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Load Management and Optimal Sizing of Special-Purpose Microgrids Using Two Stage PSO-Fuzzy Based Hybrid Approach

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Abstract: The sizing of microgrids depends on the type of load and its operational hours. The significance of understanding the load operational characteristics in special purpose islanded microgrids is much needed for economic system sizing. The load operation of special-purpose microgrids often consumes high power for a short duration and remains idle most of the time, thus reducing the load factor. The inclusion of such loads in microgrid sizing causes huge capital costs making islanded microgrids an unfeasible solution. The islanded microgrid under study is an agricultural microgrid in a village having a small Crab Processing Plant (CPP) and a Domestic Sector (DS). The CPP constitutes the major power consumption. The community has a unique load consumption trend that is dependent on the highly uncertain parameter of availability of the crabs. Interestingly, crab availability is an independent parameter and cannot be accurately scheduled. The existing system sizing of the microgrid is performed based on the conventional methods that consider the CPP for full-day operation. However, the microgrid sources, especially the storage system may be reflected as oversized if the crab processing plants do not operate for several days due to the uncertain behavior of CPP causing enormous power wastage. In this paper, an integrated fixed and operational mode strategy for uncertain heavy loads is formulated. The proposed algorithm is based on the optimal sizing methodology aided by the load scheduling control strategy. The Particle Swarm Optimization technique is used for the optimal sizing integrated with the fuzzy logic controller to manage the available load. The membership functions are available excess power and the state of the charge of storage that defines the operational conditions for CPP. Based on input membership functions, the fuzzy controller decides on power dispatch in DS or CPP, keeping considerable SoC available for night hours. The simulation result shows that the time-dependent fuzzy controller approach manages to provide power to both sectors under optimal sizing while reducing the overall cost by 24% less than the existing microgrid.

Keywords: load factor; special-purpose microgrid; economic dispatch; fuzzy logic; load management

1. Background

The special-purpose loads have unique consumption patterns and operation trends. Often, a heavy load is consumed for a very small period which significantly reduces the load factor [1,2]. On the other hand, to cater to the peak demand, system sizing increases significantly which increases the overall project cost [2]. To reduce the peak demand, scheduling can increase the load factor and reduce the overall system sizing that eventually reducing the project cost [1,2]. Researchers are addressing the economic operation of microgrids in two ways; one is fixed, which is to size the storage and solar PV systems such that during unavailability of power, the battery storage may long last ensuring reliability. The days of autonomy play an important role in the reliability of fixed systems, however, it increases the overall cost. The second is related to the operational mode of microgrids which is to manage the generation and load in real-time for optimal power dispatch and implementation of demand response schemes as per the day ahead scheduling, thus reducing the system sizing and overall project cost. It is worth mentioning here that in both fixed and real-time operational management modes, load trends are known and scheduling/sizing of loads is based on the available trends. The prior knowledge of load operational characteristics helps in devising the fixed or real-time modes of operation that helps in reducing the system cost. In the forthcoming section, a detailed literature review of the energy management schemes and storage sizing methodologies so far studied are discussed in detail.

2. Introduction

Special purpose islanded microgrids are designed for the unconventional loads serving for dedicated operation [1]. These unconventional loads have unique consumption patterns as per the requirements and objectives [2]. Military [3], small-scale industrial [4] and agricultural loads serving the irrigation systems [5] are examples of special-purpose microgrids. On the other hand, to cater to the peak demand, system sizing increases significantly which increases the overall project cost [2]. However, for scheduling the load, a comprehensive study of its operational characteristics is very important. Peak loads for a very short period are troublesome and optimization approaches have been implemented by the researchers to address the peak demands and economical system sizing. However, the load information in most of the research papers is well known which helps in better peak sheaving, managing the power and load, and implementing optimal dispatch.

2.1. Energy Management Systems

This section discusses some of the recent energy management techniques being employed. The authors in [6] have suggested a microgrid that is controlled by master-slave topology through an optimization algorithm employing the convex cost function for load demand constraint. In master-slave control, this microgrid is employed with smart meters to transfer information about the load, the cost involved, and the power generated by the RES to the main communication system. The optimized control is achieved with utility maximization, selecting the industrial load as the one with the highest priority. However, the system considerations in [6] gave generic suggestions for generalized formulations of any typical RES-based microgrid. Most of these researchers have focused on the control techniques for load shedding of low-priority loads to manage the energy demands for high-priority loads. Load management has also been suggested to save the storage systems from discharging to vulnerable conditions. Moreover, a group of authors [7] devised the fuzzy logic-based control methodology for implementing the load shedding in an isolated microgrid with an assumption of the communication system's unavailability. Using a defined set of variables, buses determine which type of load to disconnect or reconnect locally. In contemporary literature, microgrids are also employed as a secondary source of energy to fulfill the electric needs during off-hours within the main grid. The authors in [8] have put forward a microgrid design to provide an electrical backup to the priority loads when the primary utility fails. The requirement of load and energy generation is monitored during the operation of this grid to provide efficient load management using a centralized automation controller.

The researchers have worked on energy management using forecasting techniques to manage the microgrids working as secondary energy sources. In [9], authors have utilized the Neuro-Fuzzy model to determine the mode of operation of a microgrid to attain suitable load management. The major issue in this scenario is the uncertainty about the main grid off-hours, which is somehow resolved by neuro-fuzzy-based forecasting. Other researchers [10] proposed a nonlinear programming-based optimization algorithm for optimizing the economic operation of domestic load containing a microgrid framework. The aforementioned algorithm forecasts the generated power and the day-ahead demand of load to produce maximum revenue after the provision of power to the priority load. The area of installation for the RES-based microgrid also plays a vital role in power generation. Some researchers [11] analyzed the feasibility of the RES installation area with the help of mathematical modeling using RETScreen software. This analysis includes both wind and solar energy for the improved response of the system in terms of economy and load management.

The technique of power balancing between the available energy storage systems is also employed to prevent the burden on a particular storage system. Other authors [12] proposed that the drawbacks of traditional systems for energy management are compensated by power balancing. Three different cases are discussed for the load demand and generated energy. These microgrids deal with only the residential and commercial loads supplied by a combination of different renewable and non-conventional energy production techniques. The authors in [13] considered four different modes of DC microgrid operation for the automatic power balancing and the voltage regulator. To control the power balance between available energy storage units, a Fuzzy Inference System (FIS) is proposed for the adjustment of virtual resistance with the help of State of Charge (SoC) measurement. In this case, while the renewable energy system is working in droop controller mode instead of MPPT, the voltage fluctuations are reduced with the help of reference voltage adjustment in an iterative manner using FIS with an Integrator. By introducing a priority list of connected loads and a different SoC threshold for load recovery and load shedding, the power storage units avoid deep discharging. The smooth operation of DC microgrid controls is attained by using the electrical parameters in this grid.

