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HYBRID GREY WOLF AND CUCKOO SEARCH OPTIMIZATION FOR OPTIMAL ENERGY MANAGEMENT IN MICROGRID SYSTEMS

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ABSTRACT

Microgrid (MG) technology has the potential to effectively incorporate a new method to produce renewable energy on a massive scale for the grid-connected system. An Energy Management System is necessary for a microgrid to make the most efficient use of its distributed energy resources in ways that are also intelligent, protected, consistent, and synchronized. In this work, the management of battery energy storage system that is connected to a solar photovoltaic array and wind turbine system in a microgrid, as well as the control of battery charge and discharge operations using a converter based on the demand for the energy has been carried out. The strategy suggested was the daily energy management of a MG system by implementing hybrid grey wolf and cuckoo search optimization (HGWCSO) algorithm for reducing the total variable cost of energy. The output variables of each component of microgrid such as solar PV, wind turbine, grid, energy storage system as well as load power graphs. Energy storage system state of charge graphs is analysed at each instance of time and the variable cost of energy for a day were determined by using proposed algorithm. The proposed HGWCSO algorithm provided the overall system cost of 8.03%, which is less than the value obtained by heuristic approach.



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I. INTRODUCTION

Microgrids (MG) are now gaining popularity and are regarded as the future trend in distributed power systems. These are helping to supply the sustainable power to the remote areas, which are located far away from the utility grid. To ensure stability in a MG, power balance must be maintained due to the non-conventional energy sources intermittent nature of power generation [1]. Because the supply and demand of energy are out of balance, RES dependability is necessary. ESSs are a significant part of the MG since they increase the effective use of RES. The EMS is a management system that executes critical tasks in all MG to ensure that operating costs and energy costs are covered [2]. The EMS has a considerable impact on the MG reliability and efficacy. Numerous researchers have used various kinds of solution strategies to address these energy management approaches to ensure the MG performs optimally and effectively. In reference [3], the authors introduced an EMS that utilises both nonlinear and linear programming techniques. Conversely, in reference [4], the authors proposed an EMS that combines rule-based and dynamic programming approaches. In their study, the scientists developed a multi-objective EMS by employing swarm and genetic optimisation techniques [5]. In their research, the authors presented an EMS that leverages a combination of meta-heuristic methodologies. They further showcased an EMS implementation utilising a neural network and fuzzy logic. This approach was proposed in reference [6]. The authors in [7] proposed an EMS based on a multi-agent system and suggested a stochastic, robust programming approach-based EMS.

In addition to variable and constant loads, the suggested research incorporates two blocks: a PV array block serving as a RES, and other block functioning as an ESS to store energy within the system [8], [9]. The presented model outlines the sequential process involved in developing an optimisation algorithm that leverages projected price and loading conditions to efficiently manage the energy storage and sale of energy from a battery system at a grid-scale level in [10]. The availability of this real-time data is limited to a single day. The battery controller serves the purpose of storing energy within the battery storage system. In the event of surplus power within the MG, the excess energy is stored and subsequently utilised to provide supplementary power during instances of power scarcity within the MG. The methodology of controlling suggests that the microgrid doesn't solely depend on the electricity generated by the primary utility grid but also relies on solar PV systems and energy storage, which typically provide an adequate power supply. This work focuses on two approaches: heuristics method and HGWCSO algorithm. The following table provides the latest work done on energy management optimization of the hybrid microgrid system.

Table 1: Literature Survey of Energy Management of Microgrid.

Author/Ref.	Optimization Technique	Highlights
Djerioui et al. [11]	GWO	Using a fuel cell (FC) and a super capacitor hybrid energy source as the EMS, it will be possible to implement electric vehicles (EVs). The use of the GWO approach to lengthen the FC's life and minimize transients in the power system
Acharya et al. [12]	PSO (Particle Swarm Optimization) and GSA (Gravitational Search Algorithm)	To improve the power quality, PSO and GSA approaches are used. Outcomes demonstrate that the proposed technique is more effective than the PI and PSO methods.
Choudhury et al. [13]	CS (Crow Search)	The research will use a grid-integrated solid oxide fuel cell (SOFC) system. The gains of PID controllers are precisely tuned using the CS approach. Results pointed to a reduce in distortions and an increase in system effectiveness.
Choudhury et al. [14]	ISSA (Improved Squirrel Search Algorithm)	In this investigation, a PID controller adjusted using the ISSA technique is used to manage the power quality of the grid-integrated FC. SSA and PSO outcomes have been compared to those of the new, improved SSA approach.
Elmetwaly et al. [15]	MPA (Marine Predator Algorithm)	Improving an EMS for a collection of distinct MGs based on the MPA approach. Increasing overall system efficiency by using a PID-based adaptive dynamic voltage restorer.
Ferahtia et al. [16]	SSA (Salp Swarm Algorithm)	DC microgrid made up of FC, PV, and battery energy storage systems, an EMS-based approach based on the SSA method is suggested. By using the suggested technique, fuel consumption has decreased and system efficiency has increased.
B. Dey et al [17]	Hybrid CSA-JAYA algorithm	The investigation employed an EMS that relied on demand response. According to reports, the economic functioning of the MG system employed the demand response (DR) technique, leading to a notable reduction of 9% in production costs.
V.Suresh et al [18]	GA(Genetic Algorithm), PSO and ACO (Ant Colony Optimization)	Different optimisation techniques are used for microgrid energy management; however, the results show that the ant-colony algorithm is the best choice among all.
D.G. Rosero et al [19]	Machine Learning Techniques	Improve energy generation and usage predictions while minimising the cost to the service provider.
M.Rodriguez et al [20]	Meta heuristic algorithm, Fuzzy logic	The outcomes of the research indicate that the proposed methodology effectively mitigates the consumption of distributed generation (DG), enhances the utilisation of solar resources, and prolongs the lifespan of batteries by avoiding deep discharges and overcharges.
N. Alamir et al [21]	Pelican Optimization Algorithm (POA)	To reduce the peak hour load, the results of the hybrid dynamic demand response method combined with the POA method were implemented into the EMS of the MG system

Source: Authors, (2026).

