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Investigating the Reliability and Optimal Capacity of Microgrid Electricity Storage Systems with the Aim of Reducing Costs

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Abstract- Microgrids are inherently fluctuating, and their power production highly dependent on their optimal capacity and the primary energy source. Despite the unlimited availability of wind and solar resources, a self-sufficient wind or photovoltaic generator cannot supply a 24-hour load. This fluctuating nature poses challenges for power grid operation, as variations in wind and solar energy availability do not allow for meeting the demands of distributed loads consistently. Frequency changes due to fluctuations in wind power production are one of the key factors that hinder the penetration of wind generation technologies. One of the best options to address this challenge is the use of energy storage systems, which add the flexibility needed to integrate higher amounts of wind energy into the electrical grid. This alternative has been considered for many years. In fact, electricity generation systems using renewable sources require batteries to compensate for the aforementioned issues. By using batteries, wind generators can not only be used to provide the required load during peak hours, but they can also be used for frequency regulation. This research studies a microgrid including a microturbine, a wind turbine, a solar generation system, and a battery. By studying the features and specifications of common energy storage systems, the best option for the microgrid is determined, as well as its optimal storage capacity. The purpose of this research is to achieve the optimal power generation approach and improve the reliability of the system by considering the batteries during charging and discharging, in addition to the optimal capacity and the most suitable optimization algorithm.

Keywords: Microgrid, energy storage system, reliability, cost reduction, frequency changes

1. Introduction

Electrical energy storage has always been a matter of consideration in power systems. Despite the multiple advances in this field, it still faces many issues related to large-scale operations. Proof of this is the small number of power plants using energy storage technologies in comparison with traditional facilities, as well as the high costs of storage systems. Since most research has focused on determining the optimal capacity and location of these systems, most of them are related to network operation, planning, and management.

presented a planning model with a multi-year operation approach aimed at determining the optimal capacity of batteries in terms of energy and power [1]. Optimal planning decisions were made for different battery technologies, considering many ownership scenarios. The random optimization model was used to determine the optimal capacity of the batteries and their year of installation, considering the non-deterministic states of sub-grid variables. This was solved using the method of separation and decomposition of two-level optimization problems.

determined the location of energy storage systems (ESS) and their optimal charging and discharging strategy, to reduce risks and increase the profit of energy distribution companies [2]. The optimal capacity of the storage systems was determined by minimizing the cost of energy production and maximizing the use of non-renewable energy fluctuations on a scale of less than 1 h. A large number of scenarios were used to incorporate changes in wind load and unit on different days of the year. Optimizing the generator output and charging and discharging the storage devices under many scenarios can lead to a very complex optimization problem. Determining the optimal capacity of ESS in a distribution network involves considering a large area of photovoltaic (PV) cells [3-4]. The main goal of the proposed method is to optimize the capacity of batteries and analyze their associated profit and costs when used in voltage regulation and load de-peaking. To implement the proposed strategy, a system model including a physical battery model and an energy management system aimed at voltage regulation and load de-peaking was developed. Multiple methods have been presented for determining optimal battery capacity to manage the energy balance of variable generation resources [5]. The goal of many control strategies is to minimize the hour-by-hour imbalance between actual and planned production. The main problem associated with microgrid operation is voltage and frequency control. When the inertia of the entire network is low and there is no suitable control, system operation is interrupted by sudden changes in load or frequency. To solve this issue, various control structures have been proposed [6]. This paper proposes an optimal distributed control strategy for coordinating multiple distributed generation instances in an islanded microgrid. This provides a model for calculating the optimal size of energy storage while considering the reliability criterion [7]. The larger the storage, the higher the investment costs, while the operating cost of the microgrid decreases. The optimal energy storage size problem aims to minimize the expected investment (initial) and performance costs of the network. Using ESS prevents shortages caused by the interruption of existing units or by the separation of renewable units, thus satisfying the microgrid reliability criterion.

Our work details how to mathematically model resources and aspects such as battery ESS, solar generation systems, directly controllable loads, load shedding, planned intentional islanding, and generation curtailment in the optimal microgrid scheduling problem [8]. The proposed model also includes a method to determine the availability costs of battery assets and solar generators. Simulations are carried out while considering energy prices from a real- time-of-use tariff, costs based on real market data, and scenarios with planned islanding. To determine the optimal size of the battery, an optimization algorithm is employed [9]. Several scenarios and different algorithms are considered to determine the optimal battery size in a hybrid microgrid.

Loss-based inverter control strategies for microgrid applications have been introduced and described in multiple studies [10]. These articles describe the introduction of voltage drop-reactive power and frequency-active power control methods, as well as their implementation in controllable units such as batteries and microturbines. The authors [11] introduced a distribution system operator (DSO) proximity storage capacity for the microgrid capacity planning problem. This formulation has two levels: the first one deals with microgrid planning, especially concerning planning and operating costs, while the second level focuses on the DSO's service reliability. Microgrid planning, in coordination with distributed generation in the presence of DSOs, has the capacity for flexible storage resources. This proposal is a mathematical program with equilibrium constraints (MPEC), in which the decision variables of the two problems are controlled independently.

The work by [12] aims to determine the optimal location of storage systems in distribution networks while considering a high penetration of wind units, with the main goal of maximizing profit and optimizing the use of excess wind energy. Wind energy has been used by storage facilities to reduce the annual cost of electrical energy. In this article, the optimal location of storage systems is determined with the aim of minimizing the annual energy costs and attaining optimal capacity allocation, allowing to utilization of excess energy.

Microgrids are the result of integrating local distributed energy resources (DERs) into existing power systems [13]. Thus, power distribution systems can be seamlessly divided into microgrids, and end-users can be largely supported when a severe issue arises. However, due to low inertia, the optimal power capacity should be calculated to better accommodate unforeseen events. This paper presents a combined quantitative and qualitative method for selecting DERs, as well as an economic approach to meet system reliability requirements, the mathematical model of the bat algorithm, and the formulation of the variables considered. This algorithm has already been applied in the literature [14], showcasing the effect of droop control and the presence of batteries in the network to improve voltage and frequency stability [15]. In this article, two low-load and high-load scenarios are considered. In both scenarios, the energy storage system is coordinated with other units by controlling the loss of stability and improving network reliability.

During islanded operation, a microgrid's frequency stability is controlled using a wind turbine with a dual-feed induction generator, in addition to the application of small disturbances such as load changes [16]. The microgrid has different types of distributed production sources, i.e., PV systems, fuel cells, and diesel generators. To improve the frequency control, a PID frequency controller is incorporated into the turbine model, as well as a diesel generator. Moreover, to improve the performance of the proposed controller as much as possible, its coefficients are optimally adjusted using the particle swarm algorithm. The objective function is determined which involves reducing frequency fluctuations in the short term. The penetration rate of microgrids in power systems, as well as the high uncertainty of these resources, requires the analysis of possible methods [17].

The uncertain nature of renewable energy sources (wind and PV), market prices, and loads have caused issues in guaranteeing the quality of electricity and in balancing production and consumption [18]. To solve these issues, microgrids must be managed with an energy management system (EMS), which facilitates the minimization of operating (functional) costs, pollutant emissions, and peak loads while meeting technical constraints.