Microgrids using biogas along with solar, and wind energy systems are commonly known as hybrid microgrids [14]. The aforementioned microgrids are usually employed in villages to utilize biomass in a green and environment-friendly manner with the production of electricity. The authors in [14] utilized an isolated hybrid microgrid for time-varying load demands using an optimization technique based on the non-cooperative game theory. In the above literature review sections, it is observed that no technique addresses the problem of highly uncertain loads discussed in this research article. Either optimal techniques have been used to size the storage while considering the overall hours of anticipated operation or uses energy management schemes that deal with the generation and load management and do not account for such heavy unpredictable loads. On the other hand, forecasting such loads has not been precisely performed so far.

2.2. Storage Sizing Schemes

Appropriate microgrid sizing is referred to as above, a very important model for justifiable capital and operational cost. The overall system sizing of the model is dependent on the identified load trends of the community [6–15]. The load forecasting options are also available using wide parameters or indicators that help in accurate forecasting [16–23]. State-of-the-art communication modes are also available, such as the internet, for live weather forecasts, etc., that help manage the demand as per requirements [23]. Table 1 shows the optimization schemes and algorithms being employed for optimal battery storage sizing. In [20], an optimal sizing algorithm has been developed using PSO and Genetic Algorithms. However, for reliable operation, the diesel generator is used as a backup source.

In comparison to our case, the diesel generator could not be an option due to the higher cost of fuel which is unaffordable for the consumers. In [24], an optimal sizing problem for PV panels, inverters, and battery storage has been addressed for mathematical models of the sources, cost functions, and subjective constraints with known load demand using which optimization is performed. The optimal sizing of a system based on PV and batteries has been presented considering the system modeling, battery analysis, and objective function in [25]. However, known load demand for the entire year is used for optimization. A Mixed Integer Linear Programming (MILP)-based optimization technique has been applied for the optimal sizing of hybrid PV-Battery-based micro-grid while considering the different battery options to reduce the electricity bill in [26] where the number of outage events/days has been predicted providing ease to optimize the grid with known loads and the number of events with outages. In [27], an efficient sizing optimization algorithm has been applied on a hybrid battery-based micro-grid based to effectively choose PV, wind, batteries, and DG sets for the reduction in operation cost whereas an annual load curve based on the historical data is used for the optimization. The authors in [28] focus on controlling the frequency deviation using battery storage under different scenarios of load loss in the system. The grey wolf optimization approach is used to optimize the size of batteries for resilient operation and frequency control in an islanded microgrid. A fuzzy decision-based algorithm has been modeled in [29] to perform sizing of a battery-based hybrid micro-grid based on PV, Wind, and DG Sets to reduce the operation cost and better economic experience. A certain load has been considered in the overall optimization problem that has a fixed value upon which the optimization problem is assessed. A Multi-Objective Optimization (MOO) approach has been developed in [30] for optimal sizing of battery capacity, converters, and PV system in a micro-grid to reduce the capital cost and payback period of the system components. A figure of merits has been considered for the optimal sizing of the system. This figure of merits includes the Energy Autonomy factor and power autonomy factor. In both the factors known or fixed load has been considered for optimization. In [31], a time series-oriented approach has been applied using the Genetic Algorithm (GA) which regulates the sizing of the PV system and battery storage by adjusting the discharging and charging cycles of the battery for the renewable source. The genetic algorithm is used to find the optimal battery storage in which the battery size is also determined in which the fitness function is the reliability factor. Authors in [32] proposed technique to determine the sizing of an integrated hybrid micro-grid by considering three design parameters, i.e., PV modules, wind turbines, and battery storage capacity to minimize the cost of energy. Battery cost optimization is performed while using load as a fixed known parameter. In [33], A Unconstrained Multivariate Function (UMF) based optimization technique is applied to the proposed model to select the optimal size of the battery and PV system to reduce the annual net payment (ANP Optimal sizing of battery storage-based PV systems has been performed in [34] using MILP under multiple terrify conditions to reduce the peak grid consumption. One residential with one commercial load is utilized to compare optimization with Time Of Use (TOU) as well as demand tariff models whereas [35,36] have used the optimiazation techqniues to reduce the cost of the microgrid having hybrid resources. In [37], a multi-objective optimization approach has been used to model the suitable size of the battery-PV system for techno-economic analysis of various kinds of batteries. However, the mathematical model for battery storage is given in which the anatomy days can be changed and considered as the reliability factor. In [38], a K-means clustering algorithm for the sizing of mini-grids, PV/gensets, and batteries along with the forecasting of electric loads is proposed. A village load is predicted using machine learning algorithms and an optimization algorithm to design a mini-grid for this village load is developed. The Particle Swarm Optimization technique is used in [39] for the suitable size of PV/wind/battery for effective LCC in presence of EVs. This research evaluates the resources as well as demand patterns of Chamba Chaurah community loads. An optimal sizing problem for PV/battery in an off-grid has been addressed by linear programming subject to objective functions for the reduction in operational cost [40]. In [41], A stochastic optimization technique has been implemented for appropriate sizing of distributed energy resources, i.e., PV/battery/wind to maximize the economic benefits for consumers. The resource planning study is given for a U.S. military base as a load. In [42], a stepped leader propagational technique has been applied to achieve optimal sizing for standalone PV/wind/diesel/battery-based systems to decrease LCC and COE. In [43], Mixed integer liner programming MILP has been used for the optimal sizing of a micro-grid based on PV/wind/battery systems for optimized demand response and reduced COE, 1 MW load of a remote island near Okinawa.

Table 1. Optimization methodologies are compared for different parameters here.

Ref.	Year	Optimization Approach	Methodology	Load Parameter	Reliability Factors
[32]	2019	SSO	An SSO has been proposed to determine the sizing of an integrated hybrid micro-grid by considering three design parameters, i.e., PV modules, wind turbines, and battery storage capacity to minimize the cost of energy.	Annual load of the city in Saudi Arabia has been taken in study. Battery cost optimization is performed while using load as a fixed known parameter.	Loss of power supply probability (LPSP) is considered during the event of less generation compared to the running load
[33]	2019	UMF	A UMF-based optimization technique is applied to the proposed model to select the optimal size of the battery and PV system to reduce the annual net payment (ANP).	The optimum size of a BESS for any typical NZE residential load with a rooftop solar PV system to reduce yearly net energy and battery costs	SOC level of battery taken into consideration as the reliability factor in this research.
[35]	2020	MDPSO	A multi-dimensional optimization approach has been used for optimal sizing of PV and wind with a battery storage system by reducing the objective functions of cost, dump power, and reliability.	Residential dump Load of a Stand-Alone PV-WT-BT hybrid system configuration is considered.	The planning horizon consists of the total $P = H * P'$. Here H is the week, month, year. The P' is the minutes, hours, and seconds.
[36]	2020	PSO and BBO	An optimal sizing problem has been addressed using PSO and BBO algorithm for a hybrid micro-gird based on a PV system with battery storage to reduce the cost and environmental effects for load shifting.		The Sizing optimization of batteries is performed with the help of HRES.

