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Optimal Scheduling of a Renewable-based Microgrid Considering Reliability Effect

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Abstract
In the microgrids, renewable energy resources (RERs) such as photovoltaic panels, wind turbines, wave energy converters, and current type tidal turbines can be used to reduce greenhouse gas (GHG) emissions arising from fossil fuel-based generation units. However, the generated electrical power of these RERs is dependent on the wave height and wave period, solar radiation, wind speed, and tidal current speed. Due to the wide variation in the RERs, the generated electrical power of these generation units changes a lot and so, to supply the local load in the isolated microgrid, the conventional generation units and the energy storage systems (ESSs) can be utilized. In this paper, optimal scheduling of a microgrid containing conventional generation units, ESS, and RERs including wind turbines, photovoltaic panels, current type tidal turbines, and wave energy converters is performed to determine the generated power of each generation unit provided that the cost function is minimum. In the cost function, the operation cost of the generation units based on fossil fuel and the penalty cost associated with the load curtailment as the reliability cost are considered, and using the particle swarm optimization (PSO) algorithm, the cost function is minimized. To study the capability and effectiveness of the presented approach, the numerical results associated with the optimal scheduling of a microgrid containing battery, RERs, and conventional units are presented.

Keywords: Microgrid, Reliability, Optimal Scheduling, PSO Algorithm, Variation.

1. INTRODUCTION

In recent years, due to the problems associated with the large-scale power plants

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and transmission networks such as high investment costs, the microgrids containing the interconnected loads and distributed energy resources have developed in distribution networks around the world. Due to the short distance between the generation and consumption, the reliability is improved and the voltage drop and power losses are reduced in the microgrids. The main advantage of microgrids is that they can include renewable resources to generate clean electricity. Fossil fuel-based power plants lead to greenhouse gas emission that results in environmental problems such as climate change and global warming. Thus, the microgrids utilized from the clean and renewable generation units are increasingly developed around the world. However, the generated power of the renewable resources changes widely and so, in the isolated renewable-based microgrids to supply the required loads, the other dispatchable generation units or energy storage systems must be utilized. The generated power of wind turbines, photovoltaic panels, current type tidal turbines, and wave energy converters depends on the wind speed, solar radiation, tidal current speed, and wave parameters including wave period and wave height. Due to the variation in the wind speed, solar radiation, the speed of tidal currents, and the wave parameters, the output power of these renewable units changes a lot. Thus, fuel-based generation units or the energy storage system must be used in the isolated microgrid at times when the generated power of renewable resources is less than the required loads. To optimally determine the generated power of dispatch able generation units in the micro grids numerous research is performed. In [1], optimal scheduling of an isolated microgrid consisting of diesel generators, wind energy, solar energy, and battery storage systems considering the lifetime degradation of battery is performed. In this paper, the operating cost of the microgrid considering the optimal capacity of the battery and the real-time operation cost of the battery based on the discharge depth at each time interval, is minimized using the firefly algorithm. In this paper, among different renewable resources, only the wind and solar energies are considered and the impact of the reliability indices on the operating cost is not considered. In [2], the short-term scheduling of a renewable-based microgrid containing tidal units and energy storage systems is investigated. In this paper, a current type tidal turbine installed in Lake Saroma is utilized in a real microgrid, and using the multi-objective modified bird mating optimization algorithm, the scheduling of the microgrid from environmental and economic points of view is performed. In this paper, the other renewable resources such as wind, solar, and wave are not considered and the reliability cost is not considered in the objective function of the microgrid. In [3], the operation and scheduling of the electrical loads in a highly automated and distributed cyber-physical energy microgrid is analyzed. Based on the characteristics and constraints of the electrical loads and battery storage systems, rigorous mathematical expressions are established for them to study the real-time scheduling in the microgrid using the significant moments analysis method. To perform priority-based energy management in the microgrid, the proposed method can pinpoint all the crucial moments and develop a dynamic model to present the scheduling behavior of the loads. The focus of this paper is on the electrical load modeling and the modeling of renewable resources and the impact of the reliability cost on the operation of the microgrid is not considered. In [4], the stochastic optimal operation of a system including wind turbine, photovoltaic panel, combined heat and power system, fuel cell, boiler, current type tidal turbine, and energy storage system considering demand response program and the associated uncertainties, is studies based on the scenario method. In this paper, the uncertainties including variations in the wind speed, tidal currents speed, the generated power of photovoltaic panel, market price, and the electrical and thermal load can be predicted using the hybrid method of wavelet transform. For this purpose, an improved artificial neural network based on the nonlinear structure is utilized to train and learn, and the imperialist competitive algorithm is used to extract the best weights and bases for minimization of the mean square error of predictions. In this paper, the wave energy converter, as a renewable generation resource with high generation power capacity, and the impact of the reliability indices on the operating cost of the system are not taken into account. In [5], using the hydrogen storage systems, optimal generation scheduling of renewable-based microgrid is performed. In this study, to minimize the operating cost of the overall microgrid, the uncertainties associated with the renewable resources and the required loads are considered using the generation of different scenarios. For this purpose, the probability distribution function of the forecasting errors associated with the wind speed, solar radiation, and required load is determined. The wave converters and current type tidal turbines are not considered in the understudied microgrid and the reliability cost associated with the load curtailment penalty is not discussed. In [6], the optimal scheduling of a current type tidal power plant is performed so that the maximum profit is achieved from selling the energy in an electricity market. In this paper, all technical operating constraints associated with the current type of tidal power plant are considered, and using the commercially available software, the resulting optimization problem that is a mixed-integer linear problem is solved. The focus of this paper is on the current type of tidal generation units and the other renewable resources such as wind, solar, and wave energies are not taken into account in the microgrid. In addition, the reliability of the microgrid is not studied. In [7], the economic operation of the island microgrid based on the optimal scheduling of the energy storage devices is performed. In this paper, in the grid-connected microgrid, the charging of the energy storage system occurs based on the state of charge condition at valley electricity price and the discharging of the energy storage device occurs based on the state of charge condition at peak electricity price. In the isolated microgrid, the charging and discharging of the energy storage system is done based on the renewable energy power generation and state of charge value. In this paper, the diversity of renewable energy resources considered in the micro grid is low and the reliability of the system is not considered. The uncertainty nature of renewable resources leads to new approaches must be introduced to study the effect of them on the scheduling of renewable energy-based microgrids. In [8], a new hybrid forecasting framework has been suggested in digital currency time series for minimizing the negative situation and improving the forecasting accuracy. In this paper, a hybrid forecasting model based on a long short-term memory neural network and empirical wavelet decomposition along with a cuckoo search algorithm is developed for digital currency time series. In [9], a nonlinear auto-regressive exogenous neural network is proposed to estimate the wind speed on three monthly data sets. In this paper, the first and the second order curve fitting coefficients of the measured pressure, temperature, solar radiation, and humidity parameters together with the wind speed are used. To estimate the wind speed, the most suitable features are selected with the relief technique for mean square error minimization. In [10], to predict the wind speed, a method based on the nonlinear autoregressive neural networks is proposed. For this purpose, the wind speed prediction model is developed that gives a minimum error for different hidden layer neuron numbers and delays step numbers. In this paper, to forecast the next wind speed, the one-minute time series is utilized with the nonlinear autoregressive neural network model. In [11], to estimate the solar radiation on the daily data set, machine learning techniques based on the linear regression and Gaussian process regression models are utilized. For this purpose, the measured wind speed, pressure, humidity, and temperature parameters together with solar radiation are taken into account to predict the process. In [12], regression learning approaches including linear regression, support vector machines, and Gaussian support vector machines are used for the estimation of the wind speed on monthly time series. For this purpose, the moving average, weighted moving average, and exponential moving average filters are implemented on the wind speed data set by using 3 and 10 delay times. In [13], a high-performance recognition model based on random forest with a feature selection method is proposed for solar radiation to cope with nonlinear dynamics of time series. For this purpose, 45 features are extracted from the wind speed, pressure, temperature, humidity, and solar radiation data using the moving average indicator. In [14], a three-axis gimbal system mounted on the mobile platform is modeled based on a nonlinear Hammerstein block structure to control using the model predictive controller. In this paper, the real-time target tracking performance under external disturbances is also improved by applying flight scenarios of unmanned aerial vehicles.

In the microgrids that have been studied so far, the combination of wave, wind, solar, and tidal energy that is suitable for islands and coastal networks is not considered. In addition, to optimize the operation of the microgrid, the cost associated with the reliability criterion arising from load curtailment is not taken into account. To fill this gap, in this paper, a stand-alone microgrid consists of different types of renewable resources including wind turbines, photovoltaic panels, wave energy converters, and current type tidal turbines is considered to supply the local loads. However, due to the uncertain nature of these renewable resources, fuel-based generation units and energy storage systems are added to the microgrid. Thus, the aim of this paper is to optimally determine the generated power of fuel-based generation units to minimize the operation costs of the microgrid including the operating cost of the fuel-based generation units and the penalty cost of curtailed loads, using a suitable algorithm. Among different heuristic optimization techniques, the particle swarm optimization method which is a population-based evolutionary approach, due to the many advantages over other optimization methods, is used to optimize the objective function of this paper [15]. The driven-free nature of the algorithm, less sensitive to the nature of the objective function, flexible to be integrated with other optimization methods to form hybrid algorithms, requires to less parameters for adjustment, easy to implement and program with basic logic and mathematical operation, independent on the initial solution to start its iteration, suitable for optimization the objective functions with stochastic nature and having the ability to escape the local minima, are some advantages of this heuristic technique to utilize for optimization of the problems such as economic dispatch, reactive power control, and power losses reduction, optimal power flow, power system controller design and neural network training in the power system [15]. In this paper, a greater variety of renewable energy resources including wave energy conversion devices, wind turbines, photovoltaic panels, and current type tidal turbines are considered in the understudied micro grid that is suitable for coastal regions and islands. The understudied microgrid is considered to work separately from the network and so, fuel-based generation units and energy storage systems must be established in the microgrid. In the objective function, in addition to the operating cost of the fuel-based generation units, the reliability cost associated with the penalty of the load curtailment is added. Thus, the novelties of the paper can be expressed as:

- A new combination of renewable resources including wind turbines, photovoltaic panels, current type tidal turbines, and wave energy converters based on the buoy technology, are proposed to be utilized in the microgrid. This mixture of renewable resources coincides with the microgrids located in the coastal areas and islands.
- To consider the reliability criterion as an important factor in the power system, the proposed cost function includes the reliability cost associated with the penalty of curtailed load as well as the operating cost of the fuel-based generation units.
- The impact of the battery on the microgrid scheduling is considered. For this purpose, all constraints associated with the battery storage system are taken into account.
- Due to the many advantages of the particle swarm optimization (PSO) method, this algorithm is utilized to optimize the cost function of the problem.