The first challenge in utilizing ESS is determining the appropriate location and capacity while considering a system's technical and economic constraints purpose of this article is to find the best optimization algorithm to determine the optimal capacity of ESS in microgrids, aiming to improve reliability. In this research, microgrids including wind turbines, solar panels, and diesel generators with battery systems are analysed. The storage capabilities of these systems can be used for various purposes, such as increasing reliability, improving power quality, flattening the load curve, and de-peaking. In fact, electricity generation systems using renewable sources require batteries to compensate for the lack of power at times of low energy production, which entails increased productivity. This research presents an efficient framework for studying of microgrid management about to installation, maintenance, and economic issues. The fixed costs and the maintenance expenses of battery energy storage units (BESUs) are considered in microgrid optimization Simulation results show the following:

- With an optimal BESU size, the total costs of a microgrid can be reduced, as these systems can store the excess power generated by renewable energy sources, eliminating the need to purchase electricity from the main grid, especially during peak hours and times of high energy costs.
- Installing a BESU without initial charging decreases the costs of a system compared to a microgrid without any storage units. In addition, BESUs with an optimal size equivalent to the initial charge entail reduced daily costs. A solution that considers the discharge and charge efficiency of batteries.

2. Microgrids

A microgrid is a collection of small loads and DERs (such as distributed generators, or DGs) that are operated as a single system, providing both electrical power and heat. Microgrid DERs use power electronics and may include DC (e.g., solar and fuel cells) and high-frequency AC (e.g., microturbines) systems. Within a microgrid, which is a single and dense system, DERs can serve as a control tool to meet local needs regarding reliability and security. DERs can continuously and adequately supply a significant portion of the microgrid's internal demand with minimal interruption. It provides flexibility in configuration, use of power delivery system, and optimization of large networks.

Microgrids can supply loads through small individual facilities with compact substation interfaces. The benefits of microgrids are presented below:

- Cost reduction: reducing the cost of electricity and managing price volatility.
- Reliability: improving system and reliability.
- Security: increasing power security and resilience via increased power source dispersion.
- Use of green power: microgrids aid in dealing with the changing nature of renewable resources and promote the implementation and integration of environmentally friendly and energy-efficient technologies.
- Power system: microgrids help to optimize power receiving systems.
- Service separation: different quality levels for customers at different price points.

Given that microgrids may deal with many different power values in different situations, the size of the market can change significantly, as well as the interests of operators. It is estimated that the microgrids in the American network can support the load until 2020. This means that microgrids must supply the demand at a favorable price.

In order to reap the aforementioned benefits, microgrids must meet some fundamental technical requirements, i.e., efficiency, quality, design, protection, monitoring and control, flexible operation, and infrastructure. The main challenge posed by these systems is their protection and control. Microgrids must be managed by central controllers (as opposed to relying on local generation control) to accommodate a wide range of generation and load scenarios and constraints associated with faults and generation. As for external control, a microgrid must incorporate ISO telecommunication infrastructure. To maintain voltage and frequency, dedicated generators must respond quickly to load changes. Interrupting the fault current is particularly challenging, as microgrids must coordinate their protective devices during both islanded and grid-connected operations. This has accelerated the advancement of inverter-based production.

2.1. Energy Storage Sources

Electrical energy storage is widely recognized as a key component in improving the reliability and stability of a grid, and it offers many economic benefits. This includes advances in battery technology and large-scale storage systems. In general, storage devices are responsible for supporting the voltage, frequency, and transient stability of the network, in addition to improving power quality and adjusting load imbalance. Large-scale electrical energy storage technologies have numerous applications, from providing a rapid power supply for enhanced reliability to supporting long-term energy management applications for increased efficiency. These applications also include the discharge of energy in different timeframes for high-power applications.

2.2. The Effect of Energy Storage on the Eonomic Performance of a System

Small customers do not participate in many electricity markets. Instead, energy purchasing is carried out by a load collector, an entity that participates in the wholesale market and is responsible for purchasing and supplying energy to its customers. Normally, the load at any given time is determined by customer demand and the price changes only in response to this demand. In some recently implemented demand response programs, the load can be controlled (limited) by the system operator or the customers, who can adjust it according to the price of electricity.

2.3. Controlling the Frequencies and Transmission Currents Between Different Areas

Frequency and flow level control aids public service providers – who are the users of the system’s different areas – that are connected to the network. It provides the necessary ability to prevent unplanned power transfers between areas. For separate (individual power systems), the ability to prevent major frequency changes in the output power . Through a regulator, the power transfer between the areas is regularly recorded. The demand for this application is expected to increase, and battery technologies, SMES, flywheels, and capacitors are suitable for these purposes.

2.4. Integration with Renewable Resources

ESS can be integrated with renewable resources to provide adequate capacity during times of peak system demand. The power rate is higher than 1 MW in these applications, which is required for a period of 1-4 hours. In this context, batteries are being predominantly used.

2.5. Tracking Load Changes

Saving inexpensive off-peak power for use during relatively expensive peak hours is the main goal of load change tracking. This usually involves a rate of 100 MW for 1-4 hours. To this effect, storage pumps are generally used.

2.6. Transmission Line Stability

The stability of the power system in the steady state means its ability to restore itself to the original configuration after a small disturbance in the main grid.To this effect, storage units with a power capacity of over 100 MW are required for periods of several seconds. In this regard, capacitors are more suitable than other storage technologies.

2-7- Voltage regulation

The purpose of voltage regulation is to maintain the voltage difference between the production site and the end of the transmission lines at a maximum of 5%. This requires a power of 1 MW for less than 15 minutes. Batteries, capacitors, SMES, and flywheels are suitable for this type of application.

3. Objective Function

The problem formulation includes an objective function (minimization of total costs) which is subject to several constraints and is defined according to equation (1):

$$Min(Fx) = \sum_{t=1}^{NT} f_t + OM_{WT} + TCPD_{BES} \tag{1}$$

$$f_t = Cost_{grid,t} + Cost_{DG,t} + Cost_{BESS,t} \tag{2}$$

$$Cost_{grid,t} = \begin{cases} Bid_{grid,t} P_{grid,t} & if\ P_{grid,t} > 0 \\ (1 - tax) Bid_{grid,t} P_{grid,t} & if\ P_{grid,t} < 0 \\ 0 & if\ P_{grid,t} = 0 \end{cases} \tag{3}$$

$$Cost_{DG,t} = P_{WT} Bid_{WT} \tag{4}$$

$$OM_{DG} = OM_{WT} \times NT \tag{5}$$

In these equations, NT is the time horizon, OM denotes the maintenance cost of energy production units, and Bid represents the price of electricity for each piece of equipment.

The total costs of the microgrid encompass the cost of operating both the network and the ESS, the maintenance and repair costs for the ESS and the wind turbine, and the total cost per day (TCPD) of the battery. The total costs of the ESS include the instantaneous fixed costs (FC) and the annual maintenance costs (M)C.

The total cost of the energy storage system is represented as .$(FC_{BESS} + MC_{BESS}) \times C_{BESS,max}$

Here, $C_{BESS,max}$ denotes the capacity of the ESS. In this study, a time horizon of one day was selected to determine the optimal battery capacity. The investment costs of the ESS and the battery life are introduced by the IR and LT coefficients, respectively. Thus, the TCPD relationship is expressed as follows:

$$TCPD_{BESS} = \frac{C_{BESS,max}}{365} \left(\frac{IR(1+IR)^{LT}}{(1+IR)^{LT} - 1} FC_{BESS} + MC_{BESS} \right) \tag{6}$$

The proposed formulation includes the following constraints. *Electric load demand condition* $(P_{demand,t})$

For the load demand at time *t*, the power generated by the wind turbine and that absorbed/injected by the battery and the grid must be equal.

