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Wind generator and storage system scheduling for customer benefit and battery life

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ABSTRACT

Due to increased fossil fuel use and fossil fuel limitations, the Indian energy industry is migrating to non-conventional energy resources such as solar power, wind production, and fuel cells. The unpredictability of non-conventional energy sources makes it difficult to balance an electrical system when they are incorporated, necessitating the incorporation of a storage device into the grid. In a microgrid system with wind turbine generation (WTG) and a battery energy storage system (BESS), the BESS may reserve energy during periods of surplus generation and release it to the grid during times of peak demand. The suggested technique establishes the state of charge (SOC) schedule for the BESS by employing an artificial rabbit optimisation (ARO) algorithm that minimises energy costs for customers. The state of health (SOH) of the energy storage is incorporated as an ageing coefficient, which causes the BESS to behave conservatively in order to retain its lifespan. Using a time of use (TOU) tariff, simulation results suggest a substantial possibility to boost the savings of consumers in a grid-connected micro-grid. The simulation findings indicate that by efficiently scheduling the BESS power management technique, the proposed method improves a number of distribution system efficacy.

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1. INTRODUCTION

In a distribution network, smart grids (SG) enable the creation of a sustainable, cost-effective, and secure energy supply. The effective utilization of renewable energy sources (RES) in the SG is essential as the consumer load demands grows [1] day-by-day. In recent years, this has resulted in a considerable rise in India's wind energy penetration in distribution system. The inconsistent power production of wind turbine generators present a challenge in the regulated market, necessitating the use of storage systems [2]. A battery energy storage system (BESS) offers high power and energy density, flexibility in site selection, and rapid response. Additionally, BESSs may charge and discharge electricity from and to the power grid, allowing them to serve as both energy consumers and suppliers [3], [4]. These characteristics enable BESSs to address the issue of RES instability. A BESS consists of several battery banks, each of which is equipped with its own battery management system (BMS) and a common system supervisory control that mandates the BESS's control strategy [5]. The control strategy identifies the operational BESS banks. Energy and power applications are the two types of BESS applications "energy applications and power applications" [6].

A few research works have focused on the optimal placement of the BESS and the penetration capability of wind turbine generation (WTG), in addition to their respective processes and features [7]. The scheduling of RESs and tie lines, utilizes a novel stochastic multi-area unit commitment (MAUC) architecture [8]. To reduce the number of scenarios and improve the resilience of unit commitment (UC) schemes, a worst-case based scenario selection method (SSM) based on peak and valley shaving of the system, ramping-up/down rates of net load, and the dispersion of uncertainty factors is presented [9]–[11]. Zeng *et al.* [12] examines the probable relationships between uncertainties in RES while implementing a price-based demand response program. By modelling the unpredictability of renewable power output with probabilistic constraints, Chen *et al.* [13] have proposed a realistic multi-objective optimal scheduling model of grid-connected microgrids based on chance-constrained programming (CCP) for minimising operating costs and improving the user experience. In addition, from the perspective of demand-side management, a user satisfaction metric was developed [14], [15].

Multiple methods have been utilised in research to solve difficult power systems optimisation problems [16]. Bio-inspired algorithms based on swarms have been developed to address rapid convergence, enormous search space, and multi-objective optimization functions [17]. Nevertheless, there is no one optimisation algorithm capable of overcoming all obstacles. The new bio-inspired optimizers are always being developed, given that so many currently exist, reason being found in the no free lunch (NFL) theorem [18]. NFL theorem motivates more efficient bio-inspired optimizers, which is the impetus for this study. Moreover, the bulk of optimizers include several control options [19]. This article presents a unique algorithm named artificial rabbit optimization (ARO) that is inspired by the survival strategies of rabbits in the wild and their detour foraging and random hiding behavior [20]. ARO is extremely competitive in the resolution of challenging engineering optimization issues.

Even though there have been several studies of BESS paired with wind for grid level peak load regulation [21], they have focused on small scale BESS (MW-range) and covered a proportion of a grid's total wind output or implemented wind-BESS systems mainly to maximise financial metrics [22]. The scope of research has not been limited to WTG-BESS scheduling for storage health improvement. Such research is necessary to comprehend the techno-economic-environmental potential of WTG-BESS micro-grid operating issues and possible profitability while integrating with the national grid. The key contributions to this work are: i) power flow management models for grid-connected WTG systems with storage are developed, with an emphasis on effective charging and discharging of BESS scheduling to reduce consumer energy expenditures and improve energy storage simultaneously considering BESS ageing based on state of health (SOH); ii) a novel ARO technique is used to solve a highly nonlinear power system problem; and iii) sensitivity analysis was performed to examine the impact of various variables on wind generation uncertainties, such as grid price, grid power, and feed-in-tariff (FIT), on a specific summer and winter day.