From the above discussion, it can be concluded that few researchers are concentrated on the energy management strategies to reduce the cost of the system. So, in this research the goal is to reduce the adjustable tariff of hybrid MG, which is already designed for a location. The remaining of this paper is organised as follows: Sections 2 gives brief discussion of hybrid microgrid, EMS and its classification. Section 3 examines the design models of solar and batteries and their objective functions. Section 4 discusses the proposed technique, its mathematical formulation and flow chart. Section 5 also contains an analysis and discussion of simulation outcomes followed by conclusion remarks in Section 6.

II. HYBRID MICROGRID SYSTEM

The hybrid microgrid has a number of benefits, including harmonic control, economic viability, and voltage transformation [22]. Despite all the advantages listed, a hybrid microgrid has some small drawbacks, such as protection issues and difficult unit coordination, which can be fixed by using optimal operating techniques [23], [24]. However, the hybrid microgrid system (HMGS) has overall advantage over other MGs that makes it a good case study for assessing operational problems. When operating in the stand-alone mode of operation, the system is not connected to the conventional grid, and the ESS is heavily utilized, adding to the system's running costs. The excess energy cannot be stored in addition to that. This operating mode prioritizes local loads more, making it more suited for remote locations and mostly used for seasonal purposes. Due to their superior cost-effectiveness, solar PV systems account for the majority of the capacity on islanded MG [25], [26]. The authors of [27] suggested an upgraded system-level EMS for residential hybrid microgrid by utilizing the advancements provided by digitization. The suggested EMS was created for an MG that contains batteries and renewable energy sources, so it helps the green transition. The following Figure 1 represents the hybrid microgrid system.

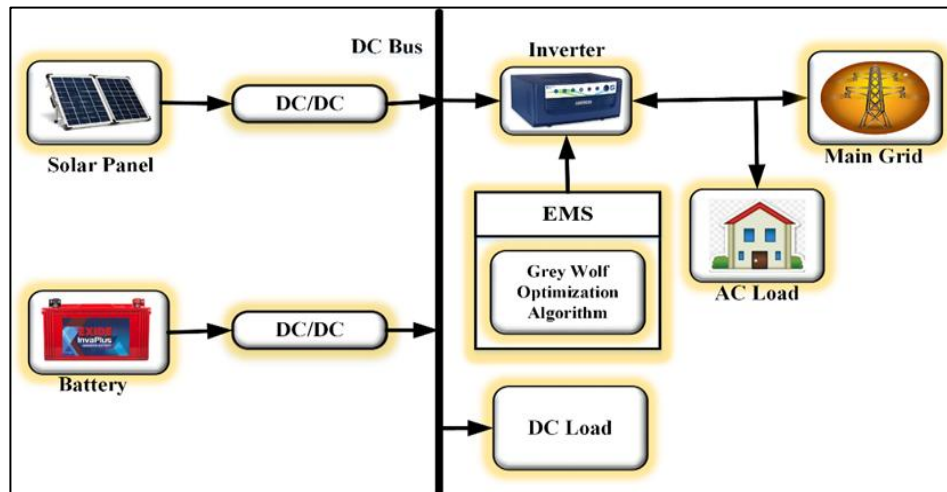


Figure 1: Hybrid microgrid system.
Source: Authors, (2026).

II.1 MICROGRID ENERGY MANAGEMENT SYSTEM

Due to the unpredictability or intermittent nature of the supply of renewable energy, integrating RES into smart grids is a source of concern since it creates stability and reliability issues in the power system. To find a remedy for this shortcoming of MG, it is required to have both an efficient battery management system as well as an appropriate forecasting algorithm [28]. It has been seen in literature that a number of different optimisation strategies be utilised to solve this challenge. These strategies involve efficiently dispatching the power that is created to achieve the most possible economic benefit while also preserving stability. In addition, these strategies involve scheduling alternate energy resources or energy storage. In the field of electrical engineering, one of the terminologies that is frequently used is EMS. The primary focus of the economic dispatch (ED) is on techniques that enhance the utilisation of renewable resources with the goal of maximising the positive effects on the environment as well as the economy. If, on the other hand, generating sources based on fossil fuels are used in conjunction with RES, then the objective of unit commitment focuses on coordinating the various power suppliers to accomplish a common goal of fulfilling the demand at a reduced cost and improving the income returns [29], [30]. This contrasts with the previous scenario, in which the unit commitment objective focuses on achieving the common goal of meeting the demand. In conclusion, the primary emphasis of the demand management goal is placed on the scheduling of usage patterns and efficient load utilisation to maximise financial gain.