To achieve the aim of the study, this paper is organized as below: in the second, section different renewable resources operated in the understudied microgrid are introduced. In the third section, the scheduling problem including the cost function, the constraints, and the solving method is explained. Numerical results associated with the optimal scheduling of a renewable-based microgrid are presented in the fourth section. The discussion of the results and the conclusion of the paper are summarized in the fifth and sixth sections.

2. RENEWABLE-BASED MICROGRID

A microgrid is a single, controllable, independent power system consisting of distributed generation (DG), load, energy storage, and control devices, in which the distributed generation and energy storage are directly connected to the demand side in parallel [16]. The short distance between the generation units and the loads leads to less feeder loss and higher local reliability of microgrids. Due to the capability of the microgrid in autonomous control, protection, and management, a microgrid can operate in two modes including grid-connected or isolated modes. In this paper, renewable-based microgrids including wind turbines, photovoltaic panels, current type tidal turbines, and wave energy converters are studied. The other components of the understudied microturbine as presented in Fig. 1, are the fuel-based conventional generation units and the energy storage systems such as batteries.

2.1. Wind Turbines

The generated power of an air mass with velocity *v*, air density ρ passing through a wind turbine with area *A* can be calculated as [17]:

$$P = \frac{1}{2} C_P \rho A v^3 \quad (1)$$

C_P, or the Betz coefficient, defines the relationship between a wind turbine's generated power and wind speed. Manufacturers create power curves for wind turbines to depict this relationship. In Fig. 2, you can observe a typical power curve for a wind turbine. The turbine produces no power at speeds below the cut-in speed or above the cut-out speed. Power generated between the cut-in and rated speeds is proportional to v^3. The turbine maintains a constant power output equal to its rated capacity for speeds between the rated and cut-out speeds.

The hourly wind speed during a year is presented in Fig. 3. The wind turbine utilized in the understudied microgrid is based on the 3MW Vestas90 wind turbine technology and its power curve is presented in Fig. 4. Using the hourly wind speed and the power curve of the understudied wind turbine, the hourly generated power of wind turbine is calculated and presented in fig. 5.

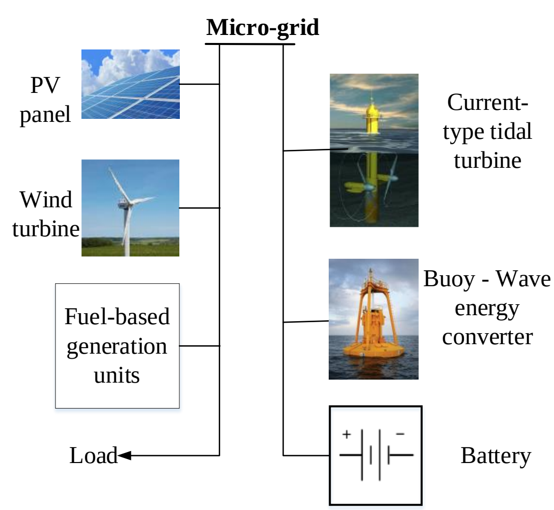


Fig. 1. The structure of the understudied microgrid.

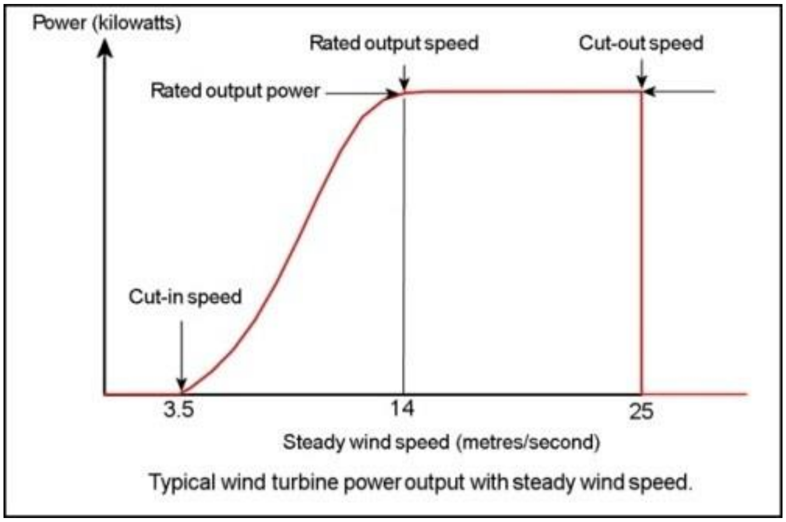


Fig. 2. Power curve of wind turbine [18].

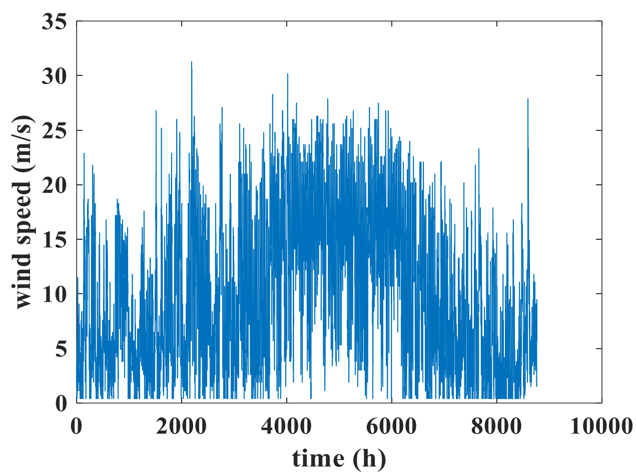


Fig. 3. The hourly wind speed during a year [19].

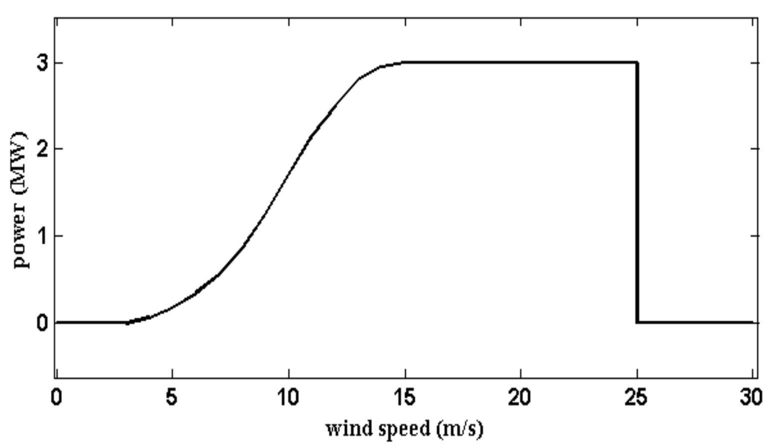
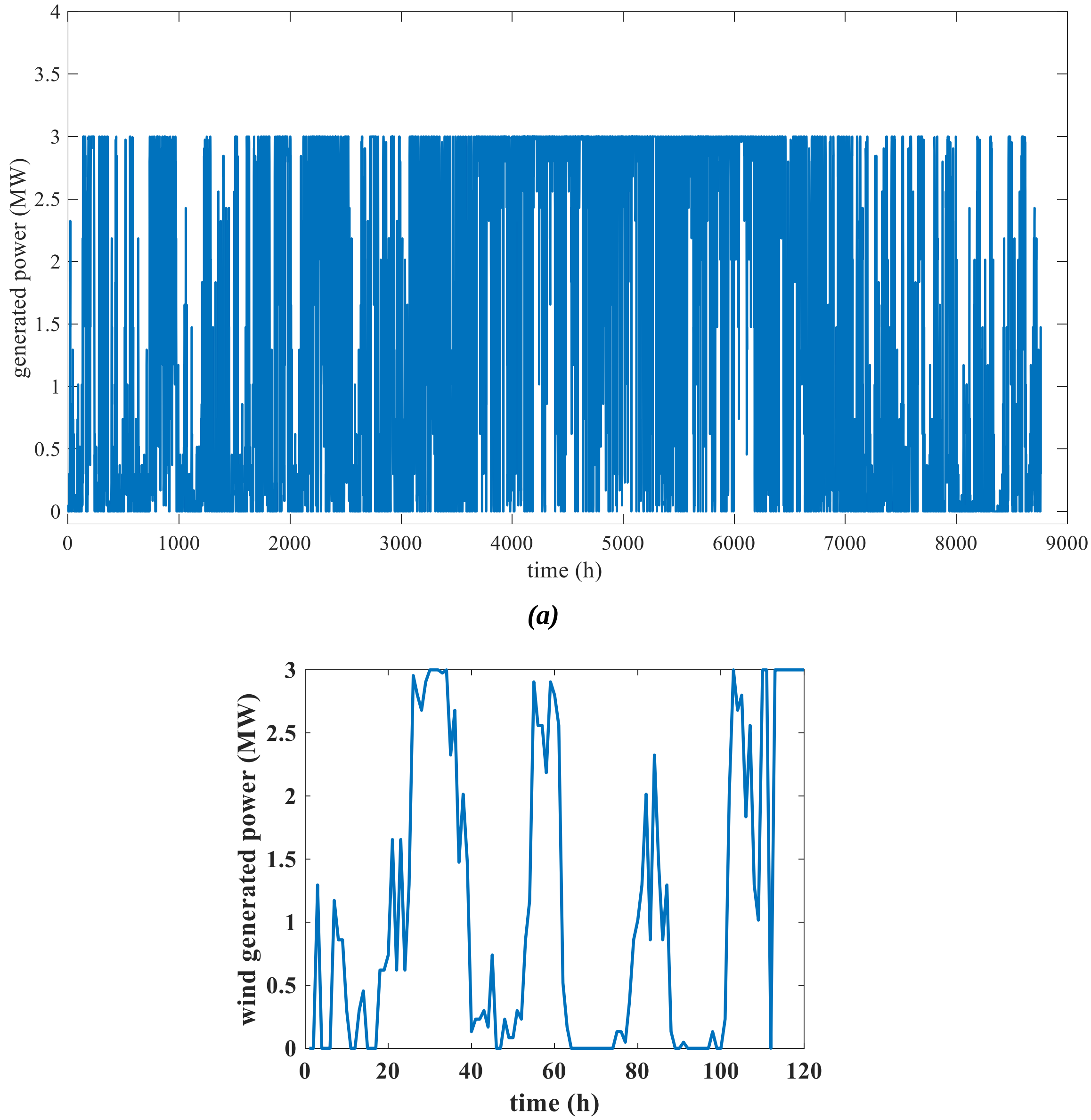


Fig. 4. The power curve of the V90 wind turbine [20].