The remainder of the research is organised as follows. Sections 2 and 3 are dedicated to system modelling and problem formulation methodologies, respectively. In section 4, the ARO algorithm is described in depth. Section 5 examines the results of the simulation and their interpretation, while section 6 concludes the study.

2. MODELLING OF SYSTEM

The system represented by Figure 1, consists of a grid tied micro-grid. In a microgrid subsystem, a residential load is taken into account alongside a WTG and BESS linked to the same bus. The microgrid's bidirectional converter regulates power flows both inside the microgrid as well as to the grid. The battery converter works as a charge controller throughout the BESS's charging procedure.

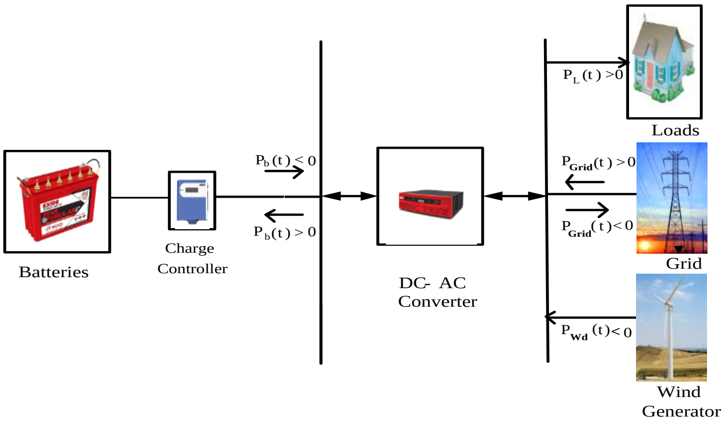

Figure 1. Radial distribution system with WTG and BESS system

2.1. Modelling of WTG

Wind generator power output is determined using the sweep area of the rotor, air density, and position of wind generators, successfully converting wind power to electrical power. The WTG specifications are as per Table 1. The mathematical expression of output power from WTG [23] can be expressed in (1):

$$P_{WTG}(t) = \begin{cases} 0 & v(t) < v_{cin} \; or \; v(t) > v_{cout} \\ \frac{1}{2}\rho \, A_s \, \eta_{WTG} \, \eta_{conve} \, N_{WTG} & v_{cin} \le v(t) \le v_{rd} \\ P_{WTG}^{max} \, N_{WTG} & v_{rd} \le v(t) \le v_{cout} \end{cases} \tag{1}$$

Wind speed data [24] for two seasons is shown in Figure 2.

Table 1. WTG and BESS specifications

WTG parameters		BESS parameters	
Name of parameter	Specification	Name of parameter	Specification
Number of wind turbines	1	Minimum state of charge (SOC)	20%
Swept area of wind turbine	41.1 m^2	Maximum SOC	90%
Pressure	1 atm	Ageing coefficient	0.00031
Wind turbine efficiency	30%	Step in SOC	0.01
Converter efficiency	95%	Minimum change in SOC	-70%
Maximum output power	1.5 kW	Maximum change in SOC	70%
Cut-in speed	2 m/sec	Starting value of SOC	50%
Cut-out speed	12 m/sec	Battery initial cost	9125 Rs/kWhr

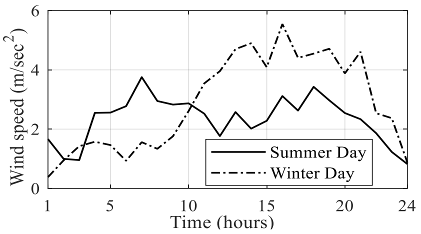

Figure 2. Hourly wind speed in a day

2.2. Modelling of BESS

A battery bank, charge controller and a power converter circuit constitute the BESS. In series arrangement, four numbers of 6 V lead acid batteries are employed. The $BESS$ has a 400 Ah energy capacity, and a 24 V power converter regulates the power flow in the system. The power $P_{bat}(t)$ at instant t can be calculated as in (2):

$$P_{bat}(t) = V_{bat}(t) \, I_{bat}(t) \tag{2}$$

$$V_{bat}(t) = [6.75 + 1.2 \times SOC(t)] N_b(t) \quad I_b > 0 \tag{3}$$

$$V_{bat}(t) = \left[6.295 - 1.02 \times \left(1 - SOC(t)\right)\right] N_b(t) \quad I_b \le 0 \tag{4}$$