Here, NT is the number of hours in a day and night.

This mode includes charging and discharging modes. For the former, the following expression is used Various technologies can be used as ESS. This study considers lithium-ion batteries, one of the most common types in microgrid applications worldwide. These batteries boast several advantages, such as a very high energy density compared to other technologies, low charge losses when they are not in use, and a wide range applications in power systems and the transportation and aerospace industries, which are in dire need of energy density.

Like in other power system optimization problems, the network constraint involves maximum and minimum limits, which are defined as follows: In most microgrids, reliability is achieved by using stored energy. In this article, no controllable and dispatching unit is considered (*e.g.*, a microturbine). The only rotating storage unit is the ESS, *i.e.*, the rotating storage of the system corresponds to the energy stored in the battery. Of course, during grid-connected operation, the rotating storage of the upstream network is considered.

$$P_{WT,t} + P_{BESS,t} + P_{grid,t} = P_{demand} \quad t = 1,2,\dots\dots\dots..,NT \tag{7}$$

$$C_{BESS,t+1} = \max\left\{\left(C_{BESS,t} - \Delta t.\frac{P_{BESS,t}}{\eta_{discharge}}\right), C_{BESS,min}\right\} \quad t = 1,2,\dots\dots NT \tag{8}$$

$$C_{BESS,t+1} = \min\left\{\left(C_{BESS,t} - \Delta t.\frac{P_{BESS,t}}{\eta_{discharge}}\right), C_{BESS,max}\right\} \quad t = 1,2,\dots\dots NT \tag{9}$$

$$P_{grid,min} \leq P_{grid,t} \leq P_{grid,max} \tag{10}$$

$$P_{grid} + P_{BESS} \geq OR + P_{demand} \tag{11}$$

In the above-presented equation, OR is the amount of usable storage.The presence of renewable energy sources is an inseparable principle of the design and implementation of microgrids. Due to the periodic nature of energy sources such as the wind and the sun, power production fluctuates, which entails the need for an ESS. ESS consist of two parts: a battery and a power electronic converter. A power electronic converter is usually a voltage source converter that is switched based on the pulse width modulation method. The batteries that are mostly used in this field are lead-acid batteries. These batteries include a positive lead dioxide electrode, a negative lead sponge electrode, and liquid sulfuric acid. These batteries are widely used in PV systems. In the dynamic models presented for the battery, the battery voltage and its internal resistance have been calculated according to the current and some battery parameters such as the state of charge (SoC). If the SoC is 1, the battery is fully charged; if it is 0, the battery is fully discharged. The SoC is calculated using the following equation: $SOC = 1 - \frac{Q_e}{C_0}$. Where is equal to the charge drawn from the battery, Q_e and Q_e is the capacity of the battery before discharge. These two variables are calculated using the following equations:$Q_e = \int_0^T \mathrm{I}dt, C_0 = SOC_0.C_n$ I denotes the discharge current, and T is the discharging duration. SOC_0 andrepresent the initial SoC and the C_n nominal capacity of each battery cell, respectively. The relationship between voltage and SoC is partially nonlinear, especially for SoC values lower than 0.2. In order to simplify the model, it is assumed that the lowest SoC is 0.2. Therefore, the internal voltage of each battery cell can be calculated:$U_{cell}^{internal} = U_{max}.SOC + U_{min}.(1 - SOC)$ .Where U_{min} is the voltage of each fully discharged cell, and U_{max} is the voltage of each fully charged cell. Considering the voltage drop caused by the resistance of each cell, the voltage is obtained through the following equation: $U_{cell} = U_{cell}^{internal} - R_{cell}.I_{cell}$. The parameter R_{cell} corresponds to the resistance of each battery cell, and I_{cell} is the current of each cell. Given that each battery is composed of a specific number of cells arranged in series and parallel, the terminal voltage of the battery is determined by the voltage of each individual cell. The N_{series} parameter specifies the battery's number of cells in series:$U = N_{series}.U_{cell}$

4. The Proposed Algorithm

Our proposal consists of two parts. In the first part, the optimal number of batteries is determined in order to optimize the objective function via PSO and based on the problem variables, to later determine the optimal number of backup batteries. In the second part, the optimal number of PV arrays and wind turbines is calculated. The battery system is analyzed in the first stage using the direct search method. At the start of the algorithm, after entering the data related to the annual load, the radiation in the region, and the costs related to the PV system, the network, the backup battery, and the wind turbine, the optimal number of batteries is selected. The appropriate backup battery capacities and the maximum area allowed for the installation of solar panels are entered in the program. The combination of input variables can have different states. If these combinations determine the specific capacity of the battery, that number will be selected as the optimal number of batteries. In other words, based on the power produced by the PV-wind system and the monthly and annual peak loads, the number of batteries, PV systems, and wind turbines is calculated. This section presents the algorithm for determining the optimal number of batteries based on the PSO algorithm, aiming to optimize the objective function (Figure 1).

5. Test System Data

The test system used in this work is shown in Figure 2. It is a microgrid including a microturbine, a PV system, a wind turbine, and an ESS (battery). This microgrid can be connected to its national power grid. The charging and discharging rate of the battery was considered to be equal to 85%. Moreover, the coefficients related to the battery investment costs and lifespan were set as 0.06 and 3, respectively. The maximum battery capacity obtained via the proposed algorithm in steps of one hour per day was taken as the optimal battery capacity. In fact, this capacity is the upper limit of the battery power in the optimization algorithm, which ensures the reliability of the network. All production coefficients and limits used in the proposed approach are listed in Table 1.

Table 1: Data information of the studied system

Used Resources	Minimum power (kW)	Maximum power (kW)	Bidding coefficient ($/kWh)	Maintenance factor ($/kWh)	Start-up and stop costs ($/kWh)
MT	6	30	0.457	0.044	0.96
PV	0	25	2.584	0.208	0
WT	0	15	1.073	0.525	0
BES	-30	30	0.380	---	0
Utility	-30	30	---	---	---

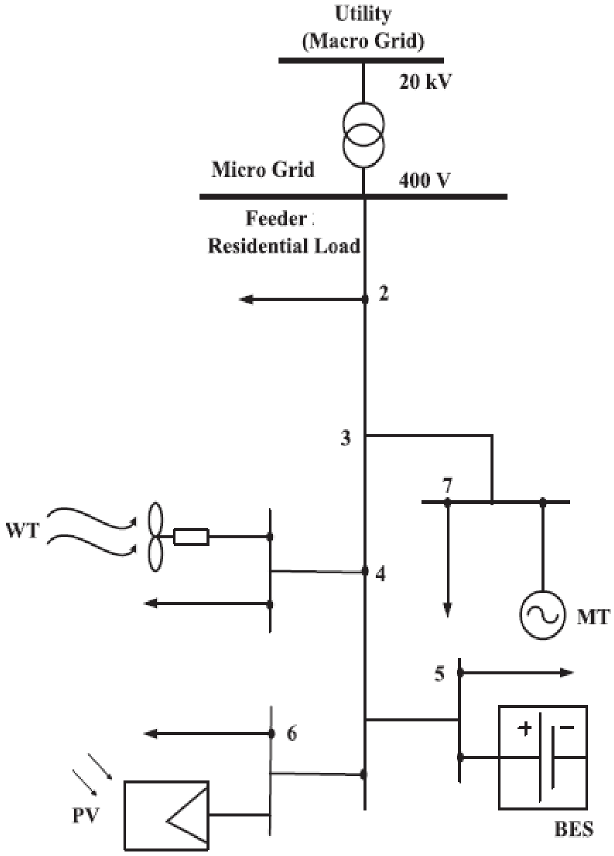

Figure 2: Microgrid including a microturbine, a PV system, a wind turbine, and an ESS