MILP: Mixed-Integral Linear Programming, **UMF:** Unconstrained Multivariate Function, **PSO:** Particle Swarm Optimization, **MDPSO:** Multi-dimensional PSO, **BBO:** Bio-geographic Based Optimizations, **IEM:** Improved Electromagnetic, **LCC:** Low Cycle Cost, **EV:** Electric Vehicle, **LSA:** Lightning Search Algorithm, **COE:** Cost of energy.

It is evident from the literature review that the unknown load trends or abrupt utilization of heavy loads have not been addressed in the literature review. Table 1 comprehensively covers the latest tools and techniques being used in for optimal sizing and operation of the microgrids. This research study is aimed to optimally size a microgrid having special load operational characteristics. The uncertainty of the low load factor is addressed while using a hybrid approach. The first step is fixed sizing which is performed based on the real-time power consumption patterns of the load, thus adding minimum days of autonomy for the CPP. The second step is intelligent scheduling of uncertain loads using the fuzzy logic controller with a defined set of membership functions.

3. Problem Statement

A special-purpose microgrid situated in a village in Pakistan is studied. The installed microgrid runs the crab processing plant and domestic load. The CPP has a very short duration of operation with no specific schedule available. The CPP runs as soon as enough crabs are caught at the site. Crab availability is the only factor on which CPP is scheduled which certainly cannot be predicted. To ensure the operation of CPP at any instant in time, the microgrid is sized at the higher end. A significant amount of power went useless when CPP does not operate, or it just operates for a very limited time thus reducing the load factor and developing an economically unviable system.

Algorithm Novelty and Contribution

The designed algorithm aims to reduce the overall system cost by reducing the sizing of the storage and developing a control algorithm to address the scheduling of CPP while having no prior information available regarding the scheduled CPP operation. A unique system sizing is performed using PSO. In the proposed sizing method, the conventional approach of considering the backups such as diesel generators and days of autonomy (in case of battery sizing) are not considered to cater to the small time peaks of heavy loads. Instead, the reliability is addressed while using an intelligent load scheduling controller based on fuzzy logic. In the first step, the system sizing is performed and in the second step, reliability is ensured by intelligent operation and scheduling of heavy load based on the available power and SoC. The hybrid approach helps in reducing the storage sizing and ensures reliability while intelligently scheduling the heavy loads to reduce the small time peaks. The following contributions are made in this paper.

1. In this research, a hybrid approach to sizing the microgrid is developed. The hybrid approach covers the reliability factor in microgrid operation using the control scheme instead of enhancing the battery sizing, days of autonomy and other reliability factors such as enhancing solar PV power and main grid support.
2. An integrated hybrid fixed and operational mode-based algorithm design to tackle the unscheduled heavy load operation in islanded microgrids with intermittent renewable energy resources.
3. Design of optimal sizing algorithm using Particle Swarm Optimization to reduce the overall system sizing cost.
4. Design of Intelligent scheduling of uncertain loads using fuzzy logic to ensure real-time reliability avoiding the small peaks during low power availability.
5. Integration, validation, and testing of the PSO sizing algorithm with Fuzzy Intelligent Scheduling.
6. Economic analysis of the proposed system compared with the actual installed system.

4. Methodology

The methodology is divided into two parts. The first part is related to the optimal system sizing and the second part is related to the intelligent control of the CPP load with the charging and discharging of batteries. To assess the current microgrid installed, at first, the existing microgrid was technically and economically analyzed in detail.

4.1. Analysis of Existing Open System Design

The existing islanded microgrid installed in a village in Pakistan is shown in Figure 1. The sizing methodology of battery storage and solar PV is based on the conventional methods being used where the days of autonomy and load are considered for reliable operation. In the current system, CPP and DS operate for the complete day where storage supports the load during the night hours for DS. The system is designed in a way that it not only supports the CPP for the complete day but also charges the battery storage at the same time for night hours to support DS. Moreover, the day of autonomy for the system is given as 5 days. This makes an overall system operate towards the high system sizing side.

The currently designed system is highly oversized and uneconomical, which makes the overall return on investment higher and the overall capital cost is also increased.

Figure 1. Actual installed microgrid.

4.2. Proposed System

The proposed system is based on optimal sizing aided by the flexible fuzzy load controller. The flow diagram of fixed and operational modes is shown in Figure 2. Figure 3 shows the block diagram of the proposed system. The load flexibility controller mainly schedules the CPP based on the available storage and solar PV conditions. The proposed algorithm has two modes of operation. The fixed mode of operation is based on the PSO sizing while the operational mode is based on the fuzzy logic controller. The fixed and operational modes are discussed in the sections below.

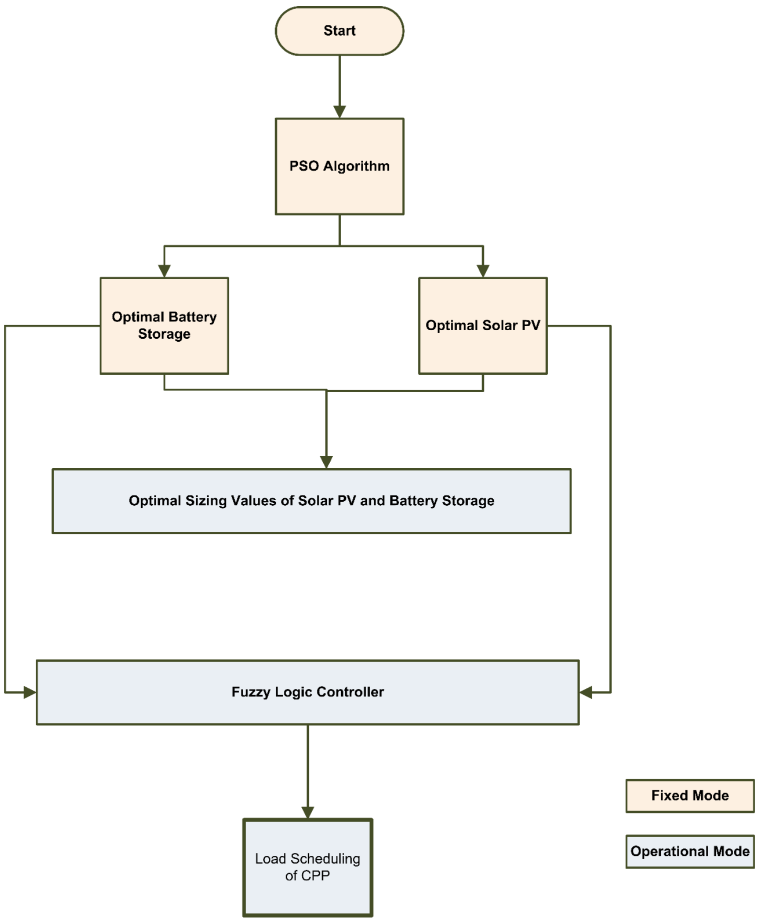

Figure 2. Flow diagram of the proposed integrated algorithm.