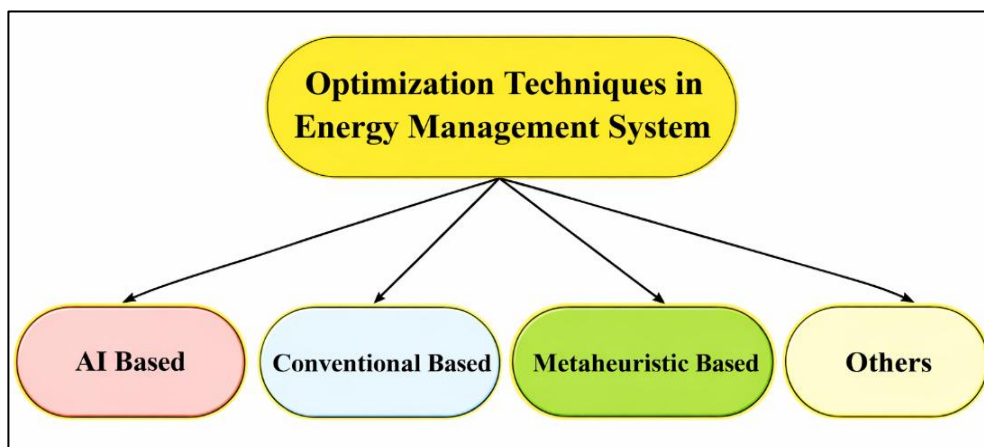


Figure 2: Different types of Optimization methods in energy management system.
Source: Authors, (2026).

To get a good understanding of the numerous energy management methods and the many optimisation strategies that are used for energy management, a comprehensive analysis of the available methodologies was carried out. The optimization strategies employed in EMS of MG are often categorized into four primary types, as illustrated in Figure 2. This research article places a greater emphasis on non-traditional strategies for addressing the electromagnetic problem, as opposed to the commonly employed conventional techniques. It aims to explore the uncharted territory of hybrid, meta-heuristics, and other non-conventional methodologies [31], [32]. This was done to find a clear grasp of the various energy management strategies. The primary purpose of this investigation is to find a way to cut down on the variable cost of electricity by applying the GWO algorithm to the EMS challenge posed by the MG.

III. MODELLING THE COMPONENTS AND OBJECTIVE FUNCTION

III.1 SOLAR PV

Various forms of solar cell materials are currently being used on a global scale. However, silicon has emerged as the predominant material employed in solar cells due to its compelling attributes, including its adaptability, and efficient light absorption [33], [34]. The solar PV array consists of a sum of 48 modules per PV array, with each array being composed of 2 solar modules per string attached in parallel and 24 strings connected in series. The 144 PV cells are arranged in a series configuration to achieve a total power output of 800 kW for the solar PV panel. The block diagram of the solar system is depicted in Figure 3.

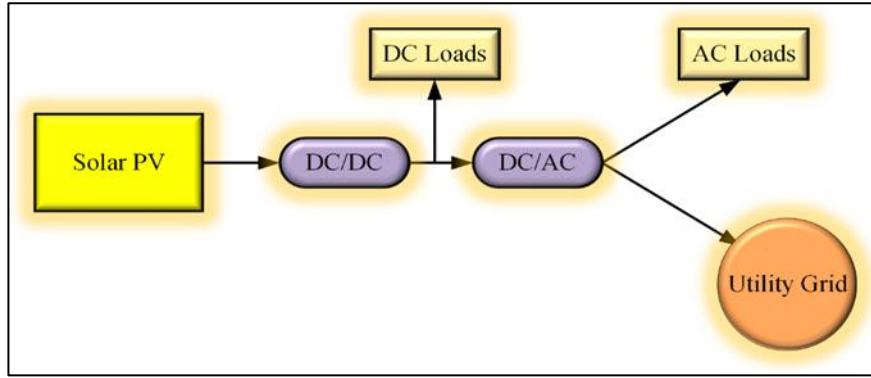


Figure 3: Modelling of Solar PV system.

Source: Authors, (2026).

The selection of materials and methods, procedures and equipment must be justified so that the work can be reproduced. Modifications or new methods must be described in detail. You must clearly define the universe and specify how the sample was selected and why it is representative. Data processing represents the practical development of a theoretical basis, deriving the model equations to program the calculation algorithm, according to the need. In materials, they include the technical specifications and the quantities, the origin and, if necessary, the method for its elaboration. The real-time control of the output power of a PV array can be achieved through the utilization of a Maximum Power Point Tracker (MPPT) in conjunction with a DC-DC converter. The MPP is influenced by variations in solar irradiance and ambient temperature. The power generated by solar PV panel is given by [35].

$$POW_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_C - T_{c,STC})] \quad (1)$$

Where Y_{PV} -the relevant capacity of the solar PV system (kW). f_{PV} -the derating factor of the PV system (%). G_T -the incident solar radiation on the PV system during the current timeframe (kW/m²). $G_{T,STC}$ -the incident radiation at standard test conditions, (kW/m²). α_P -the temperature coefficient of power for the solar PV system, -0.5% per degree Celsius (%/°C). T_C -the solar PV cell temperature during the current timeframe (°C) per degree Celsius (%/°C). $T_{c,STC}$ -the temperature of the solar PV cell at STC (25°C).