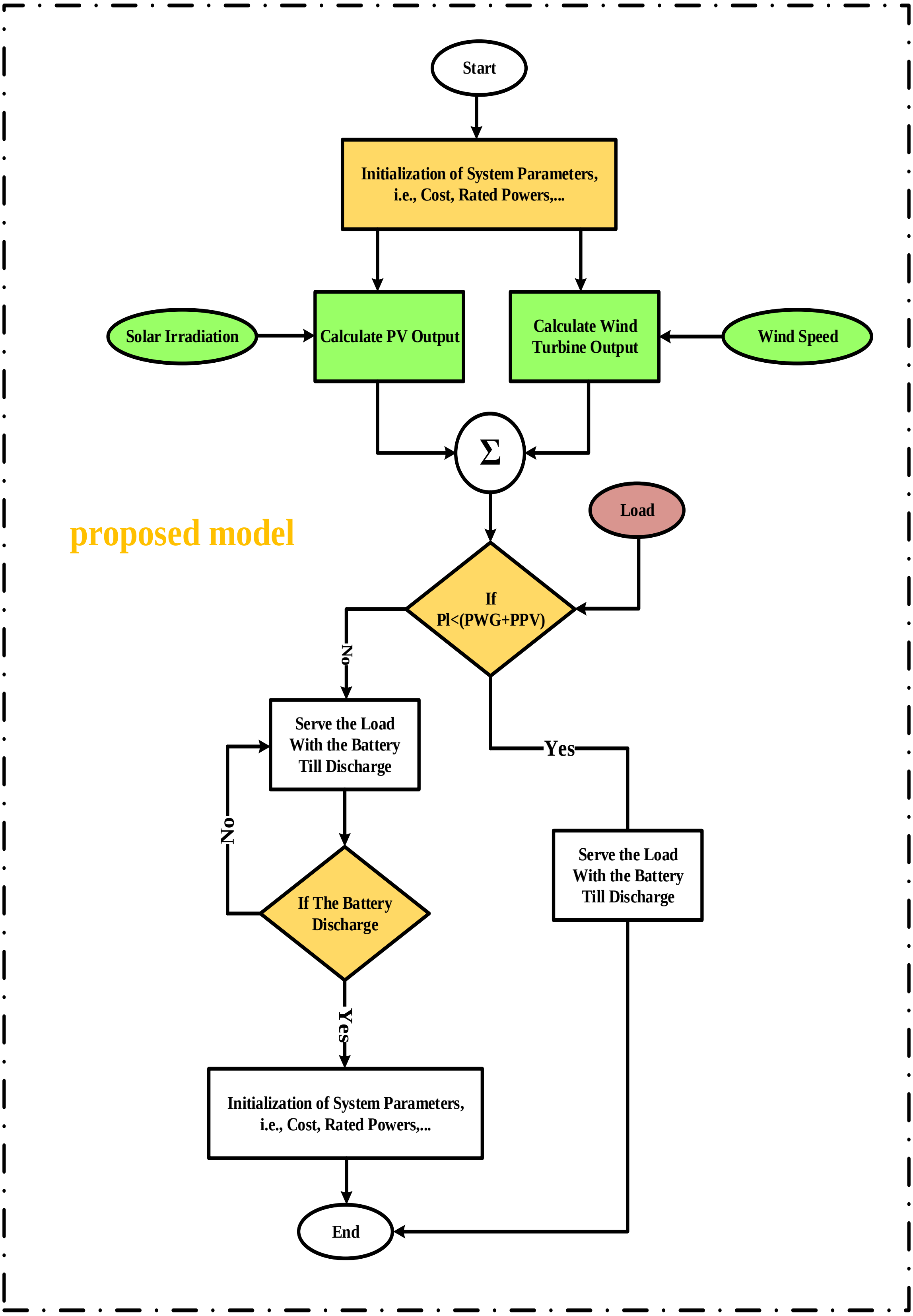

Figure 1: Proposed flowchart

6. Simulation Results

The microgrid was simulated in MATLAB. This microgrid consists of seven buses including MT, PV, WT BES and Utility.The wind turbines are connected to the 20 kV bus via a step-up transformer. The battery is connected to bus 1 through an inverter and a step-up transformer. There are also system loads in other buses. The energy price was predicted according to the real-time market and the load demand for a 24 h time horizon (Figures 3 and 4). In this case(the first scenario), the ESS has no initial charge. In general, the battery is considered to be the basic unit of the network, which can make it stable during emergencies and also improve its power quality. In this case study, in order to validate the efficiency of the ESS selection and its appropriate and optimal capacity, the maximum battery size (CBESmax) was used as a control variable. The minimum battery capacity was set as 10% of the full capacity. The full capacity was 500 kWh.

This means that CBESmax is a variable that should be optimized in the [50, 500] range, *i.e.*, after determining these variables, the energy is stored in the battery under [CBES, min, CBES, max] ranges. CBESmax is changed by 100 kWh in each step. The main disadvantage of this proposal is its high execution times. The microgrid EMS was tested in order to optimize the total operating costs, yielding the optimal battery size and the best distribution of resources and equipment. The numerical results obtained with the algorithm for the optimal distribution, batteries, and other pieces of equipment are shown in Figures 5 to 8. Note that the range between the real-time market price during peak and non-peak times creates an opportunity for the ESS to purchase energy economically. This is added to the ability to store energy from the upstream network during off-peak periods, to later sell it to the upstream network during peak load-demand periods. In this case, the overall operating cost of the microgrid EMS is 445.9 dollars per day.