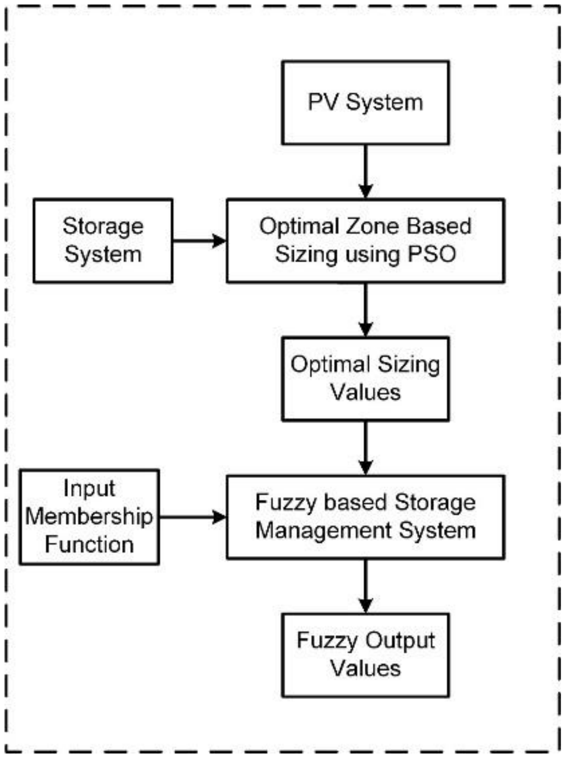

Figure 3. Block diagram of the proposed strategy.

4.3. Fixed Mode: Optimal System Sizing

An optimal system sizing is based on the particle swarm optimization algorithm.

4.3.1. Problem Formulation

The capital cost of the current system heavily depends on solar PV sizing and sizing of the battery storage. The solar PV and battery storage are dependent on the load variable. The higher the load, the higher the sizing. The system looks straightforward as load power decides the sizing of solar PV and battery storage. However, the low load factor, unscheduled operation, and small duration peaks make system sizing oversized if performed conventionally. To size, a system with a set of conditions such that solar should be sized to run the CPP in real time and manage to charge the battery while the battery storage should be sized to manage the DS for a night only, the set of constraints are required. In a nutshell, sizing under the mentioned constraints with optimal values of solar and battery storage requires optimization computation techniques to solve the problem. In the proposed system, PSO is used to perform the optimal sizing of storage and solar PV under the set of constraints that ensure the reliable operation of both CPP and DS.

The constraints are also set based on the ratings of the one-day operation of DS and CPP. The PSO decides the optimal values of watt-hours required for operation.

4.3.2. Objective Function

The objective of PSO optimization is to find minimum sizing for battery and solar PV systems to reduce the overall system cost. Given below is the objective function for the operation of the solar PV and battery storage systems.

$$IC_{min} = C_{BAT} + C_{PV} \tag{1}$$

where IC_{min} is the Cost Minimization, 'C_{BAT}' is the battery cost, and 'C_{PV}' is the cost of Solar PV. The 'IC_{min}' will give the minimum values of storage and PV energy cost with stable operation.

4.3.3. Battery Sizing

The battery sizing has been performed with (2) [15].

$$C_{BAT} = B_{req} = \frac{L_{Ah/day} \cdot N_C}{M_{DD} \times D_f} \tag{2}$$

where B_{req} is $L_{(Ah/day)}$ (the total Ah consumption of the load per day), M_{DD} is the maximum discharge depth D_f is a factor of discharging, and N_C represents the number of autonomous days [15].

$$N_P = \frac{B_{req}}{B_c} \tag{3}$$

where N_p is the number of batteries in series, B_{req} is the battery capacity required and B_c is the selected capacity of the single battery [15].

$$N_S = \frac{V_N}{B_N} \tag{4}$$

where N_s is the number of batteries in series V_N is the microgrid system voltage and B_N is the Battery voltage. The N_{BAT} can be found in [15].

$$N_{BAT} = N_P \times N_S \tag{5}$$

For Solar PV optimal sizing: The cost of the solar PV can be found while evaluating the total power plant required for PV production.

$$C_{PV} = P_{PV} = V \times I \times h \tag{6}$$

where P_{PV} is the capacity of the solar PV which can be evaluated using the capacity of the required solar energy at Rs. 30/kW. V is the voltage, I represents current, and h is the available hours of solar power.

4.3.4. Constraints

To size a battery such that it ensures the DS operation at night, the Ah of the load is settled between upper and lower bounds. The load of DS is evaluated in terms of the current required for night operation in hours.

$$L_{\frac{Ah}{day}min} \leq L_{Ah/day} \leq L_{\frac{Ah}{day}max} \tag{7}$$

$$1 \leq Days of Atunomy \leq 1.5 \tag{8}$$

The days of autonomy have been taken between 1 and 1.5 days to reduce the overall sizing. Even if the CPP operates, there will be ample time available to charge the battery during the other day. So, to reduce the overall sizing. The CPP and DS load if operated together have the value of 11 kW. To ensure the operation of the CPP in the daytime and to charge batteries at the same time for night operation, the PV power is kept greater than 11.15 kW. The MDD is kept at 0.8 and the discharge factor of 0.5. Whereas the voltage and availability of solar power for the entire day are kept at 220 V and 8 h, respectively.

$$PV \geq 11158 \tag{9}$$

Figure 4 shows the residential load for a single day, while Figure 5 shows the industrial load for a single day. For reliable operation, the PV power generation should be more than 11.15 kW. This is performed to ensure the charging of batteries and continuous operation of CPP and DS.