(a)

(b)

Fig. 5. The generated power of wind turbine during (a) a year and (b) 5 days.

2.2. Photovoltaic (PV) Panels

A solar cell is a p-n junction that converts the solar radiation to the DC electric power [21]. A branch is composed of several series of solar cells and a photovoltaic panel consists of several parallel branches. In the PV panel, to generate the maximum power, a DC/DC converter named maximum power point tracker is utilized, and to convert the DC-generated power to AC power, an inverter can be used. The generated power of the PV system as equation (2), is dependent on the solar radiation (S), the number of panels (N_{PV}), the area of each panel (A_{PV}), the efficiency of the PV system (η_{PV}) including the efficiency of different components including PV panels and electrical converters.

$$P_{PV} = \eta_{PV} N_{PV} A_{PV} S \tag{2}$$

The hourly solar radiation during a year is presented in Fig. 6. A 3MW PV system composed of 5 600kw arrays, as can be seen in Fig. 7, is considered to be installed in the microgrid. Each array consists of 50 12kw sub-arrays and each sub-array consists of 40 300w panels. Each panel is composed of 3 parallel branches and each branch consists of 32 series solar cells. The capacity of DC/DC converters and inverters are respectively 12 and 600kw, respectively. The efficiency of panels and other devices including converters, wires, and connections are considered to be 18.4 and 90 percent, respectively. The area of the panel is considered to be $2m^2$ and in the solar radiation of $900 w/m^2$, the generated power of

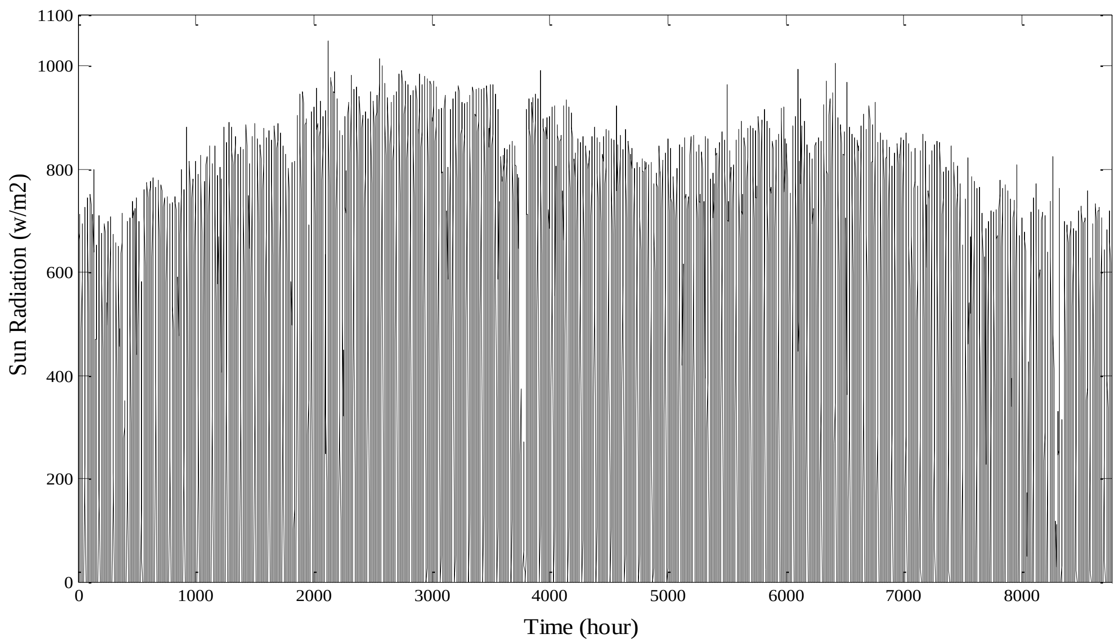


Fig. 6. The hourly solar radiation during a year [22].

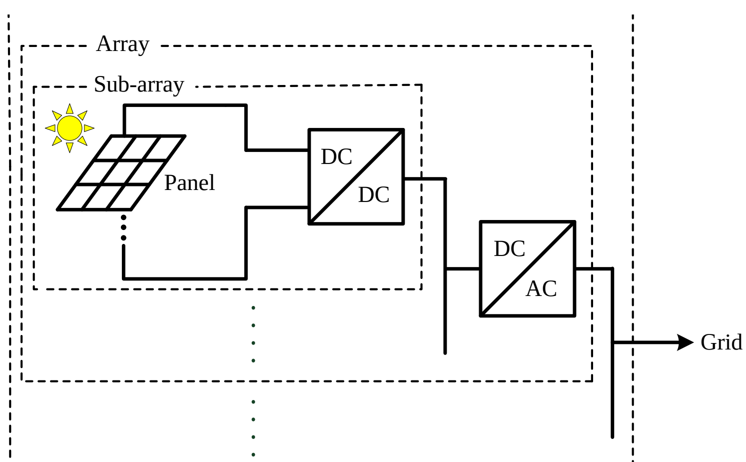
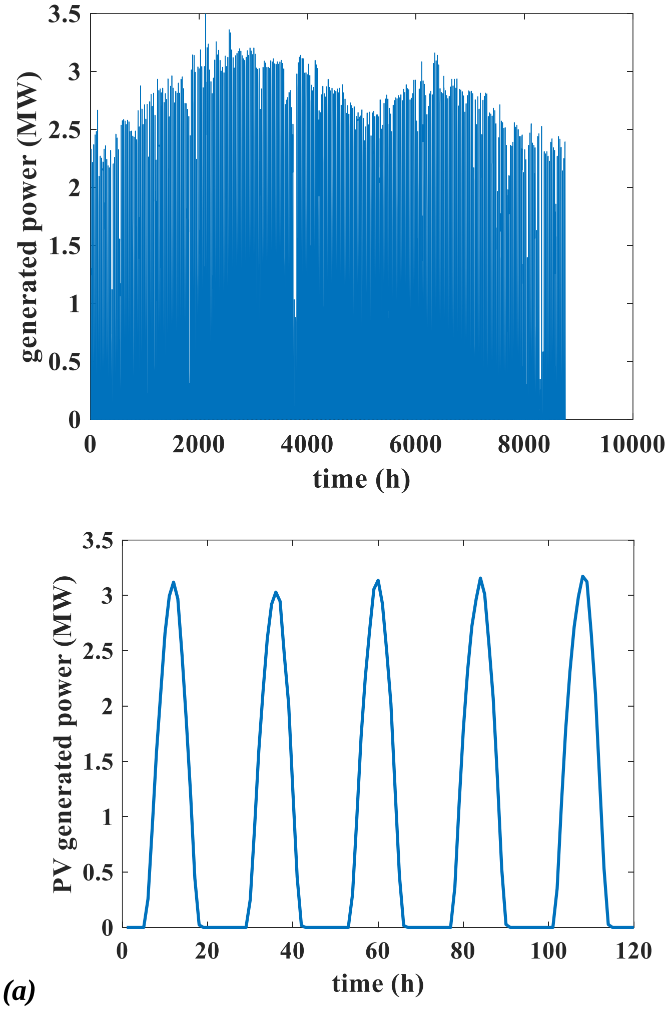


Fig. 7. The structure of the PV system [21].



(a)

(b)

Fig. 8. The generated power of the PV system during (a) a year and (b) 5 days.

the panel would be 300w. Thus, in the nominal solar radiation (900w/m^2) the generated power of the PV system would be 3MW. Based on the hourly solar radiation, the efficiency, and the area of the PV system, the generated power of the PV system is calculated and presented in Fig. 8.

2.3. Current Type Tidal Turbines

Tides occur due to the moon and Earth's movement relative to the sun, causing changes in sea levels and tidal currents. Extracting tidal energy involves two methods: barrage-type tidal power plants utilize sea level variations, while current-type tidal power plants convert kinetic energy from tidal currents into electrical power using turbines, similar to wind turbines [23]. The power generated by tidal currents, with velocity (v) and seawater density (ρ) (1025 kg/m3), passing through a tidal stream turbine with area (A), can be calculated as in equation (1). The relationship between tidal stream turbine power generation and tidal current speed is described by a power curve, akin to that of wind turbines. In tidal stream turbines, tidal current speeds are generally low and do not reach a cut-out value. A typical power curve for a tidal stream turbine is shown in Fig 9.

The hourly tidal current speed during a year and the power curve of current type tidal turbine based on the 2MW SeaGen technology are presented in Fig. 10 and 11. Using the hourly tidal current speed and power curve of the turbine, the generated power of understudied current type tidal turbines is calculated and presented in Fig. 12.

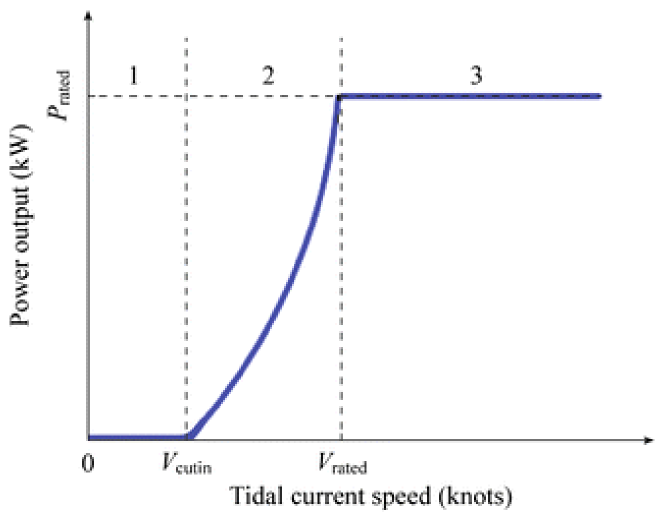


Fig. 9. Power curve of tidal stream turbine [24].