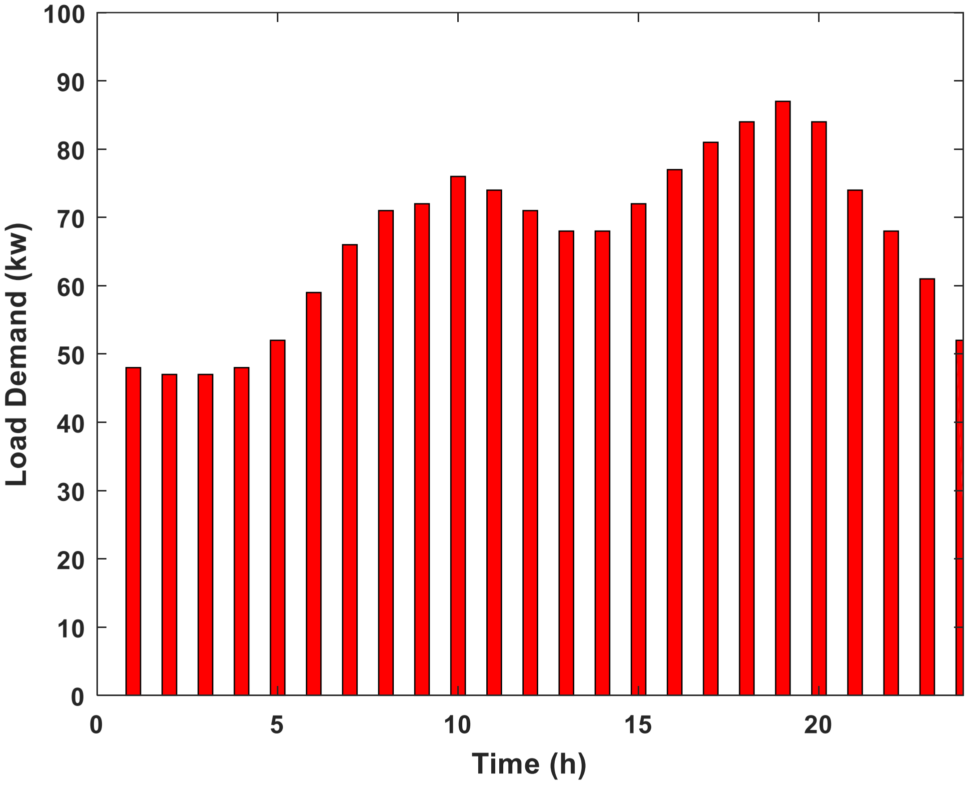

Figure 3: Load-demand profile of the studied system

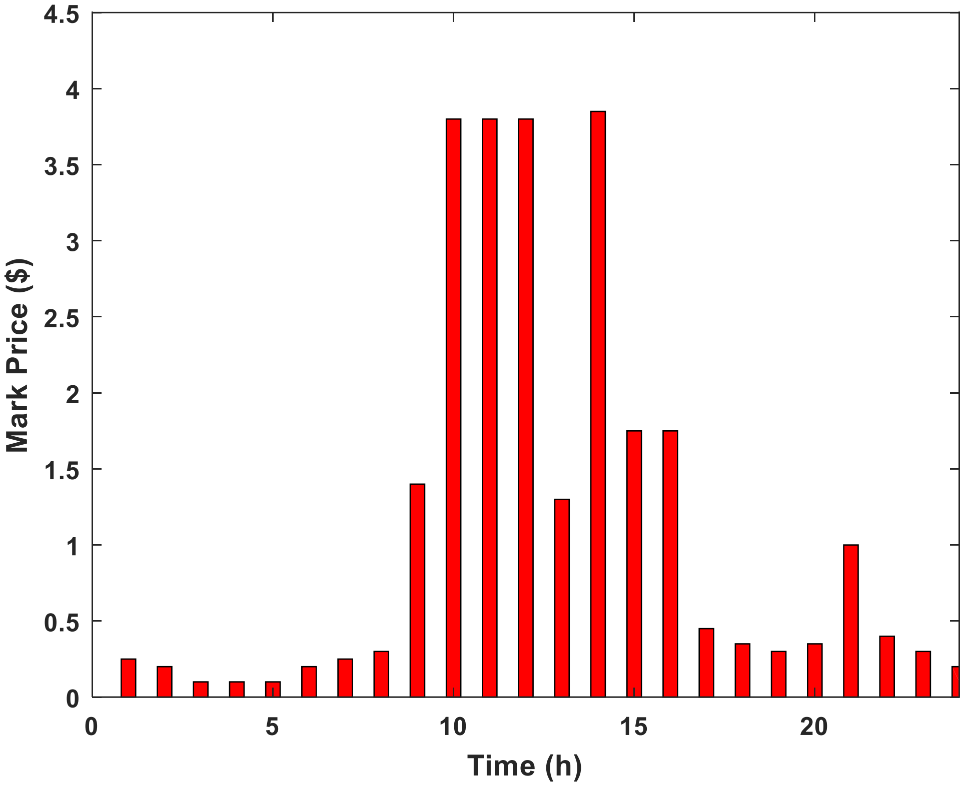

Figure 4: Market energy price profile in the studied system

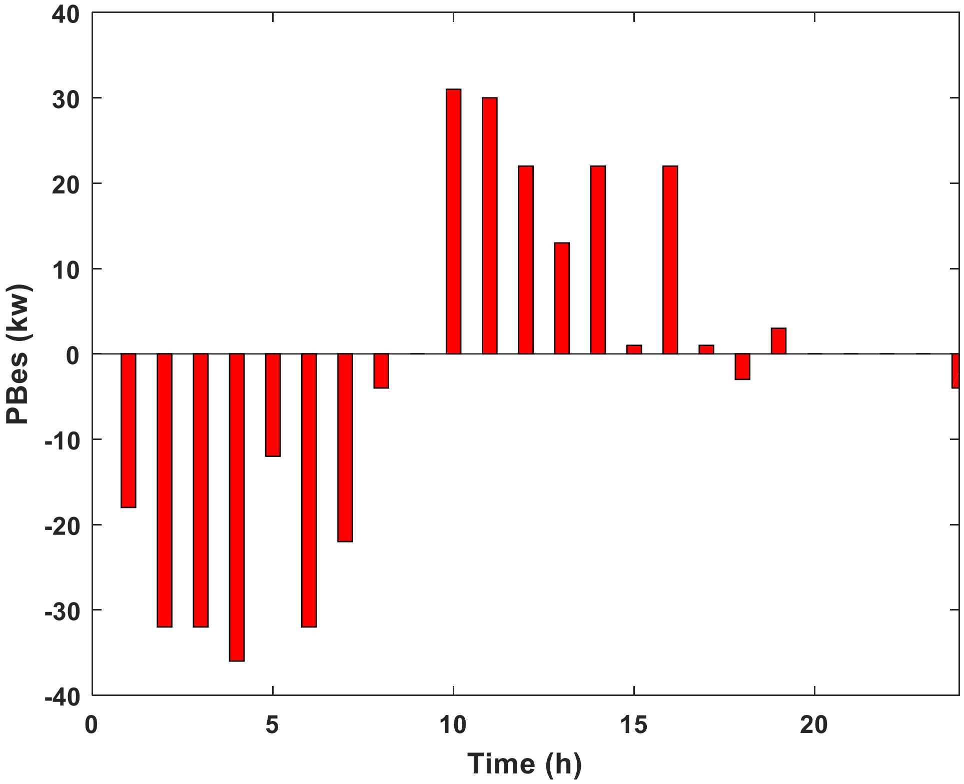

Figure 5: Optimal power of the ESS (the first scenario)