III.2 BATTERY ENERGY STORAGE SYSTEM

In this work, a distributed battery model with a capacity of 2500 kWh is developed using MATLAB. The calculation of the current state of charge ($Pbb_{bat}(T)$) is derived from the battery's initial state of charge [36]. The calculation of battery voltage is determined by

$$V_{battery}(T) = V_0(T) - \frac{n \cdot Q_{bat}(T)}{Q_{bat}(T) - \int I_{bat}(T) dt} + A \exp(-B \int I_{bat}(T) dt) \quad (2)$$

The $Pbb_{bat}(T)$ is calculated by

$$Pbb_{bat}(T) = SOC_{ini}(T) \pm \frac{I_{bat}(T) \cdot \Delta T}{Q_{bat} \cdot 3600} \quad (3)$$

In this context, ΔT is the variable denoting the changing time, while the symbols $\pm$ are utilized to signify battery charging and discharging, respectively. The calculation of the energy available for supply at any given moment is given by

$$F_{battery}^{avail}(T) = R_{bat}(T) * V_{battery}(T) * Pbb_{bat}(T) \quad (4)$$

Where, $R_{bat}(T)$ is battery capacity. The excess energy of battery storage is calculated by

$$F_{battery}^{req}(T) = F_{battery}^{rated} - F_{battery}^{avail}(T) \quad (5)$$

III.3 PROBLEM DEFINITION

The primary objective is to reduce the overall system variable cost, encompassing the cost associated with the grid and stored energy, while still following to all operational limits [37]. Hence, the objective function can be stated as.

$$D_t = \sum_{m=0}^N D_{gr}(m) * F_{gr}(m) \quad (6)$$

Where, D_t represents variable electricity price, $D_{gr}(m)$ is grid cost, $F_{gr}(m)$ is energy available in grid station. The final parameters for this research are listed below:

$$x = [G_{gr}(1:N) \text{ att}(1:N) \text{ Fbat}(1:N)]^T \quad (7)$$

In this context, $G_{gr}(1:N)$ represents the power consumed from the grid during time, $P_{bat}(1:N)$ represents the power drawn from the battery storage, and $F_{bat}(1:N)$ represents the amount of battery energy storage.

III.3.1 Constraints

The output power of battery storage system is as follows

$$F_{battery}(m) = F_{bat}(m-1) + P_{battery}(m)\Delta T \quad (8)$$

Where ΔT - the difference in time step and m is step time. The energy balancing formulae for all the buses is regarded as a set of equality requirements, which are explicitly expressed as

$$POW_{PV}(m) + P_{grid}(m) + P_{battery}(m) = P_{total L}(m) \quad (9)$$

The second belongs to output variables as

$$P_{Dg}^{min} \leq P_{Dg} \leq P_{Dg}^{max} \quad (10)$$

$$F^{min} \leq F \leq F^{max} \quad (11)$$

Where, P is the active power of generator in MW and E is the battery energy in Ah.

Table 2: The specifications of each component used in the microgrid.

PV System		Battery	
Parameters	Value	Parameters	Value
Rated Capacity	800 kW	Rated Capacity (kWh)	2500
Efficiency	17.30%	Nominal capacity (mAh)	1
Derating factor	96%	Nominal voltage (V)	12
CC	3000 \$/kW	Maximum capacity (Ah)	83.4
RC	3000 \$/kW	Efficiency (%)	80
O&M cost	10 \$/kW/year	Initial SOC (%)	50
Lifetime (yrs)	25	CC	300\$
Converter		RC	300\$
Rated power (kW)	100	O & M cost per year	10\$
CC (\$/kW)	250	SOC to Recharge (%)	11
RC (\$)	218.72	Other economic inputs	
O & M cost (\$)	6.25/year	Bus Voltage (V)	120
Efficiency (%)	95%	Frequency (Hz)	50
Lifetime (yrs)	15	Project lifetime(yrs)	25

Source: Authors, (2026).

IV. GREY WOLF OPTIMIZATION (GWO) ALGORITHM

In 2013, Mirjalili first introduced this method. The Grey Wolf Optimizer (GWO) is inspired by the social hierarchy and hunting behavior of grey wolf packs, which typically consist of five to twelve members. In this hierarchy, the leader of the pack is known as the alpha, while the beta assists the alpha by providing feedback and helping enforce decisions. The omega occupies the lowest rank and exhibits submissive behavior toward the dominant wolves. Wolves that do not belong to the core leadership hierarchy are referred to as deltas and generally play the role of hunters or subordinates. In the context of optimization problems [38], the alpha represents the best (optimal) solution, while the beta and gamma correspond to the second and third best solutions, respectively.

Alphas (α) are the leaders, and they can be either female or male. The alpha is responsible for establishing consensus on matters such as “hunting, sleeping place, waking time, and so on.” When the pack is together, the alphas (α) have their tails held down as a sign of recognition. On a rest of the pack must obey their decisions. To help the alpha (α) with decision-making and other pack activities, the betas (β) are dependent GWs. If the alpha (α) GWs dies or gets too old to continue leading, the beta (β) GWs are the most likely replacement choice. Alphas (α) rely on betas (β) for advice and discipline within the pack. The beta (β) emphasizes the alpha (α) commands and directs the alphas (α) in the right direction. The scapegoat role is typically given to Omega (ω), the lowest-ranking GW. If the GW is not an alpha (α), beta (β), and omega (ω), they are sub-ordinate know as delta (δ). δ GWs must acquiesce to alpha (α), and beta (β), but they lead ω . The hunting process of Grey Wolves is as follows

Stage 1: Consists of activities like chasing, tracking, and approaching the prey.

Stage 2: includes activities like encircling, hunting, and killing the prey until it stops moving and the last step is attacking the prey.

IV.1 MATHEMATICAL MODEL OF GWO ALGORITHM

IV.1.1 Social hierarchy of GWO

Specifically, alpha (α), beta (β), and delta (δ) are all considered to be suitable solutions in this hierarchy. Omega (ω) is assumed to be the last remaining option. α , β , and δ are responsible for hunting (optimization) in this algorithm. Omega (ω) wolves follow the patterns established by alpha (α), beta (β), and delta (δ).