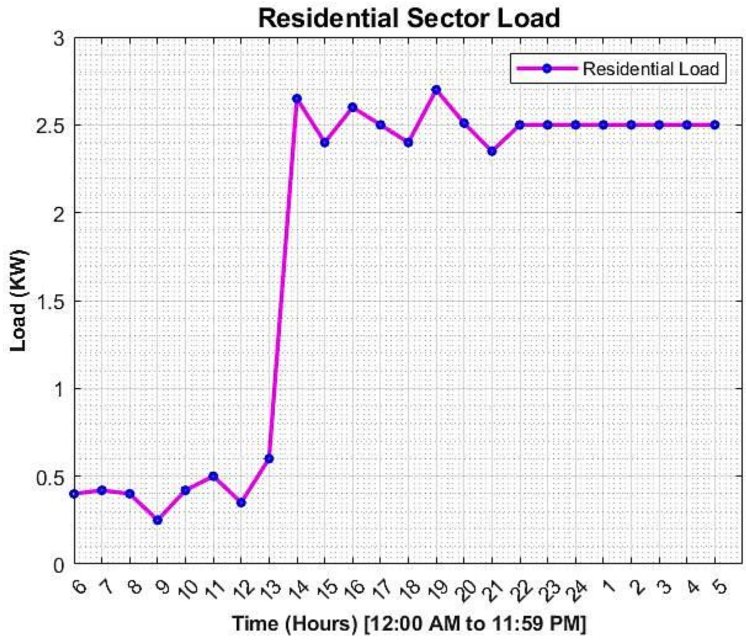

Figure 4. Residential load for a single day.

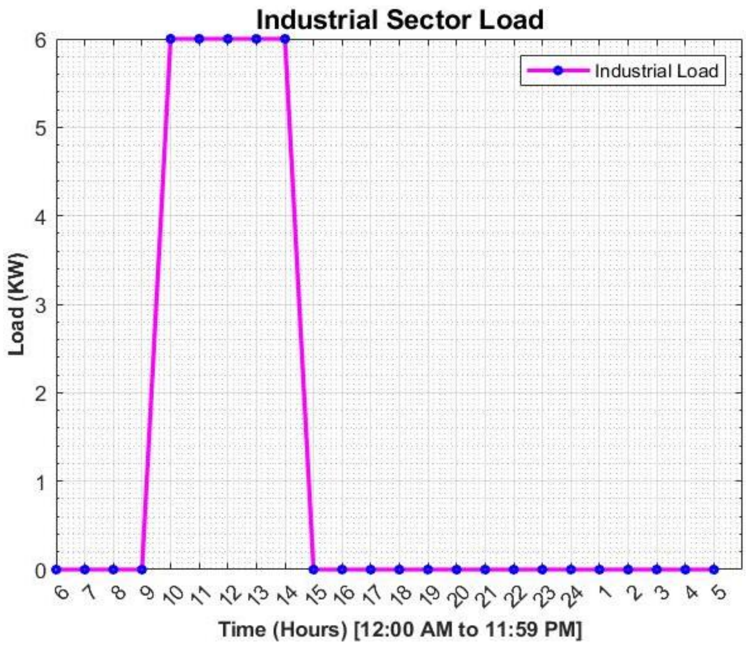

Figure 5. Industrial load for a single day.

4.3.5. Designed Algorithm for Full Load Operation

It is evident from the fixed mode of sizing that CPP can only operate when solar PV power is available and there is no provision for its operation during the night hours. To reduce the low load factor impact on the overall system and to avoid the peak load during low power availability, a fuzzy controller is designed to intelligently schedule the operation of the CPP. In case the CPP runs for longer periods, such as 4 to 5 days, the SoC of the storage decreases gradually due to PV maximum utilization during the daytime. Solar PV will charge the storage comparatively at a lesser rate. In such conditions, a controller is required to monitor the SoC and CPP operation for better SoC availability for DS during night hours.

4.3.6. Fuzzy Logic System the Load Flexibility Zones

To complement the sizing and to secure the assets from load stress, scheduling of CPP is performed using the fuzzy logic controller. The fuzzy logic controller can make decisions on linguistics and provide logical decision-making under the different grey zones of operation. It can be seen from Figure 6 below that the microgrid will have 4 zones of operation out of which three zones B, C and D are inflexible due to limited sizing. The flexibility or inflexibility of any zone is dependent on the availability of solar PV power and the battery storage state of the charge. In this case, ample solar PV power is available whereas the battery SoC is also above save limits, the zone will be considered as a flexible zone of operation as shown in Figure 6A. Similarly, low availability of solar irradiation or less SoC will be considered as an inflexible zone of operation. However, to decide on the flexible or inflexible zones of operation, a controller is required that intelligently decides on the operational zone in between the availability of SoC and Solar power values.