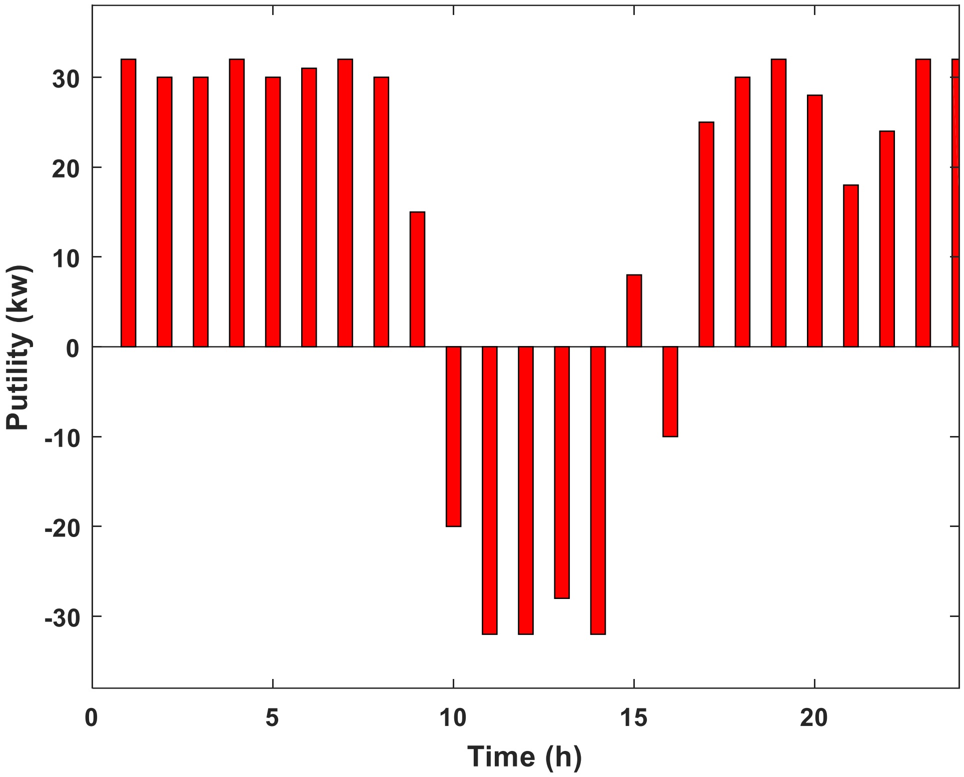

Figure 6: Optimal power of the upstream network(the first scenario)

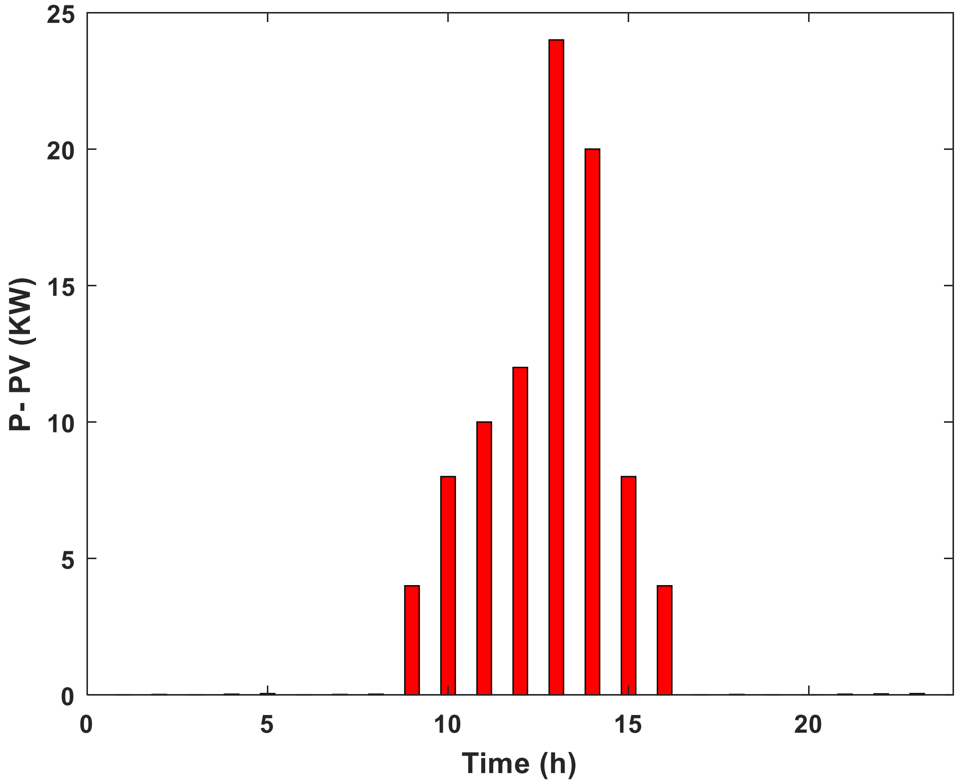

Figure 7: Optimal power of the PV system(the first scenario)

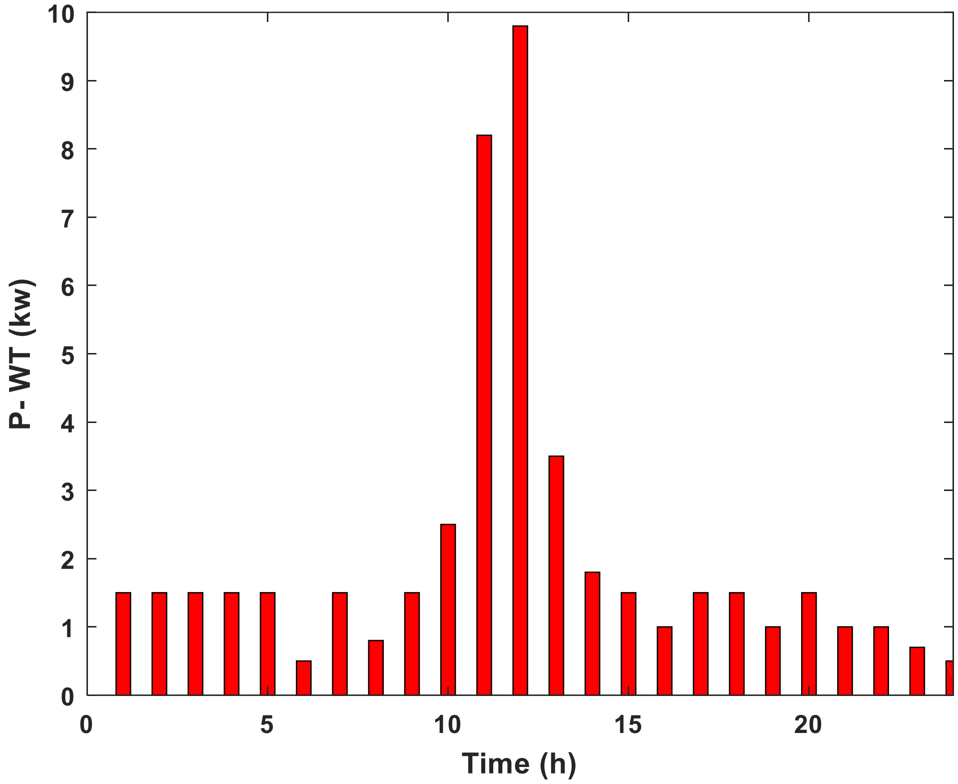

Figure 8: Optimal power of the wind turbine(the first scenario)

In this case (the second scenario), the battery is placed in the circuit with an initial charge equal to the rated capacity. Here, the network has a good opportunity to buy cheap electricity from the battery. In addition to ensuring the reliability of the microgrid, this scenario also reduces the costs associated with the upstream network during peak hours. The optimal distribution of power is shown in Figures 9 to 12 for this case. Considering the low cost of the energy provided by the ESS, it is more economical for the EMS to buy power from the battery during most of the day. Taking this system into account, the total operating costs are 332.7 dollars per day. It is clear that installing the ESS in the microgrid and considering its initial charge can yield total costs of $445.9-332.7=113.2 per day.