IV.1.2 Encircling Prey

Grey Wolves encircle the prey during the hunting process. Therefore, Eqn. 12 to Eqn. 13 is used for mathematical modelling the GW's encircling behaviour.

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)| \quad (12)$$

$$\vec{X}(t) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \quad (13)$$

Where, t -the current iteration, $\vec{X}$ & $\vec{X}_p$ -the position vector of the GWs and the prey, and $\vec{A}$, $\vec{C}$ -coefficient vectors. The $\vec{A}$, $\vec{C}$ vectors were calculated by Eqns. 14 and 15.

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r}_1 - \vec{a} \quad (14)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (15)$$

Where (r_1) and (r_2) represent the arbitrary vectors [0,1], and the value of the component a vector declines linearly from 2 to 0 when the execution is repeated. The Grey Wolves will update the prey's position at any chosen point in space using Eqns. 14 and 15.

IV.1.3 Hunting

Grey wolves could locate and enclose their prey, and the pack's leader male typically leads the pack in the hunt. It is possible that β and δ individuals will occasionally join in on the quest. Considering the α , β , and δ are provided improved information about the likely location of the prey, a mathematical model of this process is constructed. At this point in time, we have three ideal solutions: α , β , and δ . In this problem, "prey" stands for the objective function. The Omega (ω) Wolf's answer will revise their position in relation to the Eqns. 16 and 17 describe the hunting procedure in mathematical detail.

$$\vec{D}_\alpha = |\vec{C}_1 \cdot \vec{X}_\alpha - \vec{X}|, \vec{D}_\beta = |\vec{C}_2 \cdot \vec{X}_\beta - \vec{X}|, \vec{D}_\delta = |\vec{C}_3 \cdot \vec{X}_\delta - \vec{X}| \quad (16)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot (\vec{D}_\alpha), \vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot (\vec{D}_\beta), \vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot (\vec{D}_\delta) \quad (17)$$

Where $\vec{D}_\alpha$, $\vec{D}_\beta$ and $\vec{D}_\delta$ -the vector's position of the GWs in the population w.r.t α , β , and δ wolves. The $\vec{C}_1$, $\vec{C}_2$ and $\vec{C}_3$ were the generated arbitrary numbers in the range[0,2], $\vec{X}$ is the search agents, i.e., population, $\vec{X}_\alpha$, $\vec{X}_\beta$ and $\vec{X}_\delta$ were the best search agents related to the optimal solutions. $\vec{A}_1$, $\vec{A}_2$ and $\vec{A}_3$ were arbitrary numbers that depend on the $\vec{a}$. The encircling behavior is implied to obtain the new positions of Grey Wolves using Eqn. 18.

$$\vec{X}(t+1) = \frac{(\vec{X}_1 + \vec{X}_2 + \vec{X}_3)}{3} \quad (18)$$

The remaining GWs then randomly shift their position everywhere in the prey based on the predictions of alpha (α), beta (β), and delta (δ). When the target animal stops moving, the hunt is over. The alpha (α), beta (β), and delta (δ) wolves iteratively forecast where the prey is most likely to be found. To emphasize the algorithm's exploration and characteristics, an is gradually decreased from 2 to 0. Each potential answer keeps track of its current separation from the target. If $|\vec{A}| > 1$, potential solutions begin to separate from the target. Convergence of $|\vec{A}|$ 1 on the target area. The algorithm concludes successfully at last.

IV.2 INTEGRATION GWO WITH CUCKOO SEARCH ALGORITHM (CS)

Yang and Deb created the cuckoo search algorithm, a new meta-heuristic algorithm for solving optimization problems based on the obligate brood parasitism of some cuckoo species, which deposit their eggs in the nests of other host birds. The CS optimisation algorithm is based on the unusual nesting behavior of cuckoo birds and the levy-flight style [39]. Some cuckoos have particularly unique reproductive tactics, in which they do not hatch their own children but instead lay their eggs in the host's nest while the host is away; they may also remove the host bird's eggs. When certain host birds discover that the eggs belong to an outsider, they may either relocate the outsider's eggs away or abandon the nest and look for a new location to build one. Many animals exhibit levy-flight-style flying characteristics. It refers to the individual in a restricted range of activities, but there is a modest possibility of a long-range jump. It may also have a slight chance of deviating significantly from the mean value of the activities, due to the power of the CS algorithm jumping out of the local optimum. The CS algorithm must adhere to the following three idealized rules:

- Cuckoo birds choose their nest randomly and only lay one egg at a time.
- Only the best nests will exist for future generations.
- Third, the number of bird nests and the probability of egg discovery are predetermined. If the host bird discovers an outsider's egg, it abandons the nest and builds a new one.

By complying with these three rules above, the nests are updated by following equations during the iteration.

$$X_i(t+1) = x_i(t) + \alpha \oplus Levy(\lambda), i = 1, 2, 3, \dots, n \quad (19)$$

Where the product $\oplus$ - entry-wise multiplication. $X_i(t+1)$ -new solutions for cuckoo, i . $x_i(t)$ represents the current solutions. Since $\alpha > 0$ control the step size and is set to 1. The Levy-flight is providing by the following probability distribution equation:

$$Levy(\lambda) = t^{-\lambda}, 1 < \lambda \leq 3 \quad (20)$$

As a result, the CS optimisation algorithm can efficiently explore the output space since its step changes with short distance detection and occasional long-distance walking, and the length of the step increases significantly in the long run.