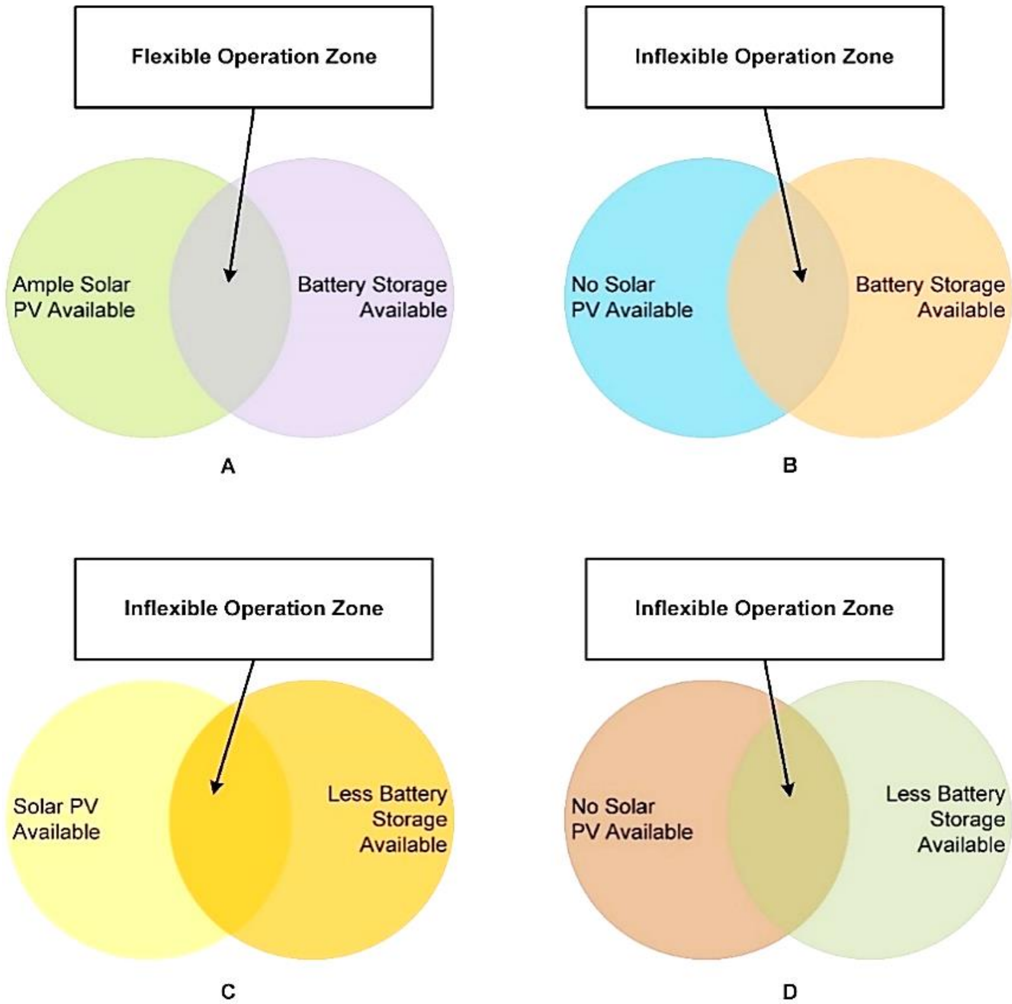

Figure 6. Zones of operation (**A**) shows the flexible zone of operation where (**B**–**D**) shows the inflexible zones of operation.

Thus, there is a need for a controller to intelligently assess the zone and take action based on the various conditions of the 4 zones. The assessment of grey zones as shown in Figure 6 cannot be accurately analyzed using conventional controlling techniques that work on crisp values. Thus, a controller that may also assess the grey zones is required. The defined membership functions in Figure 7 are excess solar power after feeding the load. Here, load means the DS operation during the daytime and charging of the batteries. The excess power is negative 'N' when the load is more than the generation. The power is 'Z' when it is in the mid-value from 0 to 40, which shows that from 0 to 40 the power generated and load consumption is at the level. The third category is ample excess power which ranges from 20 to 90, which means the solar power generation is greater than the load consumption. The second membership function is the SoC of the storage as shown in Figure 8. The low SoC range is between zero to less than 40%, the mid-range is from 35% to 65%, and the high SoC range is from 60% to 100%.

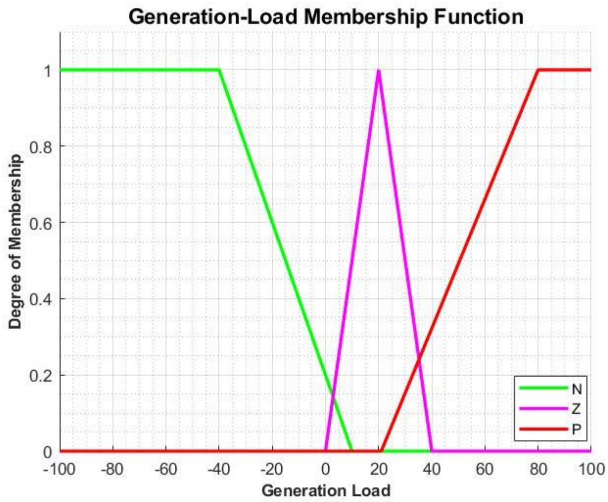

Figure 7. Fuzzy membership functions for excess power.

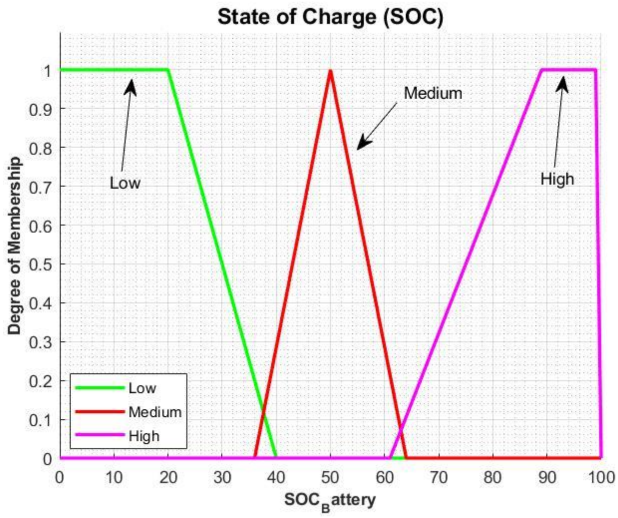

Figure 8. Fuzzy membership functions for SoC of storage.

Based on the membership functions the fuzzy controller will decide under which zone the current situation lies and will allow CPP to operate or charge the batteries. The fuzzy membership functions are based on the following equation [44]. We have considered E as a set having a real number. A fuzzy subset A *of* E is a set of ordered pairs.

$$A^{\sim} = \left\{ \frac{X, E_{p^{\sim}}(X)}{x} \in E \right\} \tag{10}$$

$$B^{\sim} = \left\{ \frac{X, SoC_{B^{\sim}}(X)}{x} \in E \right\} \tag{11}$$

The function $E_{p^{\sim}}{}^{\sim}$ denotes the membership function of fuzzy subset $A^{\sim}$, $SoC_{\mathrm{B}}{}^{\sim}$ denotes the membership function of fuzzy subset $B^{\sim}$ given as element $x \in E$. $E_{p^{\sim}}$ and SoC_B is known as membership degree, compatibility degree, and truth degree of element x in fuzzy subsets $A^{\sim}$ and $B^{\sim}$. The Support of $A^{\sim}$, $B^{\sim}$, is indicated by $Supp(A^{\sim}, B^{\sim})$ at the ordinary set.

$$Supp(A^{\sim}) = \left\{ x \in \frac{E}{\mathrm{Ep}(x)} > 0 \right\} \quad (12)$$

$$Supp(B^{\sim}) = \left\{ x \in \frac{E}{SoC_B\,(x)} > 0 \right\} \quad (13)$$

5. Discussion and Results

5.1. Optimal Sizing Values from PSO

Optimal values from the PSO algorithm are attained against the given constraints and objective functions, while Table 2 shows the parameters and their values. The values realized for storage and Solar PV is given as under. The total minimum system required for the solar system is 11158 Watts, whereas the minimum current requirement from the solar system is 50.2 Ah. The total storage sizing required is 217 Ah with a capacity of 1208 Ah. The minimum current required from the solar system is 50.2 Ah. The system calculation is based on the kW/Rs, which normally is 30 Rs/kWh. Since to accommodate the charges of a solar PV installation, labor cost, mounting structure cost, inverter, and charge controller cost, the battery and solar cost per watt/hr is kept the same at 30 Rs/kWh.

Table 2. Parameters for optimal sizing for PSO.