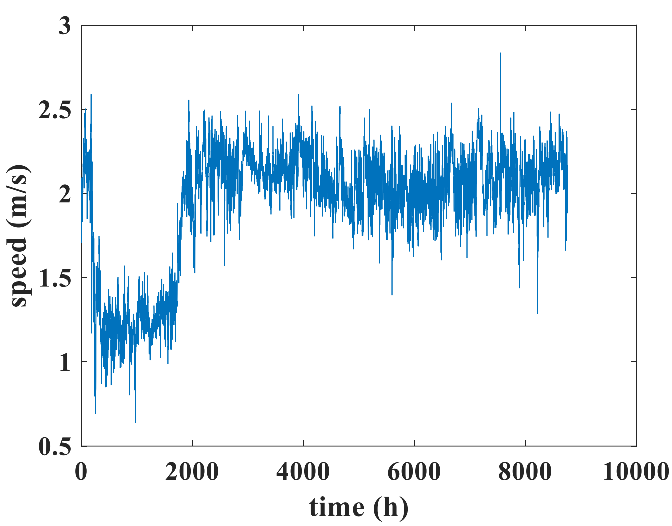


Fig. 10. The hourly tidal current speed during a year [25].

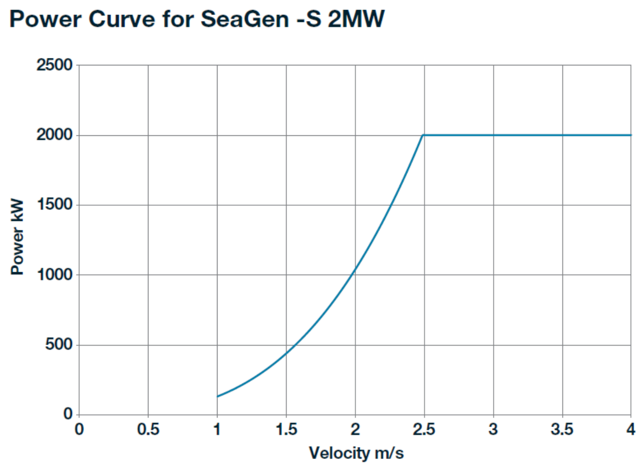
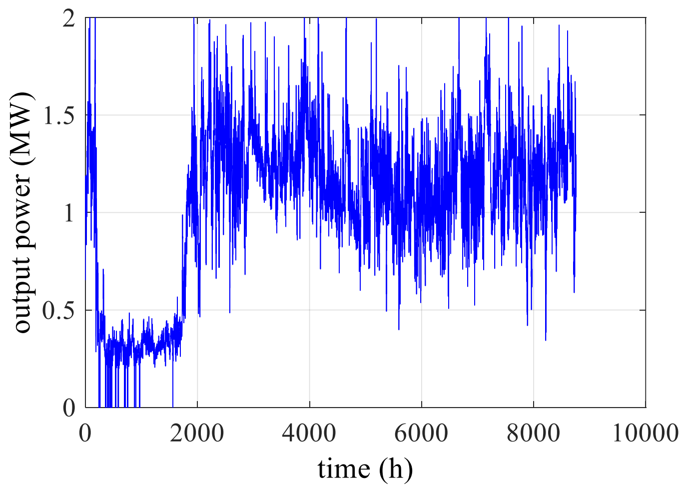
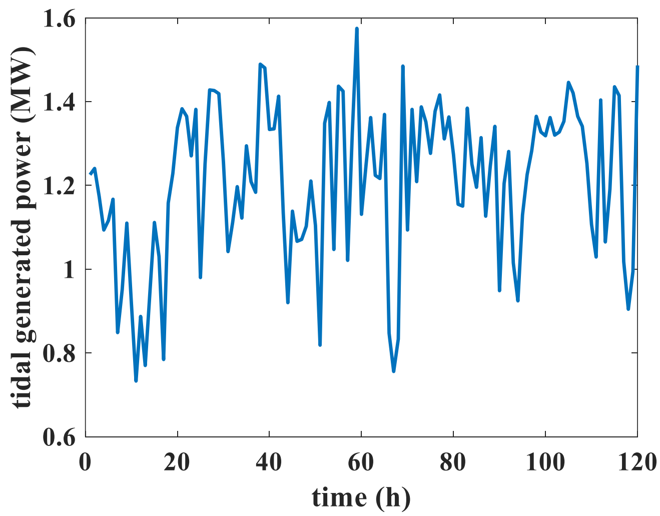


Fig. 11. Power curve of understudied tidal stream turbine [26].



(a)



(b)

Fig. 12. The generated power of tidal turbines during (a) a year and (b) 5 days.

2.4. Wave Energy Converters

The oceans cover more than 70% of the earth's surface and so the potential of this energy is estimated to be about four times the global required electricity demands [27]. Among different types of ocean energies including tidal, wave, ocean thermal energy, and salinity gradient energy, the potential of wave energy is more than the others estimated to be 2TW [28]. The wave energy flux associated to each meter of the crest length can be calculated as:

$$P = \frac{\rho g^2}{64\pi} T H^2 \tag{3}$$

where, ρ is the density of ocean water (1025 kg/m^3), g is the acceleration of gravity (9.81 m/s^2), *T* is the wave period and *H* is the wave height. There are three types of wave energy converters including oscillating water columns, oscillating body devices, and overtopping converters. In the oscillating water columns such as Limpet, Green Wave, Ocean Energy Buoy, and Oceanix, there is a semi-submerged chamber holding a trapped air pocket on top of the water column. When waves occur, the column acts like a piston that moves up and down results in forcing the air to escape and enter the chamber. This continuous movement of the air is passed through the Wells turbine and the electricity is generated using of the generator connected to the turbine. The oscillating body devices such as Power Buoy, Oyster, Seatricity, Pelamis, and Wave Star can be used floating or submerged, and using the different take off systems including hydraulic generators equipped with linear hydraulic actuators, linear electric generators, and piston pumps can convert the mechanical energy of waves to the electrical energy. The overtopping devices or terminators such as wave dragon are wave energy converters composed of a floating or bottom fixed water reservoir structure equipped with reflecting arms to collect the waves in the reservoir through a ramp structure. The reservoir is placed higher than the sea level and so when the water is returned to the sea through the turbines, the electricity is generated [29]. The dependency of the generated power of wave energy converters on the period and height of the waves is presented by the power matrix that is developed by the manufacturer. In this paper, the AquaBuoy as a wave energy converter is studied. This converter is floating on the ocean and can vertically move when the waves occur. The up and down movement of the buoy leads the attached tube to float in the water responses. The piston connected to the end of this tube leads to the movement of the hose pump. Due to the movement of the hose pump, the water is pressured and applied to the impulse turbine. The turbine is connected to a generator and the electricity is generated. In the understudied microgrid, 4 wave energy converters based on the 250 kw buoy technology are considered. The power matrix of this wave energy converter is presented in Table 1. The hourly wave height and wave period during a year are presented in Fig. 13 and 14, respectively. Using the hourly wave data and power matrix of the buoy device, the hourly generated power of the understudied wave energy converter is calculated and presented in Fig. 15.

Table. 1. ***The power matrix of 250kw buoy [30].***

T_p (s) H_s (m)	Power matrix (in kW)												
	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	8	11	12	11	10	8	7	0	0	0	0
1.5	0	13	17	25	27	26	23	19	15	12	12	12	7
2	0	24	30	44	49	47	41	34	28	23	23	23	12
2.5	0	37	47	69	77	73	64	54	43	36	36	36	19
3	0	54	68	99	111	106	92	77	63	51	51	51	27
3.5	0	0	93	135	152	144	126	105	86	70	70	70	38
4	0	0	0	122	176	198	188	164	137	112	91	91	49
4.5	0	0	0	223	250	239	208	173	142	115	115	115	62
5	0	0	0	250	250	250	250	214	175	142	142	142	77
5.5	0	0	0	250	250	250	250	250	211	172	172	172	92

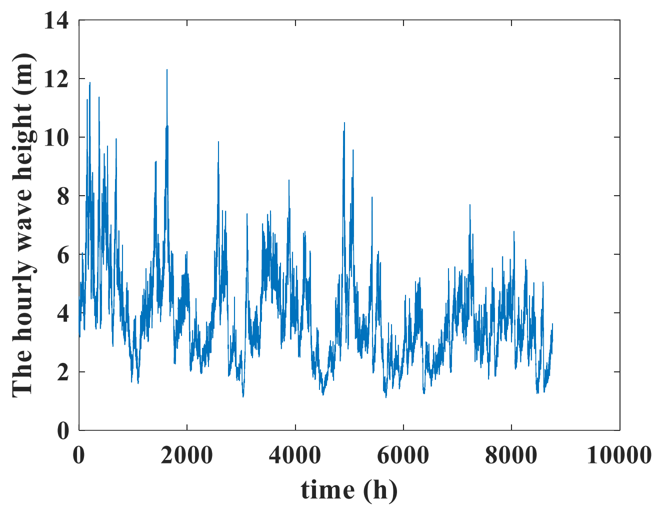


Fig. 13. The hourly wave height during a year [31].