Where, $V_{bat}(t)$ is the voltage of battery, $N_b(t) = 4$ represents the number of batteries connected in series and SOC is represented as $SOC(t)$. The voltage of the $BESS$ during charging [25] is as in (3) and during discharging is as in (4). The SOH of $BESS$ at instant t is defined as in (5):

$$SOH(t) = \frac{C_r(t)}{C_{r,nom}\,(t)} \tag{5}$$

Where, $C_{r,nom}\,(t)$ represents the nominal capacity of the battery. The $BESS$ performance degrades with every discharge. There is a loss of capacity of $BESS$, which is assumed to be a linear function of depth of discharge. The lead acid battery specifications [24] are illustrated in Table 1.

2.3. Modelling of load

In Bhubaneswar, the average power requirement for this load considered here per day is 0.9825 kW during winter day and 1.2223 kW during summer day. The maximum and minimum load demands during winter day are 1.50135 kW and 0.7079 kW, and during summer day are 1.60425 kW and 0.77495 kW, respectively. The hourly profile of load [26] for two different seasons is shown in Figure 3.

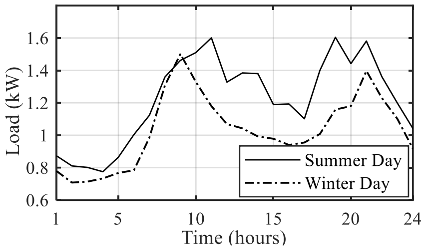

Figure 3. Hourly residential load profile in a day

2.4. Modelling of grid

The energy management system determines how much energy must be generated to satisfy demand and reserve energy in the BESS. The maximum power transfer to grid is P_{Grid}^{max} =1.4 kW, beyond which the applicable grid penalty factor (GPF) is considered to be Rs 10/kW. Two types of pricing schemes are considered in the scope of this work. The Tier 1 or fixed-cost pricing scheme assumes the FIT and electricity grid price (EGP) at Rs 4/kWhr flat rate. In Tier 2 pricing of time of use (TOU) pricing, during summer season FIT is at Rs 6/kWhr during peak hours and Rs 1/kWhr during off-peak hours and EGP is at Rs 3/kWhr during peak hours and Rs 2/kWhr during off-peak hours. In Tier 2 pricing of TOU pricing, during winter season FIT is at Rs 5/kWhr during peak hours and Rs 1/kWhr during off-peak hours and EGP is at Rs 3/kWhr during peak hours and Rs 2/kWhr during off-peak hours. The peak hours during summer season are $11\ hr \leq t \leq 22\ hr$ and during winter are $7\ hr \leq t \leq 10\ hr$ and $17\ hr \leq t \leq 20\ hr$, respectively.

3. PROBLEM FORMULATION

The objective is to optimally schedule the SOC of BESS in a WTG-BESS based grid connected micro-grid simultaneously considering consumer cash flow benefit. The load flow equations are solved considering the minimum and maximum limits of SOC and preserving the power balance of the system. The formulation of objective function also considers state of health of storage and ageing cost. The detailed formulation is mathematically represented in subsequent section.

3.1. Objective function

The objective is to minimise cash flow for a day and providing maximum benefits to consumers. As a result, the mathematical formulation can be expressed as combining two primary factors the cash received and disbursed, respectively, as in (6):

$$F_{obj} = \sum_{t=t_0}^{T} \left(C_R(t) + C_P(t) \right) \tag{6}$$

The cash received and disbursed are evaluated as in (7) and (8):

$$C_P(\Delta t) = P_{Grid}(\Delta t)\ EGP\ \Delta t + BrC(\Delta t) \quad P_{Grid}(\Delta t) \geq 0 \tag{7}$$

$$C_R(\Delta t) = P_{Grid}(\Delta t)\ FIT\ \Delta t \quad P_{Grid}(\Delta t) < 0 \tag{8}$$

The BESS ageing cost BrC, can be evaluated as in (9):

$$BrC(t) = \frac{BiC(-\Delta SOH(t))}{1-SOH^{min}} \tag{9}$$

3.2. System constraints

The system works within the confines of the following limits on equality and inequity.