IV.3 PSEUDO CODE

The pseudo code of the HGWCSO algorithm is presented as follows:

```

Initialize the grey wolf population  $X_i$  ( $i = 1, 2, \dots, n$ )
Initialize  $a, A, C$  and  $\rho_a$ 
Compute the fitness of each search agents in the pack using eq. 6
Set  $\vec{X}_\alpha$ ,  $\vec{X}_\beta$  and  $\vec{X}_\delta$  according to the fitness
 $t = 0$  (iteration=0)
while ( $t \leq \text{Max number of iterations}$ )
  for wolf (each search agent)
    Update the position of the current search agent by equation 12-18
  end for
  update  $a, A, C$ 
  Run load flow analysis with constraints
  Calculate the fitness function using equation 6
  Update  $\vec{X}_\alpha$ ,  $\vec{X}_\beta$  and  $\vec{X}_\delta$ 
  For  $\vec{X}_\alpha$ ,  $\vec{X}_\beta$  and  $\vec{X}_\delta$ 
    Equation 19 updates the position with the CS algorithm and the Levy flight method [40].
    If the random integer is greater than  $\rho_a$ ,
    the wolf's position will be changed randomly.
    Calculate the fitness function and update it based on fitness.
  End for
   $t=t+1$ 
End while
Return ( $\vec{X}_\alpha$ )  $\rightarrow$  output value.

```

V. SIMULATION RESULTS

This proposed research employs a MG configuration that incorporates solar PV technology as the major source of power generation. Additionally, any surplus power generated is stored in a battery for future use. In this discussion pertains to solar PV generation and its maximum power output. The electricity generated by the solar PV system is then stored in the battery energy storage system, in accordance with its capacity. The proposed system incorporates a conventional grid with a capacity of 13.8 kV. The conventional grid is interconnected by a 3-phase, two-winding transformer. The primary winding of the 3- ϕ transformer has a voltage rating of 13.8 kV, while the secondary winding has a voltage rating of 5 kV. The load capacity is currently, measuring 704.86 kW.

The component in the system is the solar PV array, boasting a capacity of 535 kW. The ESS, which functions as the central component of the system. The ESS possesses a power rating of 535 kW and a storage capacity of 2500 kWh. This study used a heuristic approach, specifically the HGWOCS, to calculate and compare the overall cost of power.

V.1 HEURISTIC APPROACH

The simulated waveforms of a one-day analysis utilising a heuristic technique are depicted in Figure 4. The first waveform depicts the RMS voltage of the microgrid, illustrating the variations in voltage due to alterations in load requirements and power generation. The second waveform illustrates the state of charge (SOC) of the ESS, while the third waveform depicts grid power pricing. The fourth waveform illustrates the power produced by solar PV system, the grid, the battery, and the load. During the time period ranging (0 to 2) $\times 10^4$ seconds, the power demand remains below 80 kW. Consequently, the SOC of the ESS during this duration reflects its starting capacity, specifically 50%. Therefore, it can be inferred that the operational cost is at its lowest. During the time span ranging (2 to 4) $\times 10^4$ sec, the load experiences an increment up to 80 kW. Simultaneously, the solar PV power demonstrates an upward trend, while the power stored in the battery exhibits a negative decline. As a result of the amplified solar PV capacity surpassing the load demand, excess electricity is produced and subsequently stored in the battery system. This implies that the battery undergoes a gradual process of recharging. Furthermore, due to the minimal expense associated with renewable energy generation, the overall cost continues to remain low.

During the time span ranging (4 to 6) $\times 10^4$ seconds, the load exhibits consistent behaviour while the voltage of the battery attains the nominal voltage of the battery, hence transitioning into the charging mode. Consequently, the SOC is accompanied by a charging performance index that is expected to exceed 85%. In the same manner, the power output of the solar PV system decreases, leading to a gradual initiation of power supply from the battery, resulting in the discharge of the battery. The cost remains low due to the utilisation of stored battery power derived from renewable sources. During the time span ranging from (6 to 8) $\times 10^4$ seconds, the load experiences a gradual increase, reaching a level of 80 kW. However, it is important to note that the power derived from the battery continues to decline, despite the reducing of solar PV power. At a particular moment, the battery becomes completely depleted, and the power generated by the solar PV system becomes insignificant. Subsequently, the power supply switches to the grid. The load's power requirements are met by the utilisation of grid electricity, resulting in an increase in costs to their maximum level. The heuristic technique yields a total cost of \$209 for a day.