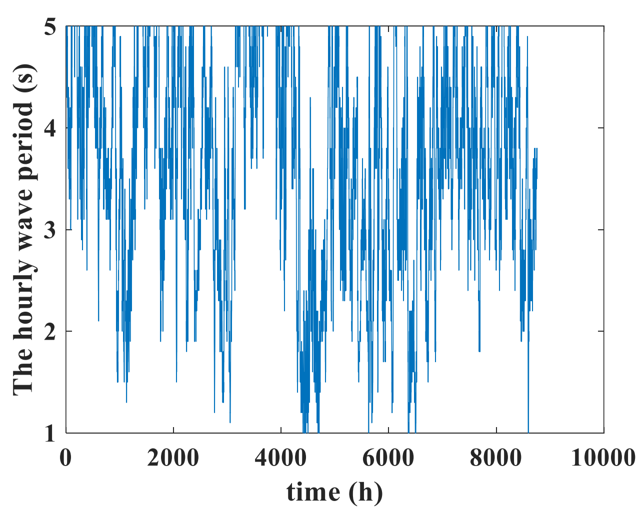
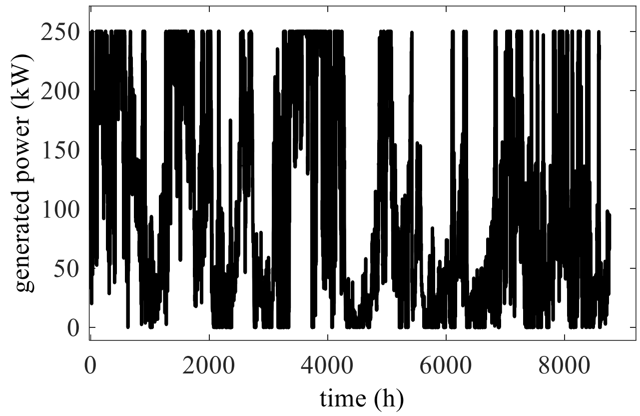
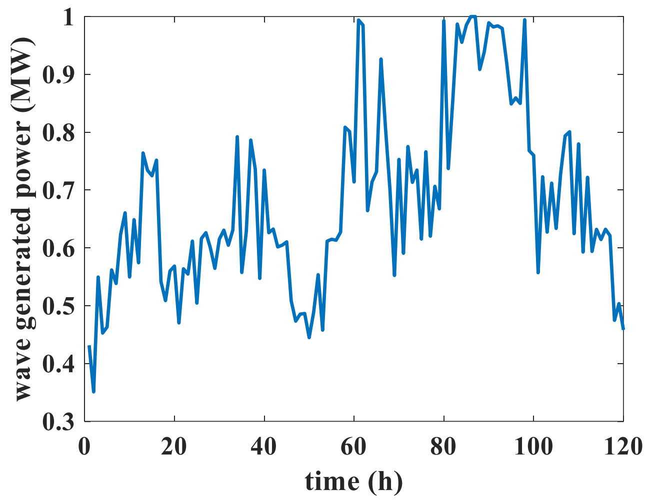


Fig. 14. The hourly wave period during a year [31].



(a)



(b)

Fig. 15. The hourly generated power of wave energy converter during (a) a year and (b) 5 days.

2.5. Energy Storage System

In this study, the microgrid is operated in the stand-alone mode, and so due to the variation in the generated power of renewable generation units, an energy storage system based on the battery is utilized in the microgrid to reduce the variation in the output power of the microgrid. The excess generated power can be stored in the battery when the generated power of the renewable resources is more than the required load, and when the required load is more than the generated power of the microgrid, the battery can discharge and provide part or all the rest of power required the load [32]. The characteristics of the understudied battery are 500kw capacity, 1000Ah, 500V, 1000A maximum discharging current, and 500A maximum charging current. The minimum capacity of the battery is considered to be zero, i.e. the battery can fully discharge.

3. OPTIMAL SCHEDULE SCHEME OF MICROGRID

This paper aims to investigate how renewable energy sources and energy storage systems impact the operation of a microgrid situated in coastal areas and harnessing ocean energies, including tides and waves. Because of the challenges associated with constructing transmission lines, this microgrid operates independently. It relies on wind, solar, tidal, and wave energy, along with fuel-based generators and energy storage systems, to meet its power needs.

Renewable energy sources like wind turbines, current-type tidal turbines, wave energy converters, and PV panels contribute power depending on available resources. However, since the output from these sources is variable and uncontrollable due to changes in wind speed, solar radiation, tidal current speed, and wave conditions, additional power generation units and energy storage systems are integrated into the microgrid. Even though renewable resources have no operating costs, fuel-based generators are utilized when there's a power deficit. In this microgrid, the maximum power generated by renewable sources is initially allocated to the load. If the load exceeds the renewable power generation, the energy storage system steps in to bridge the gap. When neither renewable sources nor the energy storage system can fully meet the load, the remaining power requirements are distributed among the fuel-based generators. If the renewable resources generate more power than the load requires, the surplus energy can be stored in the energy storage system.

The operating cost associated with the fuel consumption of dispatchable generation units is dependent on the generated power of these units as:

$$C_i = a_i P_i^2 + b_i P_i + c_i \tag{4}$$

where, C_i is the operation cost, and P_i is the generated power of i^{th} unit, and a_i, b_i, and c_i are constants. In this study, the scheduling of generation units is performed provided that microgrid operating cost is minimal. In operation studies of the understudied microgrid, in addition to the operation cost of fuel-based generation units, reliability cost is also considered. For this purpose, the interruption cost or penalty associated with the energy not supplied is determined as:

$$C_{\text{interruption}} = EENS \times VOLL \tag{5}$$

where, the EENS is the expected energy not supplied as a reliability index and the VOLL is the value of lost load that is expressed in $ per MWh [16]. Thus, the cost function of the microgrid including *n* fuel-based generation units associated with each hour that must be minimized is as:

$$\text{total cost} = \text{operation cost} + \text{reliability cost} = \sum_{i=1}^{n} C_{ih} + (EENS_h \times VOLL) \tag{6}$$

where, C_{ih} is the operation cost of i^{th} unit associated to hour *h*. The constraints of this problem are as below: the balance between generation and consumption must be established, i.e. total generated power that is the summation of produced power of the renewable and non-renewable power plants and battery (in charging state is minus and, in the discharging state is positive) must be equal to the required load. If the generated power of units and battery is less than the required load, some of the load is curtailed so the associated interruption cost must be taken into account.

$$P_{renewable}(h)+\sum_{i=1}^{n}P_i(h)+P_{battery}(h)= P_{load}(h)+lost\,load\ \ (h) \qquad (7)$$

where, $P_{renewable}(h)$, $P_i(h)$, $P_{load}(h)$, $P_{battery}(h)$ and *lost load(h)* are the generated power of the renewable power plants, generating power of i^{th} fuel-based generation unit, the required load, the power of the battery and the interrupted load in hour *h*, respectively. The produced power of dispatchable power plants must be in the permissible range so that:

$$P_{i\,\min} \le P_i(h) \le P_{i\,\max} \qquad (8)$$

where, P_{imin} and P_{imax} are respectively, minimum and maximum powers of i^{th} unit in hour *h*. The stored power of the battery must also be in the permissible range. The stored energy, charging, and discharging rate of the battery must be less than the associated maximum values. In this paper, to optimize the cost function, particle swarm optimization is utilized using MATLAB software. This optimization technique is a social search approach invented from the social behavior of birds. In the PSO

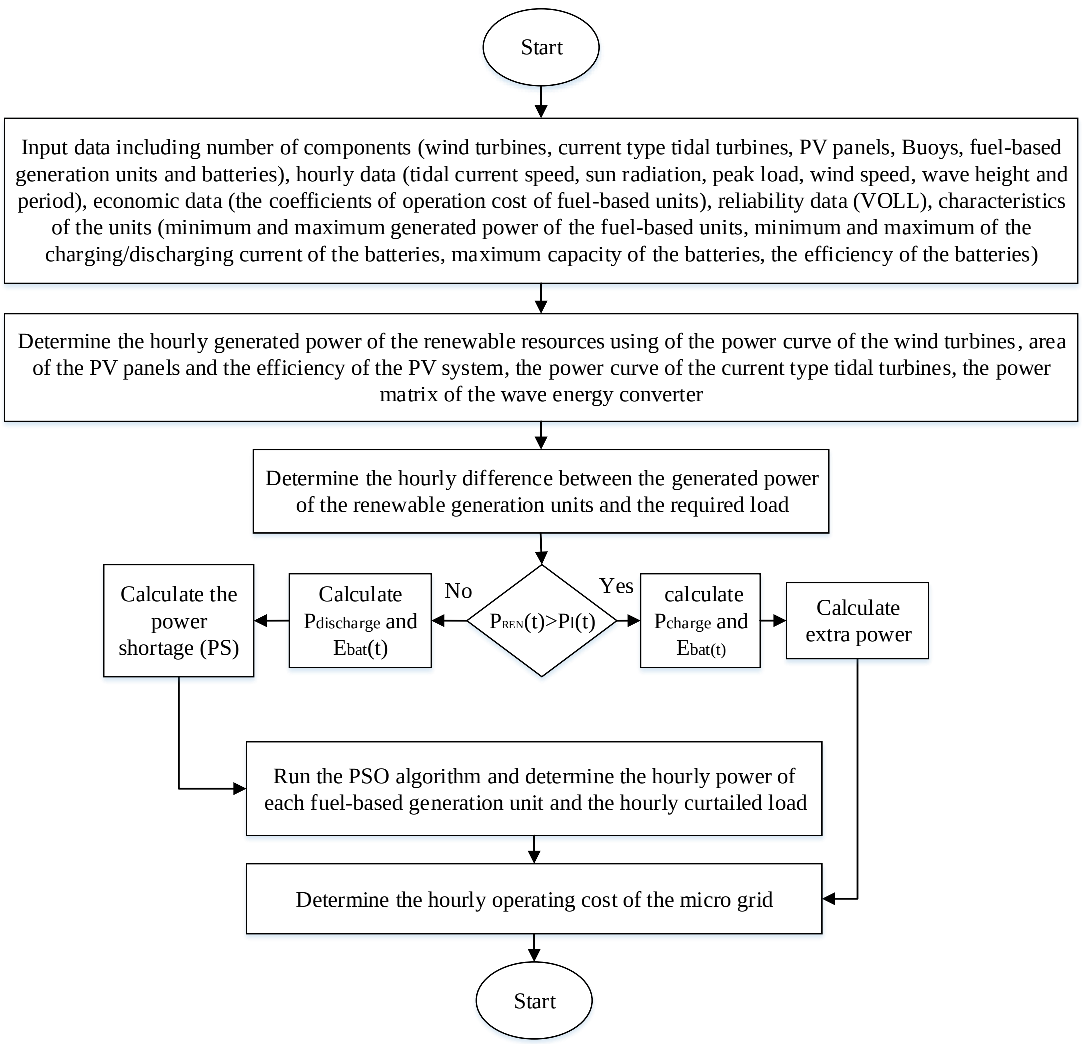


Fig. 16. The flowchart of the proposed method.

technique, at all moments, particles place their positions in search space at the best places they have ever been and the best places in their entire neighborhood [17]. Due to simplicity in the coding, high convergence speed, and low parameter regulation, the PSO algorithm is widely used in the scheduling of power systems and distribution networks, especially in the operation studies of the microgrids.