$$P_{Grid}(t) = P_{load}(t) - P_{WTG}(t) \mp P_{bat}(t) \tag{10}$$

$$SOC^{min} \leq SOC(t) \leq SOC^{max} \tag{11}$$

$$P_{bat}^{min} \leq P_{bat}(t) \leq P_{bat}^{max} \tag{12}$$

$$SOH(t) \geq SOH^{min} \tag{13}$$

$$P_{Grid}(t) \ \leq \ P_{Grid}^{max} \tag{14}$$

The constraints specify the laws of power conservation, protects the BESS from health degradation owing to excessive charging and high depth of battery depletion, and limits the battery's degradation.

4. ARTIFICIAL RABBITS OPTIMISATION ALGORITHM

ARO is a novel bio-inspired algorithm that takes cues from rabbits' strategies for survival to tackle the challenging issue of nonlinear optimization [16]. The ARO algorithm was developed with inspiration from survival strategies including foraging and hiding in unexpected places. Such survival strategies are mathematically illustrated in this study.

4.1. Detour foraging

Rabbits don't bother with nearby food sources while they're foraging. It's called "detour foraging" because they never eat grass from their own yards, but rather ingest it at random from other areas. It is assumed that each rabit in the colony has its own area, having food and d burrows, and that the rabbits graze at random between themselves. The fact is that rabbits will hunt around in the ground to find enough to eat. ARO's detour foraging behaviour shows that each search individual would rather update its position in relation to a different, randomly chosen search individual in the swarm in order to create a diversion.

4.2. Random hiding

A rabbit will create a complex network of tunnels around its den to hide it from potential predators. To decrease its chances of getting eaten, a rabbit in ARO always constructs d burrows along the search space at each iteration and chooses a tunnel at random for hiding. The burrows are first created in a larger area around a rabbit. As the number of iterations increases, this neighbourhood is also diminished.

4.3. Energy shrinks

In ARO, rabbits usually do detour foraging during the early phase of iterations, but they commonly practise random hiding during the final phase. This search mechanism is powered by the energy of a rabbit, which will diminish progressively over time. Consequently, an energy component is created to simulate the transition. The high energy factor value indicates that the individual has adequate energy and physical power for detour foraging. In contrast, the low value of the energy component suggests that a rabbit is less physically active, and hence requires random concealment. The flowchart is shown in Figure 4. Table 2 compares the performance characteristics of particle swarm optimisation (PSO), differential evolution (DE), gravitational search algorithm (GSA), teaching-learning-based optimisation (TLBO) method, and ARO. As seen in the table, ARO yields superior outcomes compared to other optimization techniques.