Parameter	Optimal Values
Number of Batteries	2
Current in Ah	217
Solar PV	11,158
Current in A	52.2

Table 3 shows the comparison between the proposed model and the actually installed model in terms of systems sizing and economic cost. The parameters to be compared are the sizing values of solar PV, several battery units, battery capacity, and the overall cost involved. In the actual installed system, the battery capacity is 64,000 Ah having 24 units. The cost per unit of the battery is 30,000 which equals 720,000 Rs for 24 units. On the other hand, the solar PV installed in the actual system is 20 kW to support the system CPP and DS. It was assumed during the sizing that CPP will operate every day for 8 h. However, the uncertainty in the operation of CPP has made the system significantly oversized.

Table 3. Cost comparison of the previous and proposed optimal system at 30 Rs/kWh.

Sizing Based on PSO					Actual Sizing of the Microgrid Installed				
Parameter	**Optimal Values**	**Number of Units**	**Cost per Unit**	**Optimal Cost**	**Parameter**	**Previous Values**	**Number of Units**	**Cost per Unit**	**Optimal Cost**
Battery Capacity	2024	02	30,000	60,000	Battery Capacity	64,000	24	30,000	720,000
Solar PV Power	11,158	37	30,000	592,000	Solar PV Power	20,000	66	30,000	1,980,000
Total Cost				652,000	**Total**				2,700,000

In comparison to the actual model, the proposed model has the optimal value of only two batteries required for the operation as CPP is not considered to be operated through batteries. To charge the two batteries, and power the DS and CPP at the same time the solar PV is considered as 11.1 kW compared to the actual system of 20 kW. The overall system cost of the proposed system is 652,000 compared to the actual system cost which is 2,700,000.

5.2. Fuzzy Simulation Results

The prime objective of the fuzzy controller is to schedule the CPP load and manage the available battery storage under various conditions. The fuzzy controller monitors the availability of excess power and the state of the charge of storage to perform either battery charging or restrict charging to provide power to the industrial load. The simulated scenario considers a good sunny day to validate the following states

1. Operation of the CPP during excess power availability;
2. Operation of the DS during the night and daytime;
3. Charging of the battery storage during the daytime;
4. Restriction or turning off the CPP as per the availability of the solar PV.

Figure 9 below shows the solar power generation. It can be seen that solar power remains good during the peak daytime. During the daytime, excess solar power was available from 7 to 16 h as shown in Figure 10 which means CPP may operate during that time.

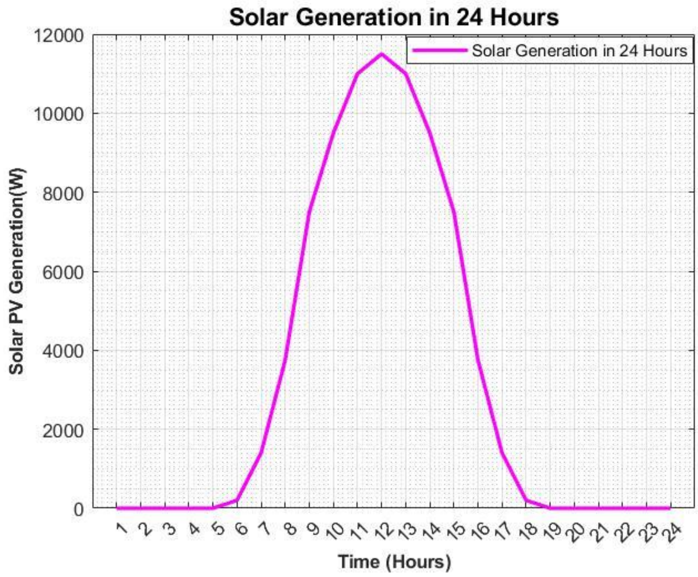

Figure 9. Solar power for the entire day.

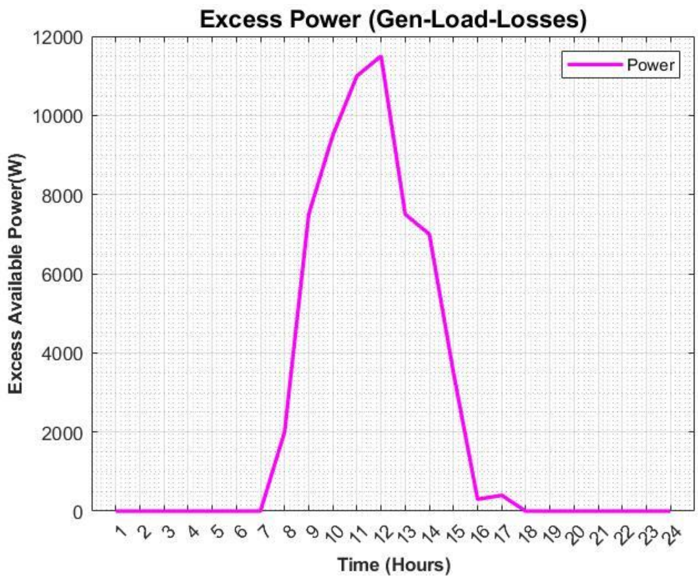

Figure 10. Excess power available after feeding the DS and charging batteries.

However, the battery SoC shown in Figure 11 was very low due to its operation during the night hours. The fuzzy controller charges the battery from 5 to 12 h. The battery SoC is fully charged as shown in Figure 12 at the 13th hour.

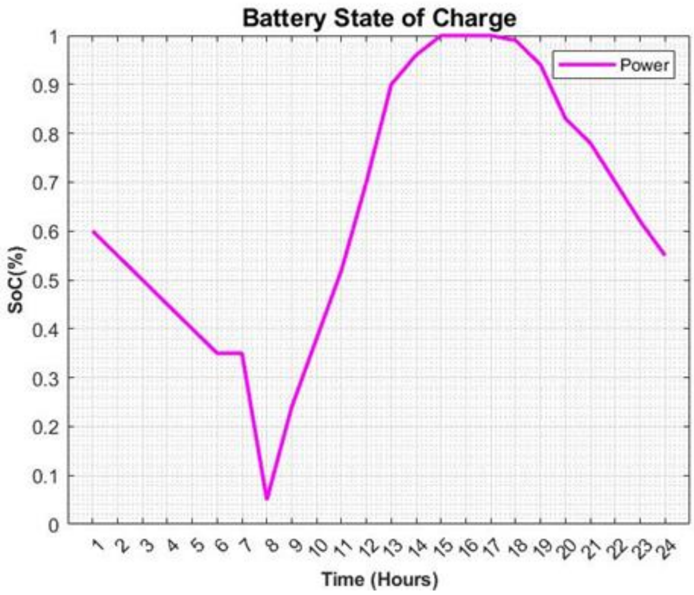

Figure 11. SoC of the battery.