Thus, the proposed method for optimal scheduling of microgrid is performed in the following steps:

Step 1. All required data include hourly wind speed, the power curve of wind turbines, hourly sun irradiance, efficiency of the photovoltaic power plant, hourly tidal current speed, power curve of tidal turbines, hourly wave period and height, power matrix of wave converters, hourly demand, operating cost function of fuel-based generation units, minimum and maximum power of units, minimum and maximum power of batteries, maximum charging and discharging rates of the batteries, efficiencies associated to charging and discharging of batteries and value of lost load.

Step 2. At each hour, the generated power of renewable resources is determined. Then, according to the generated power of renewable resources and demand, the charging or discharging state of the batteries is determined.

Step 3. If the generated power of renewable resources and stored energy of batteries can not supply the required load, by optimization method based on the PSO, the generated power of fuel-based generation units and also the interrupted load are determined. In the optimization algorithm, the operating cost of fuel-based generation units and the penalty of interrupted load must be minimized.

Step 4. The proposed method is performed during the horizon of the operating study.

The flowchart associated with the proposed method used for optimal scheduling of the microgrid is depicted in Fig. 16.

4. NUMERICAL RESULTS

In this section, the optimal scheduling of a renewable-based microgrid is performed using the proposed technique, and the optimal generated power of dispatchable units is determined during 5 days.

4.1.The characteristics of the understudied microgrid

The understudied isolated microgrid consists of a wind turbine, a current type tidal turbine, four wave energy converters, a PV system, a battery, and three fuel-based generation units. The characteristics of the renewable-based generation units and the energy storage system of the understudied microgrid are given in Section 2. The constant parameters (*a*, *b*, *c*) associated with the operating cost *($/MW)* of three fuel-based generation units are presented in Table 2. In this paper, scheduling of the understudied microgrid is performed for 5 days (120 hours) and so, the generated power of these three units (three variables in each hour and 360 variables during 120 hours) is calculated using the optimization algorithm. The hourly peak load

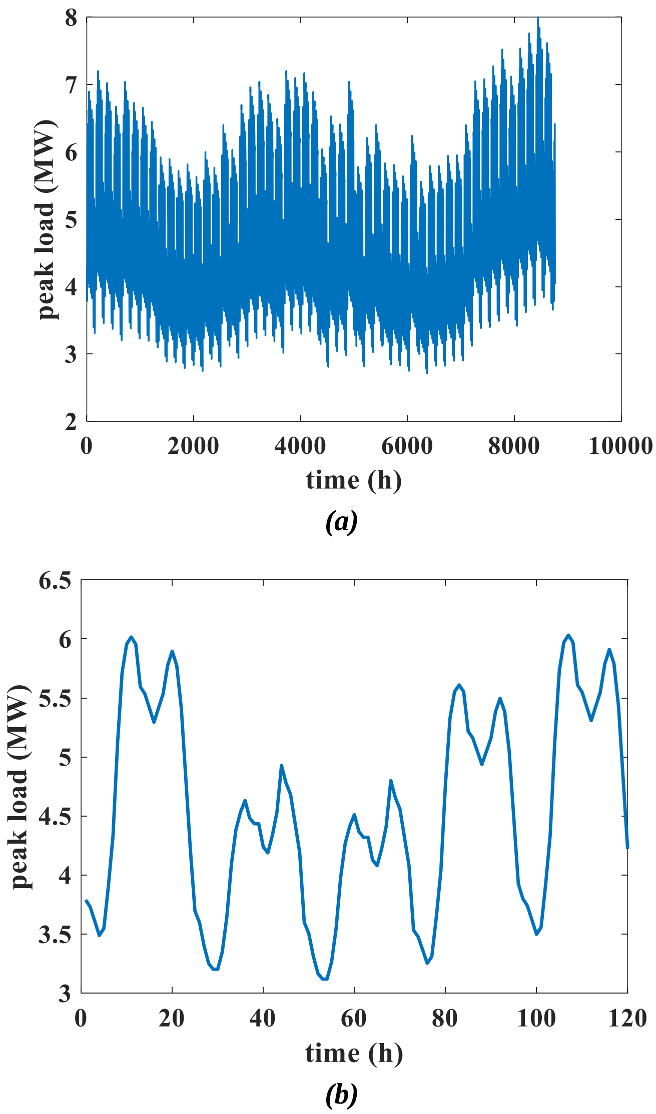
Table. 2. ***The cost function coefficient of fuel-based units [1].***

Parameters	for DG1	for DG2	for DG3
a	100	100	98
b	43.8	47.9	48.1
c	0.3	0.5	0.2

of the understudied microgrid during a year and 5 days is presented in Fig. 17. The generated power of the dispatchable units must be between 0 and 2 MW.

4.2. The Generated Power of Different Generation Units of The Microgrid

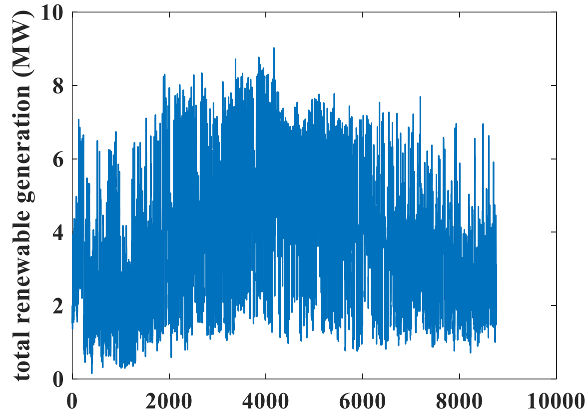
The PSO algorithm is repeated for 100 iterations to determine the generated power of each fuel-based unit in each hour. In this study, 100 populations are considered in the PSO algorithm. The value of the lost load is considered to be 3000 $ for a MW load interruption. In this paper, to perform optimal scheduling, first, the generated power of renewable resources is determined. Then, based on the generated power of renewable



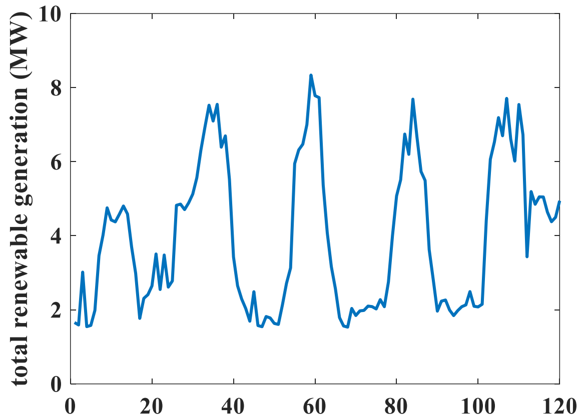
(a)

(b)

Fig. 17. The hourly peak load during (a) a year and (b) 5 days [35].



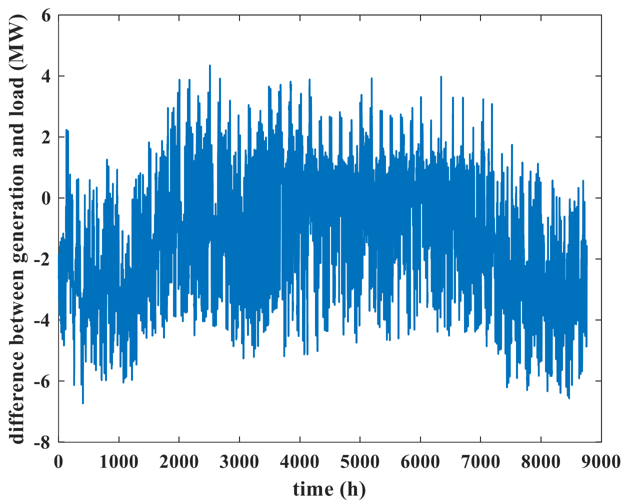
(a)



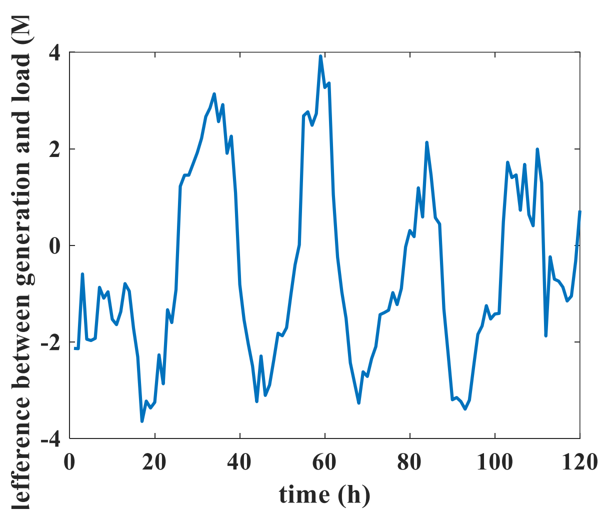
(b)

Fig. 18. The hourly total generated power of renewable resources during (a) a year and (b) 5 days.

units and the required load, considering the battery characteristics, the battery state of charge or discharge associated with the understudied hour is determined. The hourly total generated power of renewable resources, the hourly difference between the generated renewable power and the peak load, the hourly stored power in the battery, the hourly difference between the generated renewable power and the peak load considering the effect of the battery and the hourly remaining load that must be supplied by the dispatchable units, are presented in Fig. 18 to 22. As can be seen from the figures, the generated power of each renewable resource including wind turbines, PV panels, current type tidal turbines, and wave energy converters changes widely that has arisen from the variation in the wind speed, solar radiation, tidal currents speed, height and period of waves. However, the variation of the total generated power of the renewable resources is less than the variation of each individual generation unit. Thus, the proposed combination of understudied renewable resources in the microgrid leads to the variation of the generated power being reduced; as can be seen, the total produced power of renewable generation units is most of the time non-zero. However, due to the mismatch between the generated power of the renewable resources and the required load, the difference between the renewable generated power and the required load is both positive and negative. Thus, the energy storage systems must be used in the understudied microgrid to store the excess produced power of the renewable generation units and results in the economic operation of the microgrid. As can be seen from the figure, the battery is charged to full capacity when the renewable generated power is more than the required load and is discharged when the required load is more than the power produced by the renewable generation units. However, the excess power, i.e. the difference between the generated power of the renewable resources and the required load is around 0 to 4MW and so, the number of batteries or the capacity of the battery can be increased.