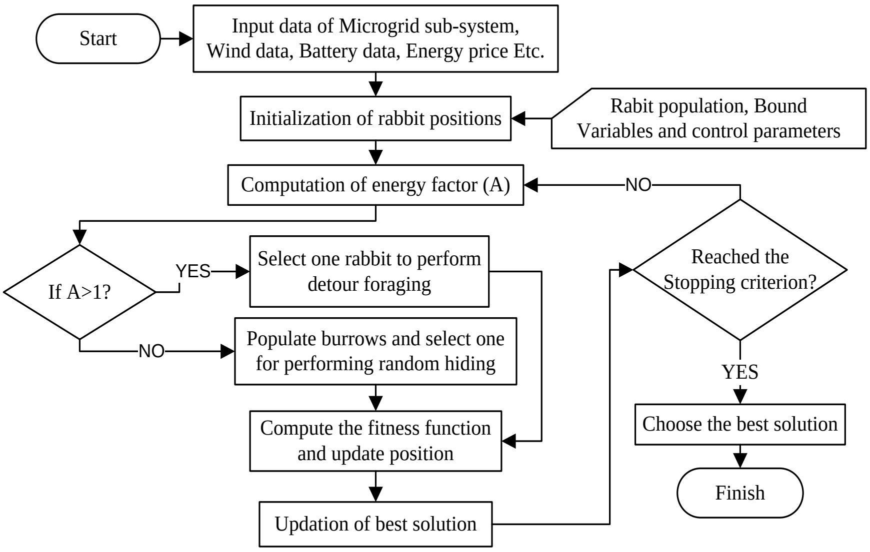

Figure 4. Flowchart of ARO algorithm

Table 2. Results of performance metric comparison

Function	Parameter	PSO	DE	GSA	TLBO	ARO
$\sum_{i=1}^{n} x_i^2$	Mean	2.15E−04	3.64E−14	2.19E−17	3.64E−87	1.82E−124
	Std	2.25E−04	6.06E−14	6.38E−18	1.67E−88	6.63E−124
	Best	2.99E−06	1.26E−15	1.15E−17	1.53E−89	2.29E−142
$\sum_{i=1}^{n} \left(\sum_{j=1}^{i} x_j\right)^2$	Mean	2.84E+03	5.69E+00	2.22E+02	5.65E−17	1.24E−95
	Std	1.34E+03	3.91E+00	7.07E+01	2.28E−17	6.78E−94
	Best	1.14E+03	9.26E−01	8.53E+01	4.02E−19	7.00E−115
$\sum_{i=1}^{n-1} (100(x_{i+1} - x_i)^2) + (x_i - 1)^2$	Mean	9.47E+01	3.00E+01	2.67E+01	2.14E+01	4.55E−03
	Std	7.90E+01	1.76E+01	2.67E+00	1.11E+00	5.12E−03
	Best	7.62E+00	4.01E+00	2.57E+01	1.76E+01	2.41E−04
$\sum_{i=1}^{n} (ix_i^4 + random\ [0,1])$	Mean	5.64E−02	2.15E−01	1.91E−02	5.62E−04	2.51E−04
	Std	2.03E−02	7.24E−02	6.87E−03	1.72E−04	1.07E−04
	Best	1.92E−02	1.16E−01	7.73E−03	1.47E−04	6.28E−05

5. SIMULATION RESULTS AND DISCUSSION

The system consists of one wind turbine generator having a maximum power of 1.4 kW connected in series with the grid-connected microgrid having a battery bank and residential load. The optimal power flow management is based on the load profiles and wind speed datasets for the summer and winter seasons. The simulation for each season has been executed in MATLAB for the Tier 1 price (fixed) and Tier 2 price (TOU) schemes. In Figures 5 and 6, the BESS charging, discharging, load and grid power sharing are shown by positive and negative, respectively. Figure 5 describes the power contribution strategy for the fixed price (Tier 1) scenario on a typical summer day. The wind speed on a typical summer day is lower and the WTG power output is within 0.5 kW of its maximum in a day. The cash flow is Rs 102.68/day, which the consumer is required to pay for the day. Figure 6 describes the power contribution strategy for the fixed price (Tier 1) scenario on a typical winter day. The wind speed on a typical summer day is higher and the WTG power output is within 1.2 kW of its maximum in a day. The cash flow is Rs 64.24/day.

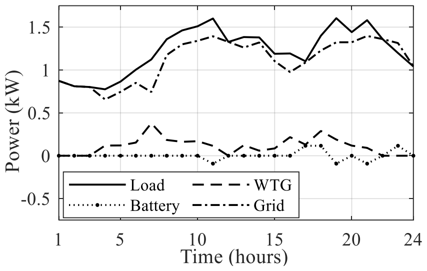

Figure 5. Power sharing in a summer day (Tier 1)

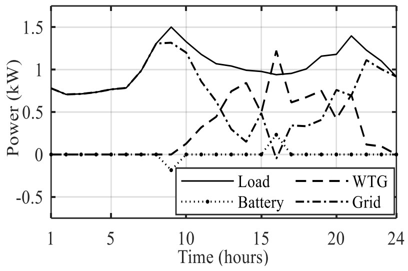

Figure 6. Power sharing in a winter day (Tier 1)

Figure 7 depicts the battery's SOC schedule. Figure 8 depicts the battery's current status indicating charging and discharging pattern based on energy management for the Tier 1 pricing scheme. Figure 9 represents the voltage of BESS during a typical summer day and winter day.

In Figure 10, the power contribution strategy for the TOU price (Tier 2) scenario on a typical summer day is shown. The cash flow is Rs 824.32/day, which the consumer is required to pay for the day. Figure 11 describes the power contribution strategy for the fixed price (Tier 2) scenario on a typical winter day. The cash flow is Rs 32.17/day. In both cases, the effective battery management strategy helped reduce the peak load demand from the grid and improve the SOH of the battery system.