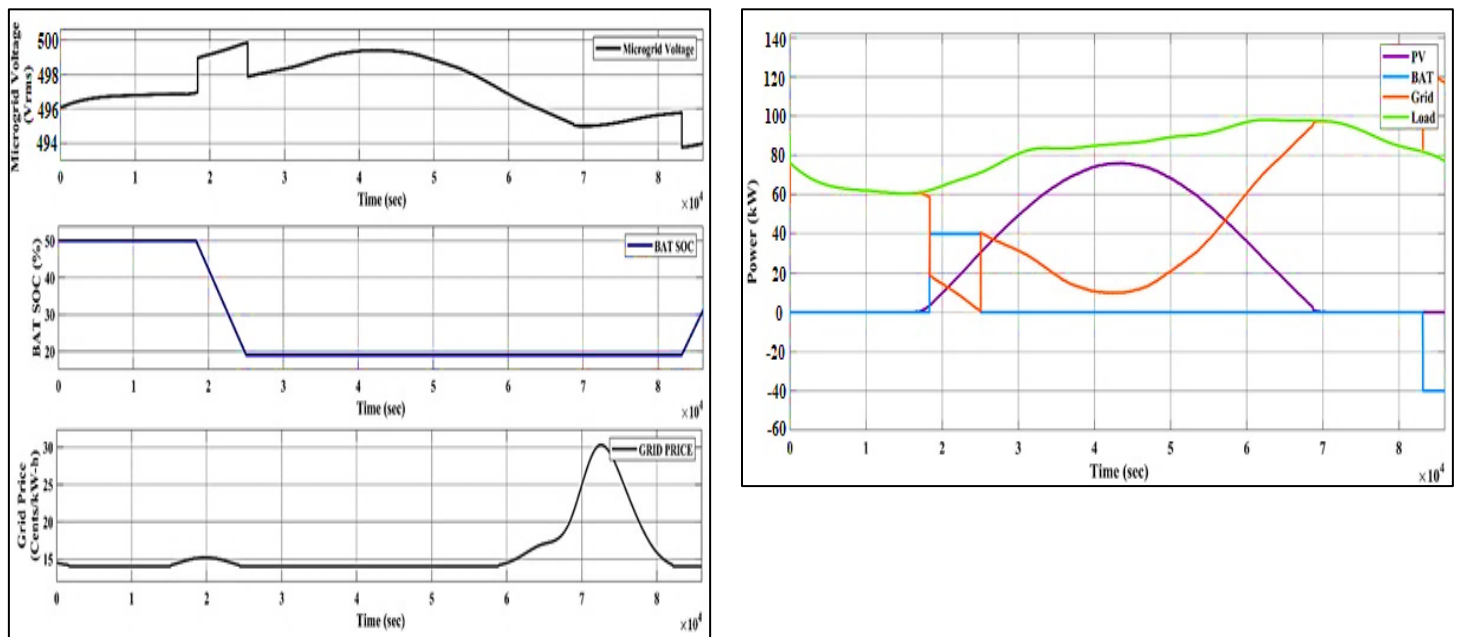


Figure 4: The waveforms of the proposed system using heuristic approach.

Source: Authors, (2026).

V.2 PROPOSED HGWOCS ALGORITHM

Figure 5 displays the simulated waveforms obtained from a one-day study utilising the proposed HGWOCS technique. During the time range (0 to 2) $\times 10^4$ secs, the load demand exhibits a decrease, resulting in the solar PV and battery system not providing any power during this period. The power grid provides electricity, which allows the battery to become fully charged within the specified time frame. Subsequently, the grid supply experiences a decline due to the utilisation of solar photovoltaic (PV) arrays and battery systems for power provision, resulting in the gradual discharge of the stored energy within the batteries. In a similar vein, the operational cost is at a minimum. During a time interval ranging from (2 to 4) $\times 10^4$ secs, the load exhibits a gradual increase, reaching a maximum value of 80 kW. The utilisation of solar PV power is experiencing a notable upward trend. Concurrently, the level of battery power is diminishing.

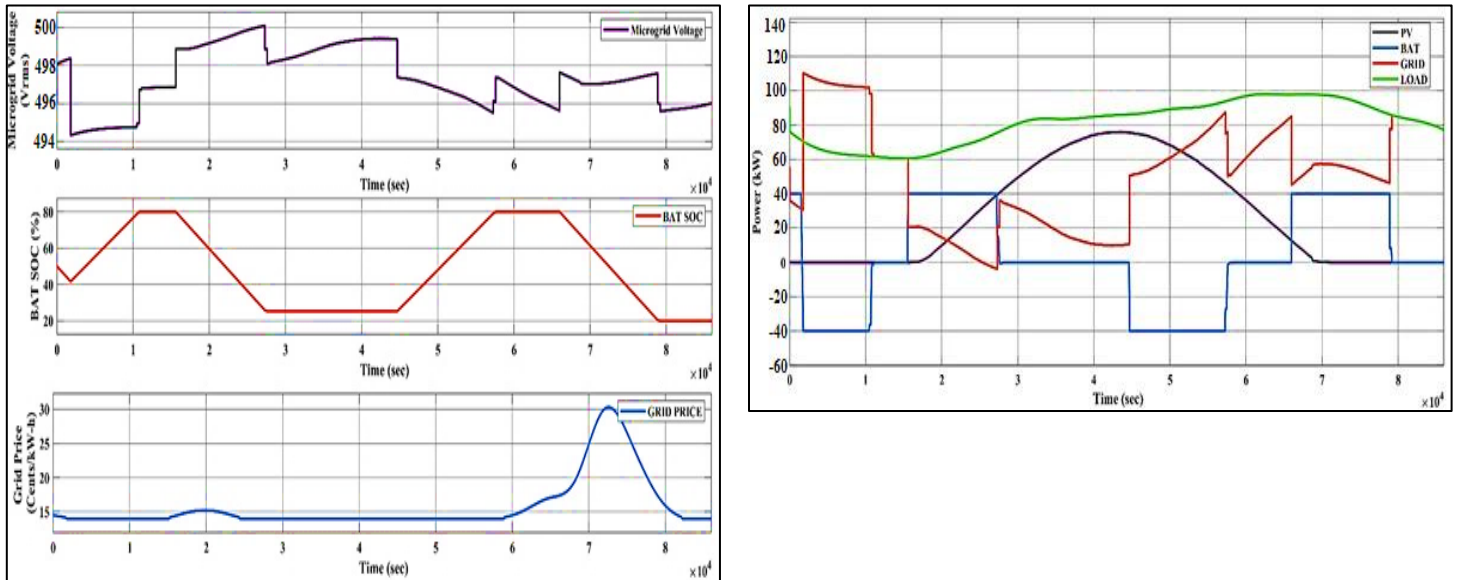


Figure 5: The waveforms of the proposed system using HGWOCS approach.