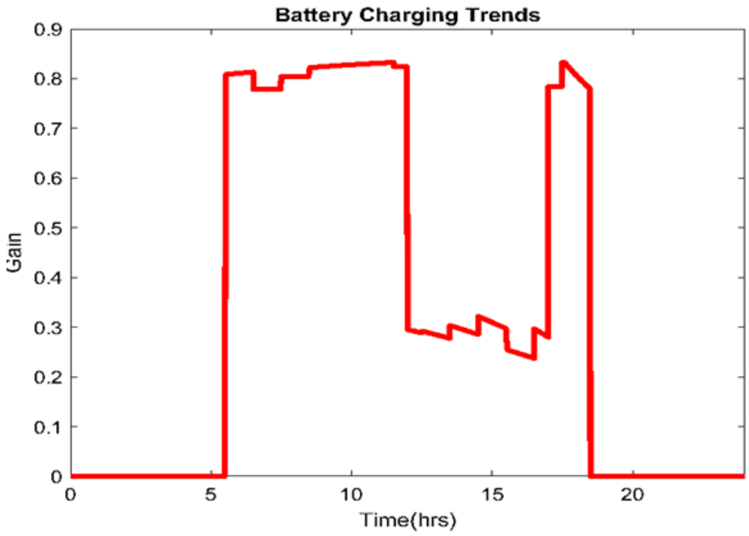

Figure 12. Battery Charging Trends based on Fuzzy Control.

During the 13th hour, solar excess power is available and battery storage is fully charged that satisfies the condition of operation of CPP. Figure 13 shows the operation of the CPP when all conditions of the controller satisfy its operation. Figure 13 shows an operation of the CPP from 13 h to 16 h. After the 16th hour, the solar irradiations go lower and so does the excess power, which turns off the CPP. During the operation of CPP, the load on DS remained lower on the other hand SoC remains stable and above the save limits to operate during the night hours.

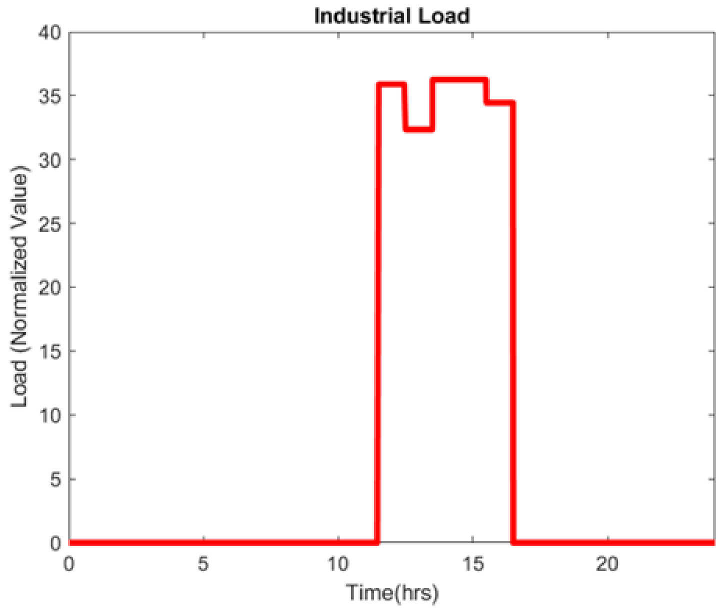

Figure 13. Operation of CPP.

The stability in the overall condition proves that CPP operation does not affect the battery storage and the optimum values set from PSO were well complemented by the fuzzy controller. As shown in Figure 14, during the night hours, as the DS load goes high after the 16th hour, the battery SoC started depleting but remained under save limits until the next day. The SoC until the next was 50% which is well under the save limits hence proving that the fuzzy controller charges the battery well during the daytime and managed the CPP operation as well.

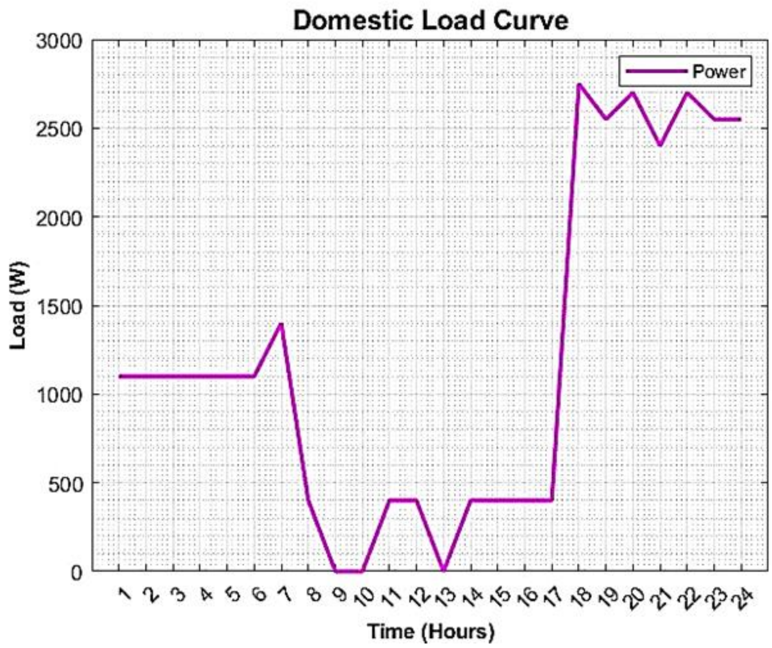

Figure 14. Operation of domestic load.

6. Conclusions and Future Work

In this research, a hybrid algorithm having integrated fixed and operational modes has been developed to reduce the overall sizing of the microgrids, reduce the impact of low load factor loads on the overall systems, and improve the economics of the overall microgrid in terms of capital cost. Results have shown that the operational mode complements the sizing of the fixed mode while intelligently using the uncertain heavy load and managing the available battery storage reserves.

It is revealed from the research study that the system can be sized with limited backup power to reduce the economic cost and scheduling the heavy loads through an intelligent controller can complement the limited sizing, thus, an integrated hybrid approach of sizing and scheduling the heavy load is effective. The case study under consideration was an open-loop system in which the microgrid was sized based on the uncertain operation of the major loads. The overall cost is 24% less than the system installed at a site, whereas the observed blackouts with the proposed algorithm were zero. The proposed system is equally good for the implementation of any uncertain loads that operate without having any prior schedule.

The shortcoming of this project is that it was not tested on an actual microgrid. In the future, the same methodology can be tested on actual installed microgrids while developing a fuzzy logic controller. The performance of the fuzzy logic controller can also be increased while using more membership functions to enhance the accuracy and performance of the controller.

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