fig. 6.

Table 4. Evaluation of the proposed MOMVO with metaheuristic algorithms for pattern-3 performance analysis

Methodology	Power rating (W)	Extracted power (w)	Time Tracking (s)	Number of Iterations	Maximum Efficiency (%)
MOMVO -MP&O	157.95	158.48	0.35	12	98.80
MVO -P&O		157.69	1.25	20	90.54
MVO -MP&O		157.75	0.10	17	94.34
MOMVO-P&O		157.65	1.40	14	93.80

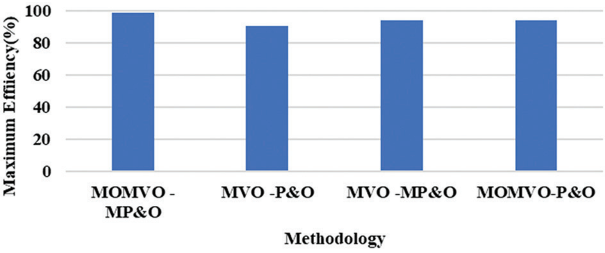

Fig. 6. Graphical representation of the proposed method for pattern-3

3.4. COMPARATIVE ANALYSIS

To test the efficiency of grid-connected RES using the MOMVO controller, a comparative analysis is conducted against the pre-established RES system designs, MF-DPC [19] and ANFIS [22]. This comparison primarily focuses on evaluating the MOMVO-MP&O controller's performance in terms of THD. From the results, it is evident that the existing method MF-DFC achieves 3.9% and ANFIS achieves 3.85% for THD performance matrices. When contrasted against the existing methods, the introduced method accomplishes a superior THD value of 1.86%. The novel MOMVO-MP&O strategically addresses the existing issues by minimizing the harmonic distortion more effectively than the existing approaches. Its meticulous parameter tuning and innovative algorithmic design synergistically mitigate distortions, showcasing commendable performance in harmonic reduction across diverse scenarios. Table 5 and Fig. 7 exhibit the contrast between the proposed method and previous methods.

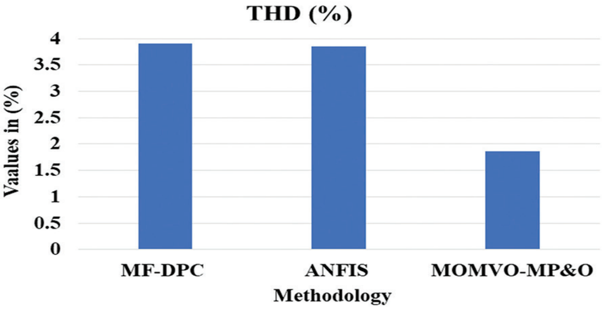

Fig. 7. Comparison of THD for MOMVO and existing methods

Table 5. Comparison of THD for MOMVO and existing methods

Method	THD (%)
MF-DPC [19]	3.9
ANFIS [22]	3.85
MOMVO-MP&O	1.86

4. CONCLUSION

This research proposed the combination of MP&O with MOMVO to design an efficient EMS that involves PV, wind, and battery system. The system's total energy density is increased when a battery is used together with the RES. Applying the modulation index from MOMVO, the battery and wind turbine can be switched on and off efficiently. Additionally, the MP&O technique is used to obtain steady power from the grid-connected RES by enabling the DC-DC converter. Furthermore, capacitor banks are used to prevent power spikes in the given power. The grid-connected RES system MOMVO-MP&O controller is examined at different temperatures and irradiance levels. With the inclusion of the MP&O's current change and the increased MOMVO convergence rate, an efficient EMS operated by a PV, wind, and battery system can be produced. Additionally, when compared to existing methods namely MF-DPC and ANFIS the proposed MOMVO-MP&O have achieved better performances in terms of THD. The results demonstrated that a significantly higher THD value of 1.86% which is relatively higher than existing models. In future, the proposed model can be enhanced by considering more random and uncertain factors in the generation, load demand and smart battery charging technology.

5. REFERENCES

[1] A. Naderipour, H. Kamyab, J. J. Klemeš, R. Ebrahimi, S. Chelliapan, S. A. Nowdeh, A. Abdullah, M. H. Marzbali, "Optimal design of hybrid grid-connected photovoltaic/wind/battery sustainable energy system improving reliability, cost and emission", Energy, Vol. 257, 2022, p. 124679.

[2] A. L. Konde, M. Kusaf, M. Dagbasi, "An effective design method for grid-connected solar PV power plants for power supply reliability", Energy for Sustainable Development, Vol. 70, 2022, pp. 301-313.

[3] N. Niveditha, M. M. R. Singaravel, "Optimal sizing of hybrid PV–Wind–Battery storage system for Net Zero Energy Buildings to reduce grid burden", Applied Energy, Vol. 324, 2022, p. 119713.

[4] S. Bhattacharyya, S. Puchalapalli, B. Singh, "Operation of Grid-Connected PV-Battery-Wind Driven DFIG Based System", IEEE Transactions on Industry Applications, Vol. 58, No. 5, 2022, pp. 6448-6458.

[5] S. K. Thirumalai, A. Karthick, P. K. Dhal, S. Pundir, "Photovoltaic-wind-battery and diesel generator-based hybrid energy system for residential buildings in smart city Coimbatore", Environmental Science and Pollution Research, Vol. 31, 2024, pp. 14229-14238.