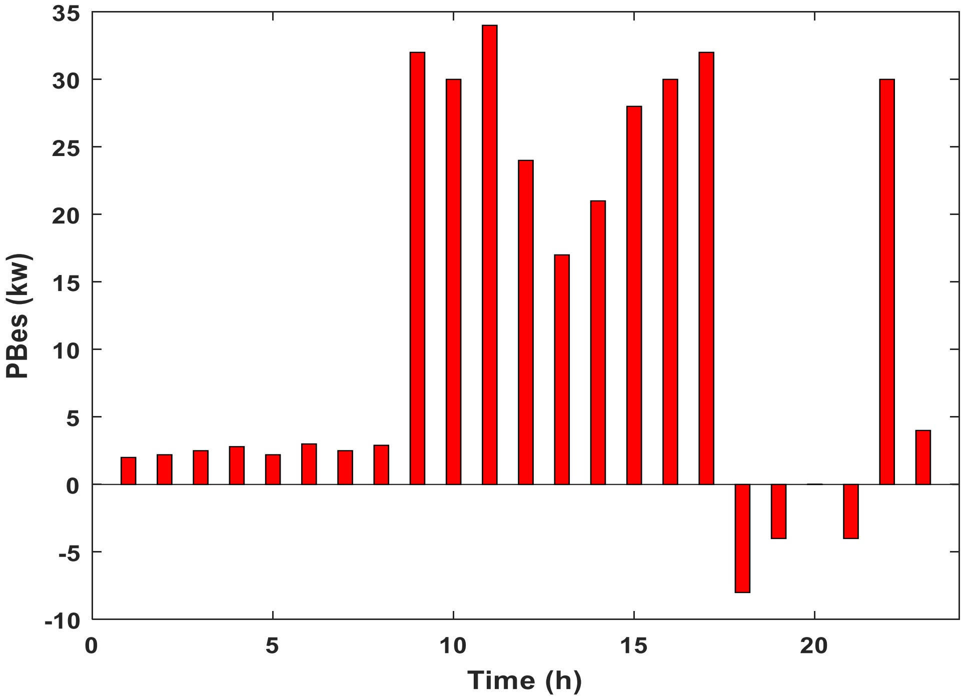

Figure 9: Optimal power of the ESS(the second scenario)

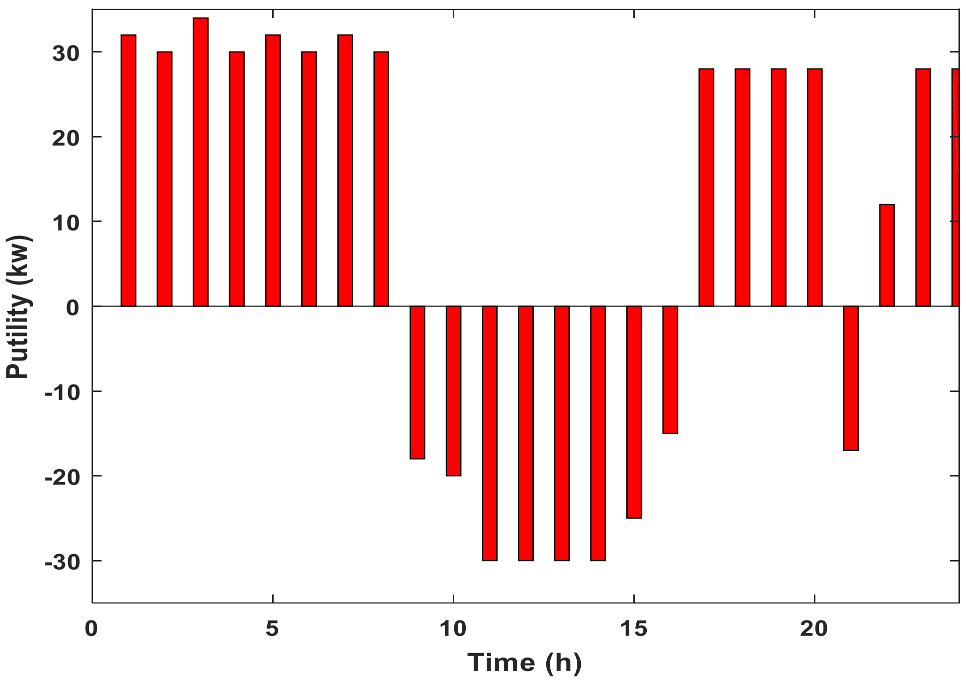

Figure 10: Optimal power of the upstream network(the second scenario)

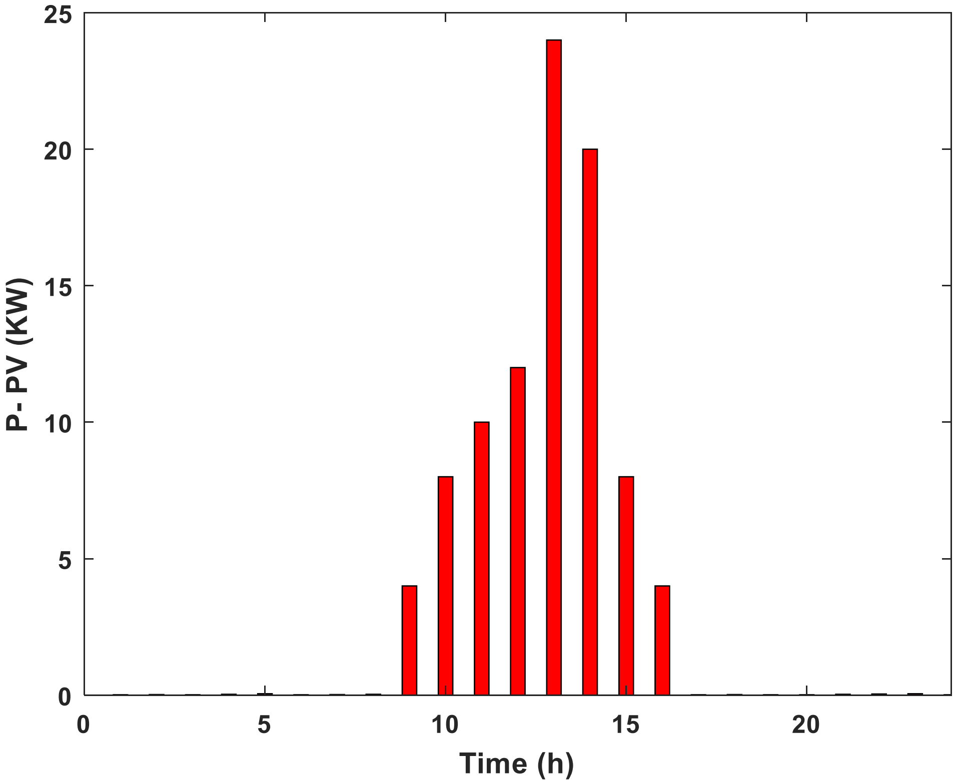

Figure 11: Optimal power of the PV system(the second scenario)