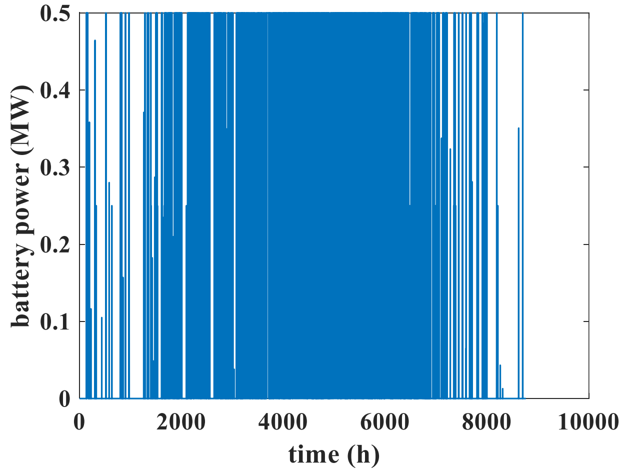


(a)

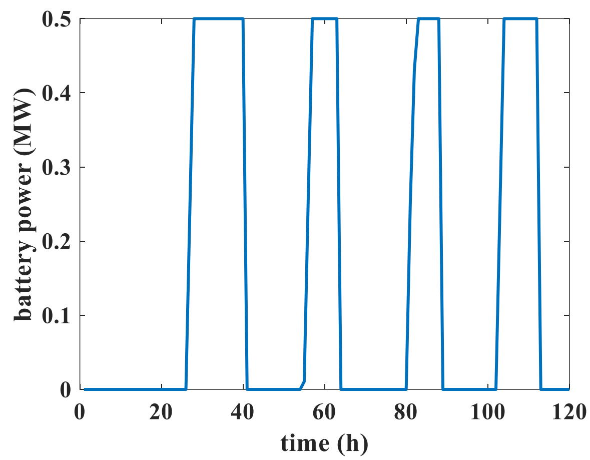


(b)

Fig. 19. The hourly difference between the renewable generated power and the peak load during (a) a year and (b) 5 days.



(a)



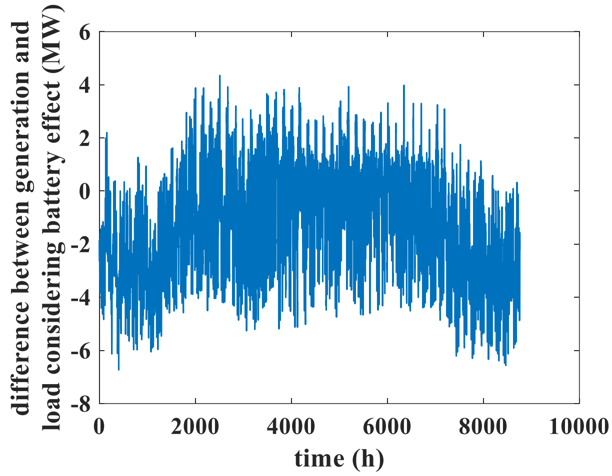
(b)

Fig. 20. The stored power in the battery during (a) a year and (b) 5 days.

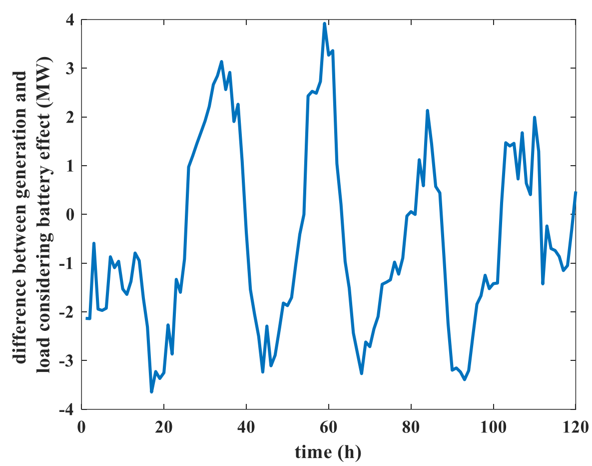
Using the proposed optimization algorithm, the generated power of the dispatchable generation units in each hour is determined and presented in Fig. 23. As can be seen from the figure, the required power optimally is dispatched on the fuel-based generation units. Because the coefficients of the unit cost function of the understudied generation units are almost the same, the power allocated to the units is almost the same. In some times such as 25 to 40 hours, the generated power of the renewable resources is adequately high to supply the required load, and so, the fuel-based generation units produce no power in these times.

4.3.The Operating Cost of the Microgrid

The hourly operating cost including the operation cost of the fuel-based units and the reliability cost arising from the penalty associated with the curtailed loads, and also the interrupted loads are presented in Fig. 24 and 25, respectively. As can be seen in the

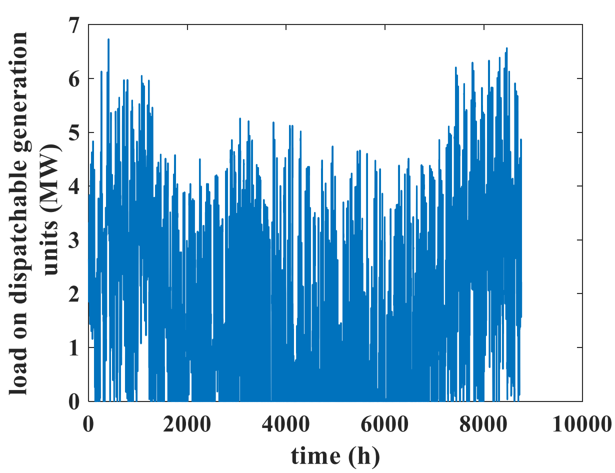


(a)

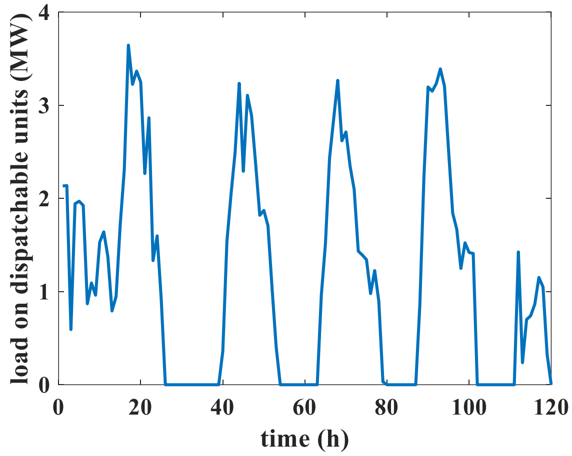


(b)

Fig. 21. The hourly difference between the renewable generated power and the peak load considering the effect of the battery during (a) a year and (b) 5 days.



(a)



(b)

Fig. 22. The hourly remaining load that must be supplied by the fuel-based units during (a) a year and (b) 5 days.

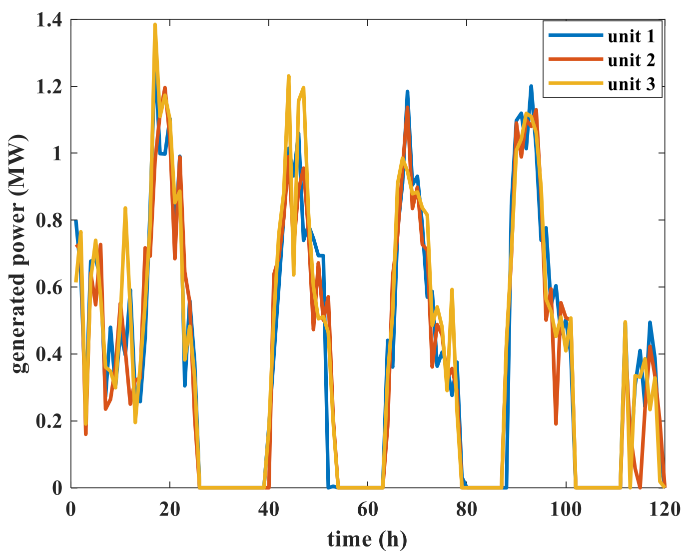


Fig. 23. The hourly generated power of dispatchable generation units during 5 days.

figures, the operating cost of the microgrid is zero, when the generated power of the renewable resources is more than the required load and the generated power of the fuel-based power plant is zero. However, when the generated power of the renewable resources is less than the required load, the fuel-based generation units produce the load shortage and so, the operating cost is not zero.

It is deduced from Fig. 25, that the load of the system is interrupted at some times, which shows that the cost of interrupting the load is less than the cost of power generation by the fuel-based power plants in those times. This is dependent on the value of the lost load associated with the load points and the cost of the power produced by the fuel-based power plants.

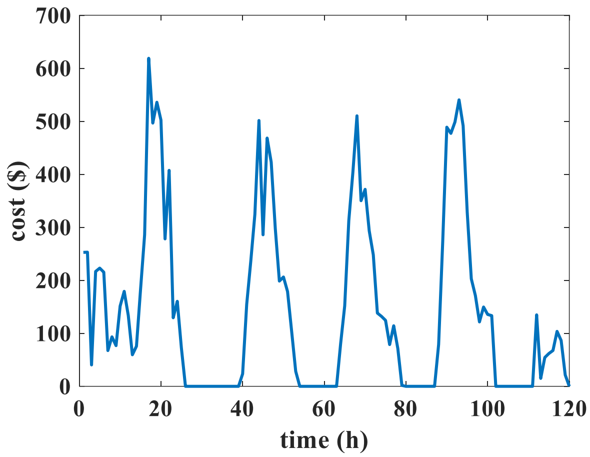


Fig. 24. The hourly operating cost during 5 days.