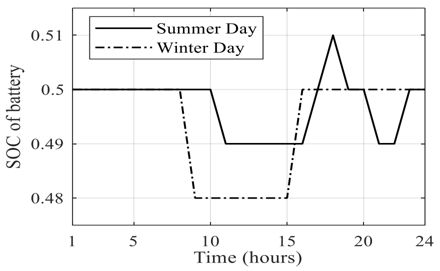

Figure 7. SOC schedule of BESS in a day (Tier 1)

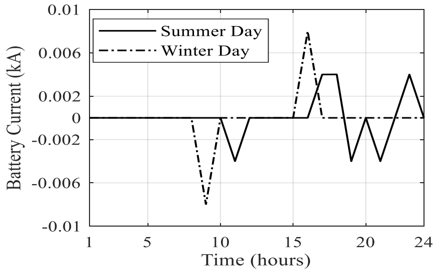

Figure 8. Current of the BESS in a day (Tier 1)

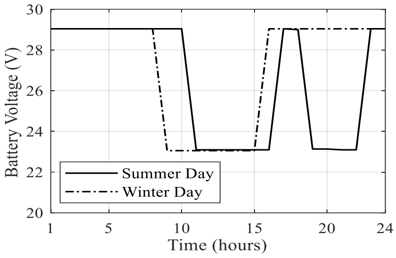

Figure 9. Voltage of the BESS in a day (Tier 1)

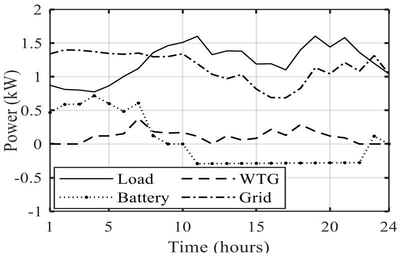

Figure 10. Power sharing in a summer day (Tier 2)

Figure 12 illustrates the state of charge after one cycle, which changes between the predefined lower and higher limits throughout a complete dispatch cycle. Figure 13 shows the current status of the BESS. Figure 14 shows the voltage profile of BESS for the Tier 2 pricing scheme.

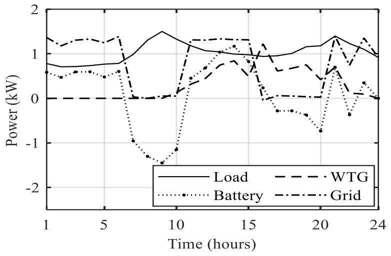

Figure 11. Power sharing in a winter day (Tier 2)

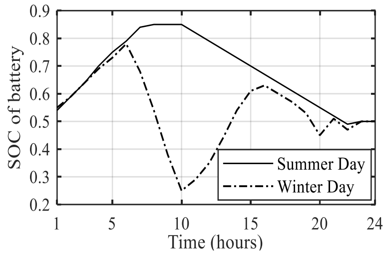

Figure 12. SOC schedule of BESS in a day (Tier 2)

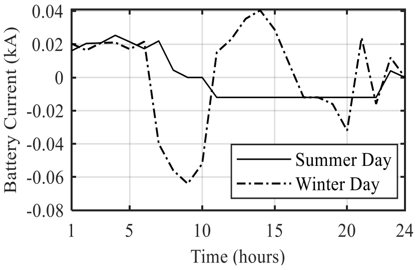

Figure 13. Current of the BESS in a day (Tier 2)

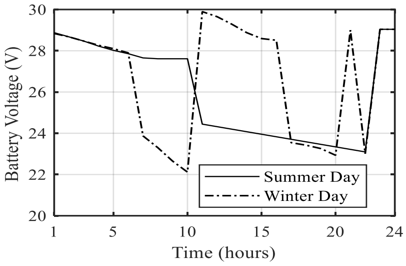

Figure 14. Voltage of the BESS in a day (Tier 2)

6. CONCLUSION

This research provides a novel BESS management technique that maximises the battery's SOH while minimising customer cash flows in grid-connected microgrids. The suggested system is optimised using the ARO algorithm. The integration of a WTG-BESS unit with a grid provides the benefits of demand-side management. Using the recommended strategy is known to enhance the cost savings. The proposed system takes into account the FIT and EGP tariffs in fixed and dynamic pricing scenarios and determines SOC during the summer and winter months. The factors impacting WTG power generation are also investigated, and the simulation is conducted using wind speed and residential load data from Bhubaneswar, India, collected in real time. The results highlight the technical and economic advantages of combining WTG with BESS in India while considering the SOH of the storage.

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