[6] S. Boualem, O. Kraa, M. Benmeddour, M. Kermadi, M. Maamir, H. Cherif, "Power management strategy based on Elman neural network for grid-connected photovoltaic-wind-battery hybrid system", Computers and Electrical Engineering, Vol. 99, 2022, p. 107823.

[7] M. A. Judge, A. Khan, A. Manzoor, H. A. Khattak, "Overview of smart grid implementation: Frameworks, impact, performance and challenges," Journal of Energy Storage, Vol. 49, 2022, p.104056.

[8] P. A. Gbadega, X. Y. Sun, "JAYA algorithm-based energy management for a grid-connected microgrid with PV-wind-microturbine-storage energy system", International Journal of Engineering Research in Africa, Vol. 63, 2023, pp. 159-184.

[9] P. Rajesh, F. H. Shajin, B. Rajani, D. Sharma, "An optimal hybrid control scheme to achieve power quality enhancement in micro grid connected system", International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, Vol. 35, No. 6, 2022, p. e3019.

[10] R. Z. Falama, V. Dumbrava, A. S. Saidi, E. T. Houdji, C. B. Salah, S. Y. Doka, "A Comparative-Analysis-Based Multi-Criteria Assessment of On/Off-Grid-Connected Renewable Energy Systems: A Case Study", Energies, Vol. 16, No. 3, 2023, p. 1540.

[11] L. Garg, S. Prasad, "A review on controller scalability for VSC-MTDC grids: challenges and applications", Smart Science, Vol. 11, No. 1, 2023, pp. 102-119.

[12] R. Fathi, B. Tousi, S. Galvani, "Allocation of renewable resources with radial distribution network reconfiguration using improved salp swarm algorithm", Applied Soft Computing, Vol. 132, 2023, p. 109828.

[13] R. Bisht, A. Sikander, "A novel hybrid architecture for MPPT of PV array under partial shading conditions", Soft Computing, Vol. 28, No, 2, 2024, pp. 1351-1365.

[14] A. Khosravani, E. Safaei, M. Reynolds, K. E. Kelly, K. M. Powell, "Challenges of reaching high renewable fractions in hybrid renewable energy systems", Energy Reports, Vol. 9, 2023, pp. 1000-1017.

[15] A. M. Jasim, B. H. Jasim, A. Flah, V. Bolshev, L. Mihet-Popa, "A new optimized demand management system for smart grid-based residential buildings adopting renewable and storage energies", Energy Reports, Vol. 9, 2023, pp. 4018-4035.

[16] M. Mishra, P. Mahajan, R. Garg, "Implementation and comparison of metaheuristically modified ANN MPPT controllers under varying solar irradiance conditions", Electrical Engineering, Vol. 106, 2023, pp. 3427-3443.

[17] T. Zhang, B. Sobhani, "Optimal economic programming of an energy hub in the power system while taking into account the uncertainty of renewable resources, risk-taking and electric vehicles using a developed routing method", Energy, Vol. 271, 2023, p. 126938.

[18] B. Lin, C. Huang, "Promoting variable renewable energy integration: The moderating effect of digitalization", Applied Energy, Vol. 337, 2023, p. 120891.

[19] Y. Sahri, S. Tamalouzt, S. L. Belaid, M. Bajaj, S. S. M. Ghoneim, H. M. Zawbaa, S. Kamel, "Performance improvement of hybrid system based DFIG-wind/PV/batteries connected to DC and AC grid by applying intelligent control", Energy Reports, Vol. 9, 2023, pp. 2027-2043.

[20] M. M. Gulzar, A. Iqbal, D. Sibtain, M. Khalid, "An Innovative Converterless Solar PV Control Strategy for a Grid Connected Hybrid PV/Wind/Fuel-Cell System Coupled with Battery Energy Storage", IEEE Access, Vol. 11, 2023, pp. 23245-23259.

[21] M. Maaruf, K. Khan, M. Khalid, "Robust Control for Optimized Islanded and Grid-Connected Operation of Solar/Wind/Battery Hybrid Energy", Sustainability, Vol. 14, No. 9, 2022, p. 5673.

[22] P. Cholamuthu, B. Irusappan, S. K. Paramasivam, S. K. Ramu, S. Muthusamy, H. Panchal, R. S. S. Nuvvula, P. P. Kumar, B. Khan, "A Grid-Connected Solar PV/Wind Turbine Based Hybrid Energy System Using ANFIS Controller for Hybrid Series Active Power Filter to Improve the Power Quality", International Transactions on Electrical Energy Systems, Vol. 2022, 2022, p. 9374638.

[23] A. Ibáñez-Rioja, L. Järvinen, P. Puranen, A. Kosonen, V. Ruuskanen, K. Hynynen, J. Ahola, P. Kauranen, "Off-grid solar PV–wind power–battery–water electrolyzer plant: Simultaneous optimization of component capacities and system control", Applied Energy, Vol. 345, 2023, p. 121277.

[24] A. O. Amole, S. Oladipo, O. E. Olabode, K. A. Makinde, P. Gbadega, "Analysis of grid/solar photovoltaic power generation for improved village energy supply: A case of Ikose in Oyo State Nigeria", Renewable Energy Focus, Vol. 44, 2023, pp. 186-211.

[25] N. J. Bodele, P. S. Kulkarni, "Modular battery-integrated bidirectional single-stage DC–DC converter for solar PV based DC Nano-grid application", Solar Energy, Vol. 259, 2023, pp. 1-14.