Source: Authors, (2026).

In this scenario, the solar PV system generates a greater amount of electricity, resulting in a drop in power sourced from the grid. Consequently, the battery does not contribute to the power supply. Once again, because of the minimal cost associated with renewable generation, the overall cost remains low. During the time span ranging $(4 \text{ to } 6) \times 10^4$ secs, the load exhibits consistent behaviour while the voltage of the battery attains the nominal voltage of the battery, hence transitioning into the charging mode. Consequently, the SOC is equipped with a charging performance index that is predicted to exceed 85%. Nevertheless, the expenses persist at a minimal level due to the utilization of stored energy of the battery derived from RES. During the time span ranging $(6 \text{ to } 8) \times 10^4$ seconds, the load experiences a gradual increase to a level of 800 kW. However, it is noteworthy that the power supply continues to be sourced from the battery, despite a simultaneous decline in the power output of the solar PV array. During a certain moment, the battery undergoes a gradual drain while the contribution of solar power is insignificant, followed using grid electricity. The load's power requirements are met by the utilisation of grid electricity, resulting in an increase in costs to their maximum level. The overall expenditure associated with a day utilising the proposed GWO algorithm amounts to \$191.

V.3 GRID ELECTRICITY COST COMPARISON DURING A DAY

Figure 6 depicts a cost comparison between cost of the grid and grid consumption during a period of 24-hours. The initial waveform corresponds to the cost of the grid, whereas the subsequent waveform shows the utilisation of the grid. Initially, the utilisation of grid electricity is minimal due to the availability of power source from solar PV arrays and batteries. During that specific period, the cost of maintaining by the grid is relatively low. Subsequently, solar energy exhibits fluctuations because of alterations in meteorological conditions, necessitating the reliance on grid-supplied power. Consequently, the prices also exhibit variation. At the conclusion, there is a notable increase in power consumption accompanied by a corresponding rise in grid price.

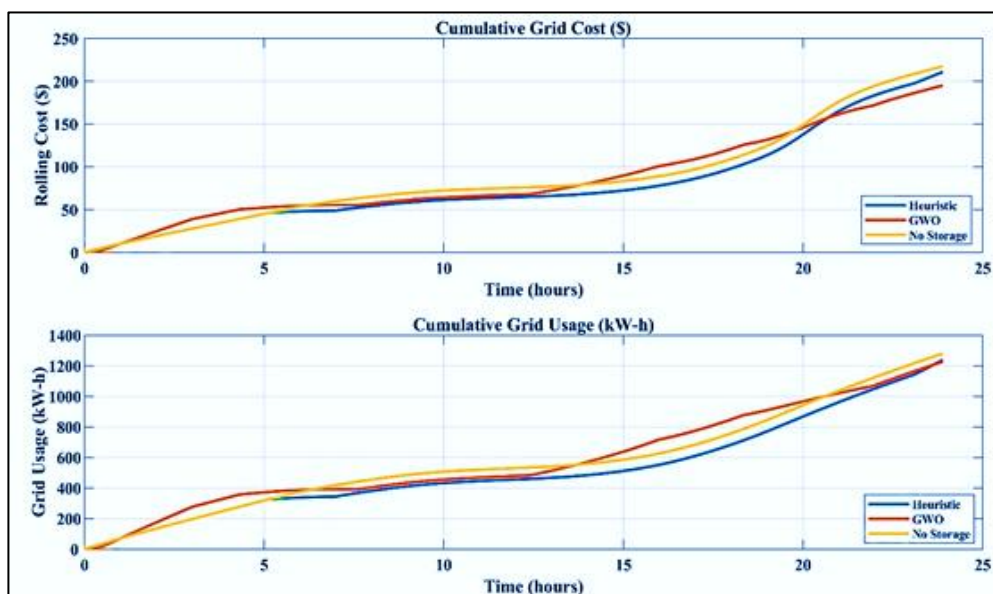


Figure 6: Comparison of grid electricity cost in case of Heuristic approach and HGWOCS approach.

Source: Authors, (2026).

Based on the data, it can be noted that the cumulative grid cost is lower when utilising the proposed method compared to the heuristic approach daily. The HGWOCS algorithm demonstrates superior performance compared to the heuristic technique.

VI. CONCLUSIONS

In this work a heuristic optimisation technique, HGWOCS proposed integrated EMS model for hybrid MG. The proposed system's primary goal is to reduce the amount that the MG needs to charge for its variable cost of electricity. Several authors have discussed this issue and proposed potential remedies after doing exhaustive literature reviews and gathering as much information as possible. The selection of these procedures was determined by the reliability and accessibility of resources inside the MG setting. Both the heuristic and the HGWOCS strategies are utilised in this investigation; however, the heuristic method is the primary focus. There is a discussion over a cost comparison between the heuristic approach and the HGWOCS algorithm. The findings suggested that the HGWOCS algorithm approach gave the costs (8.03%) that are optimal, which is a benefit of the strategy that is being proposed here. Because of the significant role it plays in maintaining the safe and cost-effective functioning of the load, EMS is an extremely important component.

VII. AUTHOR'S CONTRIBUTION

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Supervision: P Vijayapriya, Reshma Gopi R.

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