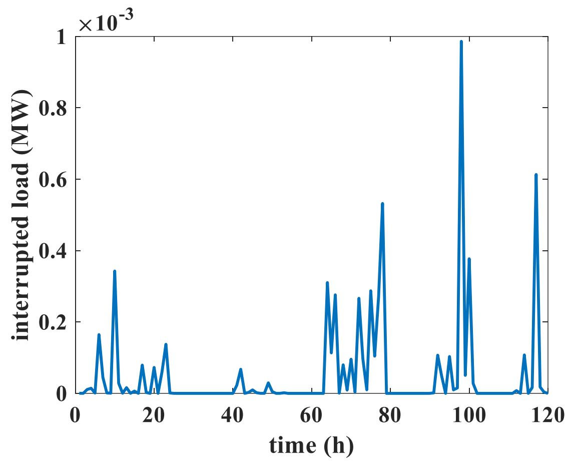


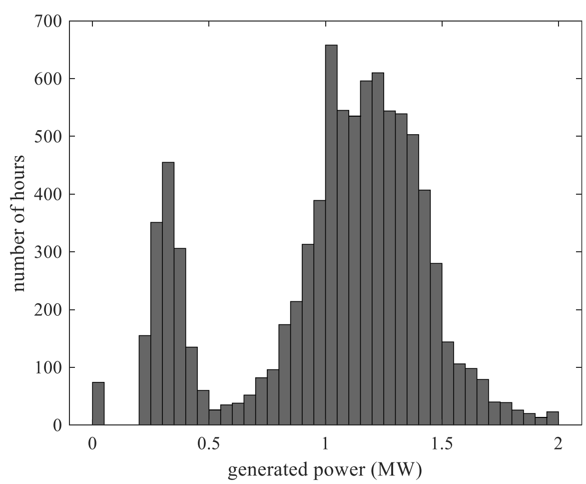
Fig. 25. The hourly interrupted loads during 5 days.

5. DISCUSSION

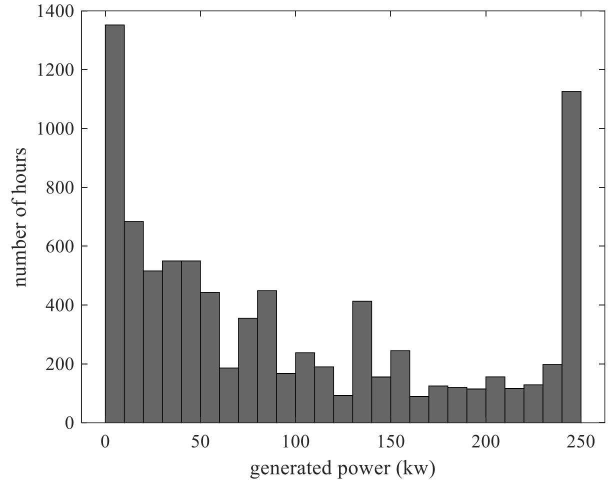
In this study, a renewable energy-based microgrid including a wind turbine, wave energy conversion device, PV panel, and current type tidal turbine is considered to work separately from the network and so, the fuel-based generation units and the batteries are established in the microgrid. It is deduced from the numerical results and the histogram of the generated power presented in Fig. 26 and 27 that the variation in the generated power of the individual renewable units is more than the total generated power of the renewable generation units. Thus, in the microgrid, the diversity of the use of different renewable resources causes the uncertain nature of the generated power associated with the renewable resources to be reduced.

In the stand-alone microgrids, the matching between the generated power of the renewable resources and the required load is important. If the peak and valley of the required load are coincident with the generated power of the renewable resources, the energy storage systems and the fuel-based generation units are not required in the microgrid. However, in the understudied microgrid, the peak of the generated power of the renewable units and the peak load do not occur at the same time so, the controllable generation units and the energy storage devices are required. It is concluded from the figures that, when the generated power of the renewable resources is low and the stored energy of the battery is insignificant, to supply the required load, the fuel-based generation units are committed to the microgrid and, thus, the operating cost of the microgrid is increased. In this study, the coefficients associated with the operation cost of the fuel-based generation units are almost equal and so, the generated power of the fuel-based generation units is almost the same. Thus, the results of the scheduling program are dependent on the variety of the renewable generation units considered in the microgrid, the coincident between the generated power of the renewable generation units and the required load, the capacity of the energy storage system, and the coefficients associated to the cost function of the fuel-based generation units. The other parameter that is effective in the numerical results is the value of lost load associated with different load points. If the value of reliability or the value of the curtailed load is higher than the operating cost of the fuel-based power plants, the curtailed load would be insignificant. In the understudied microgrid, as can be seen from Fig. 24, sometimes, the load is curtailed. Some discussions concluded from the insight of the main results are:

- The mixture of different renewable resources such as wind, wave, solar and tidal energies, results in the reduction of variation in the total generated power of renewable energy-based generation units.
- The reliability cost associated to the penalty of the curtailed load affects the scheduling program of the understudied microgrid. If the VOLL is high, the value of the interrupted load reduces.
- The results of the scheduling program are dependent on the variety of the renewable generation units considered in the microgrid, the coincident between the generated power of the renewable generation units and the required load, the capacity of the energy storage system, and the coefficients associated to the cost function of the fuel-based generation units.



(a)



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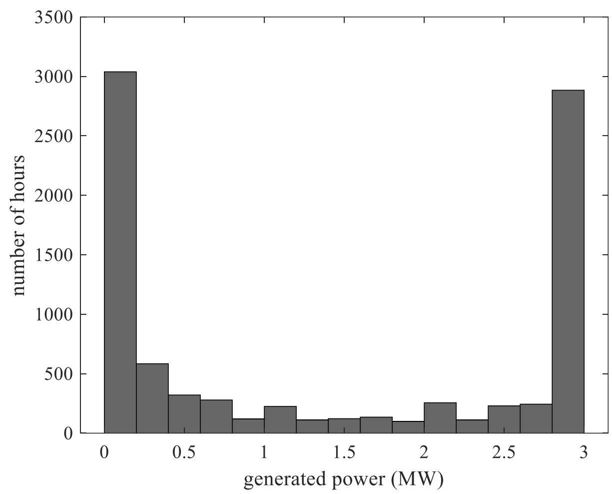
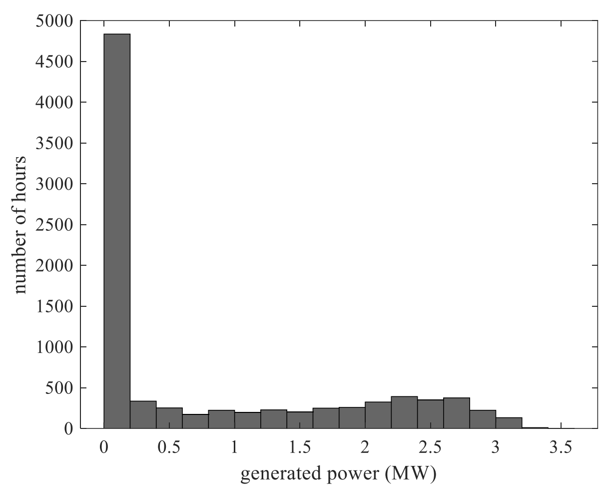


(c)



(d)

Fig. 26. The histogram of generated power of renewable resources, (a) tidal, (b) wave, (c) wind, and (d) PV.

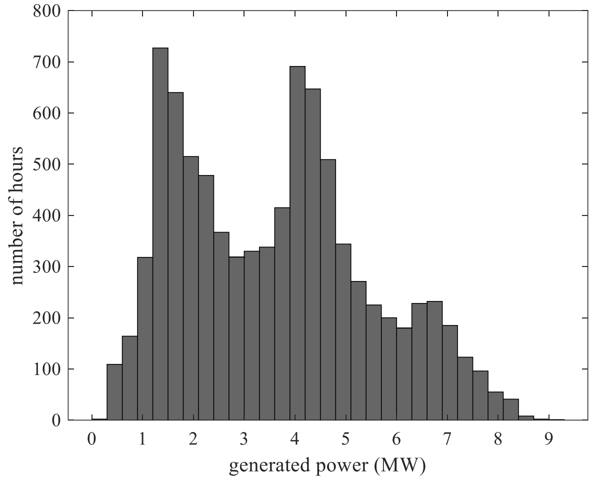


Fig. 27. The histogram of total generated power of renewable resources.

6. CONCLUSION

In this study, the optimal scheduling of a microgrid containing conventional generation units, energy storage system, and renewable resources including wind turbines, photovoltaic panels, current type tidal turbines, and wave energy converters is performed to determine the generated power of each generation unit provided. The mixture of the renewable resources considered in the understudied microgrid is coincident with the microgrids located in the coastal areas and islands. Due to the variation in the generated power of renewable resources, an energy storage system based on the battery technology and several dispatchable generation units are integrated into the understudied microgrid. In this study, all constraints related to the battery operation including the limitations associated with the stored power, stored energy, the charging and discharging rate, and the efficiency of the battery are taken into account. The objective function considered in this study includes the operating cost of the dispatchable generation units as well as the reliability cost associated with the penalty of the curtailed loads. To determine, the generated power of each fuel-based generation unit, the particle swarm optimization algorithm is utilized to minimize the objective function. In the reliability assessment of the microgrid, the time horizon of operation studies is short and so, it can be neglected from the failure of different generation units and also the battery. Thus, the reliability cost is considered to be the penalty associated with the curtailed loads that can be calculated by multiplying the expected energy not supplied by the value of the lost load. The proposed scheduling technique is applied to a renewable-based microgrid, and using the PSO algorithm in the MATLAB software, the generated power of each fuel-based generation unit and the interrupted loads in each hour are determined. It is concluded from the numerical results that, when the generated power of the renewable resources is low and the stored energy of the battery is insufficient, to supply the required load, the fuel-based generation units are committed to the microgrid and, thus, the operating cost of the microgrid is increased. In this study, the coefficients associated with the operation cost of the fuel-based generation units are almost equal and so, the generated power of the fuel-based generation units is almost the same. Thus, the results of the scheduling program are dependent on the variety of the renewable generation units considered in the microgrid, the coincident between the generated power of the renewable generation units and the required load, the capacity of the energy storage system, and the coefficients associated to the cost function of the fuel-based generation units. The other parameter that is effective in the numerical results is the value of lost load associated with different load points. If the value of reliability or the value of the curtailed load is higher than the operating cost of the fuel-based power plants, the curtailed load would be insignificant. In the understudied microgrid, as can be seen from the results, sometimes, the load is curtailed. It can be used from other renewable resources including barrage-type tidal generation units, ocean thermal energy conversion systems, heliostat generation units, and other wave energy converters such as limpet and sea-wave slot-cone generators in the understudied micro grid suitable for coastal areas and islands for future works. In addition, the objective function can include the environmental impact as emission cost associated with the fuel-based power plants. To select the best heuristic method, other optimization methods can be used and compared, to optimize the objective function of the study.

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