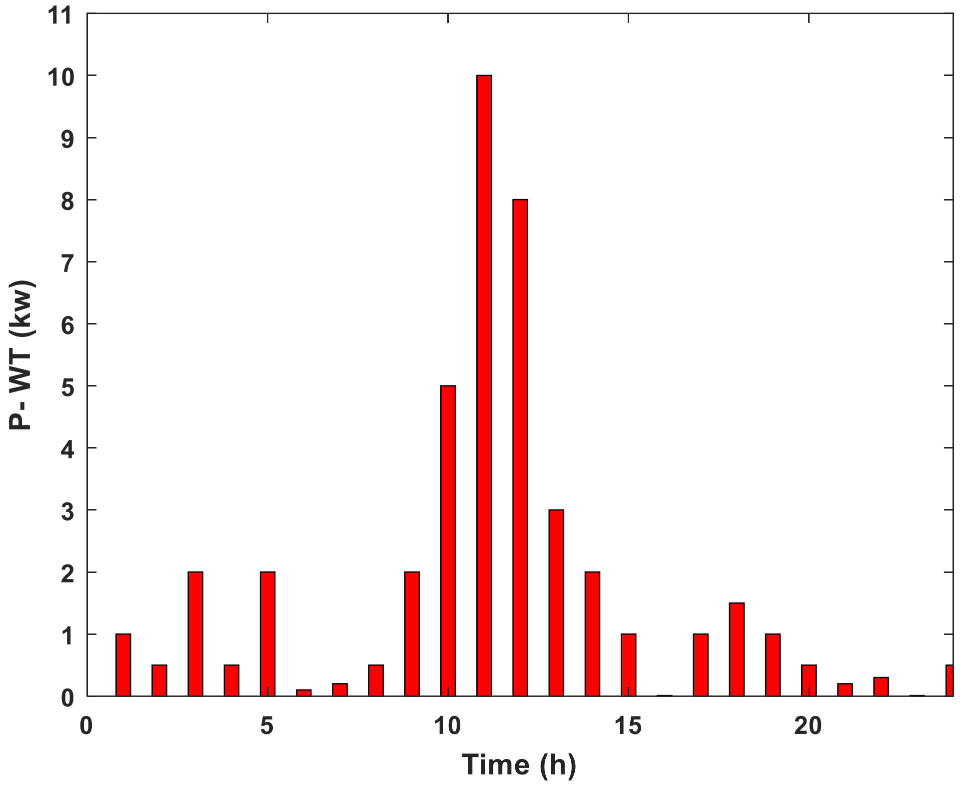

Figure 12: Optimal power of the wind turbine(the second scenario)

To validate the reliability of the microgrid, a simulation was performed. In this simulation, the battery was controlled via the droop control method, improving the transient stability of the system during emergencies. Note that, in the normal operating mode, the upstream network is connected to the microgrid. At t =20 s, due to an error, the microgrid was separated from the upstream network. When this happens, the aforementioned controller must ensure voltage and frequency stability by changing power references (Figures 13 and 14).

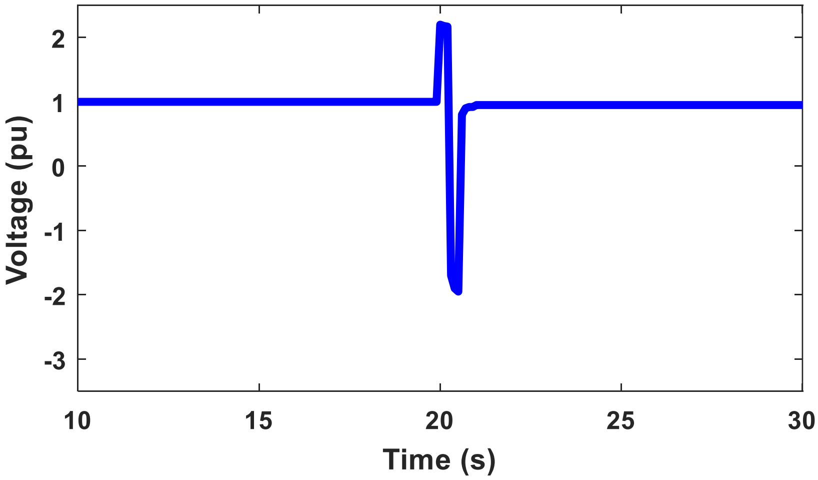

Figure 13: Microgrid voltage changes

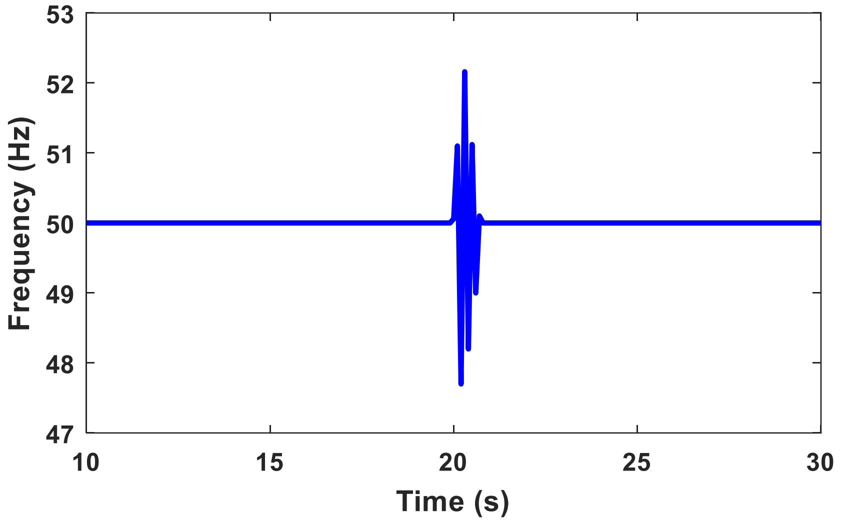

Figure 14: Microgrid frequency changes

7. Conclusion

In this paper, an optimization algorithm was used to determine the optimal capacity of battery systems. To this effect, the optimization problem was mathematically modeled while considering an objective function. This mathematical model was then coded in MATLAB. To validate the proposed algorithm, two different scenarios were considered. To evaluate the reliability of the system, a microgrid including a wind turbine and a battery that can be connected to the grid was simulated. The controllable unit (*i.e.*, the battery set and its inverter) was equipped with a droop controller. Then, the optimal battery capacity was calculated as the final capacity in a static simulation. The results show that the proposed control method ensures the transient stability of the system and provides reliability in the face of errors. Considering the technical advantages of battery energy storage units in microgrids aids in determining their optimal size. The main results of this work are as follows:

- The quantitative results of the case study show that the use of optimally sized batteries can reduce the cost of a microgrid. This is due to the fact that battery energy storage units can store excess power from renewable energy systems and redistribute it appropriately. Moreover, they can stabilize resource operation and reduce costs by lowering the switching frequency.

- Installing a battery energy storage unit with no initial charge reduces the costs by about 45% per day compared to a microgrid without ESS. In addition, an optimally sized battery with a pre-charge equivalent reduces the cost by about 74% in comparison with a grid that includes battery energy storage units with no pre-charge. Considering the discharge and charge efficiency of battery energy storage units also reduces their charging and discharging frequency.

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