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Optimal Operation of Microgrids Containing Tidal Barrage with Hydro-Pumps

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Abstract— *For providing required load in n coastal and island regions, tidal barrage can be integrated in microgrids. To produce electricity from tides, in tidal barrage, water is moved between sea and reservoir through sluices containing turbines to generate electricity. In operation phase, produced power of tidal barrages depends on number of turbines, sluices and hydro-pumps. Thus, to maximize generated energy of tidal barrage, optimum number of turbines, sluices and hydro-pumps can be obtained through heuristic optimization techniques. Because of tidal level variation, generated power of tidal barrages changes over time. Thus, for load supplying, other renewable resources such as photovoltaic units, batteries, fuel-based generation units and grid-connected mode of microgrid are utilized. In this research, two-stage optimal operation of microgrids composed of tidal barrage, photovoltaic units, batteries and fuel-based generation units is done. In first stage, optimum number of turbines, sluices and hydro-pumps related to tidal barrage is determined for maximizing produced energy of tidal unit during time horizon of the study. In second stage, remaining load of microgrid is provided by photovoltaic units, batteries, fuel-based generation units and main network. To this end, generated power of fuel-based plants and power exchanged between microgrid and main grid are determined for minimizing operating cost of microgrid. The operating cost including operating cost of fuel-based generation units, cost of exchanged power between main grid and microgrid and penalties of load curtailment is optimized using particle swarm optimization method. Numerical results presents among different optimization algorithms, particle swarm method has performed best in operation studies of tidal barrage. For understudied microgrid, maximum generated energy of tidal barrage is 25.052 MWh, and minimum operating cost of the microgrid is 39868 $.*

Keywords—Barrage type tidal power plant, Battery, Microgrid, Optimal operation, Photovoltaic system.

NOMENCLATURE

Parameters	Description	Dimension
P	Produced power of tidal unit	Watt
η_{TUR}	turbine efficiency	Dimensionless
η_{GEN}	generator efficiency	Dimensionless
n_{TUR}	Number of turbines	Dimensionless
n_S	Number of sluices	Dimensionless
n_P	Number of hydro-pumps	Dimensionless
ρ	seawater density	kg/m^3
g	gravitational acceleration	m/s^2
h_R	reservoir level	m
h_E	sea height in ebb occurrence state	m
q_E	water flow rate of turbines in ebb occurrence state	m^3/s
q_{En}	nominal water flow rate passing through turbines in ebb occurrence state	m^3/s
$D_{HUB-TUR}$	tip diameter of turbines	m
$D_{TIP-TUR}$	hub diameter of turbines	m
q_F	water flow rate of the sluices at flood occurrence mode	m^3/s
h_F	sea height in flood occurrence state	m
W_S	width of sluices	m
P_{con-P}	Hydro-pump consumed power	Watt
q_P	Hydro-pump water flow rate	m^3/s
η_P	hydro-pumps efficiency	Dimensionless
$P_{PV}(r,\theta)$	Power of PV system in solar radiation and air temperature r and θ	Watt
r_0	Solar radiation intensity associated to the test conditions	Watt/m^2
θ_0	Air temperature associated to the test conditions	$^{\circ}C$
N	number of panels	Dimensionless
P_{P0}	nominal power of each panel at the test conditions	Watt
β	temperature coefficient associated to power parameter	Dimensionless
$C_k(t)$	operating cost of kth plant at time t	$
$P_k(t)$	generated power of kth plant at time t	Watt
a_k, b_k, c_k	constant coefficients associated to kth generation unit	Dimensionless
$P_{bat}(t)$	power of batteries at time t	Watt
n_{bat}	number of batteries	Dimensionless
P_{ch-max}	allowable maximum charging power of the batteries	Watt
η_{ch}	battery charging efficiency	Dimensionless
$P_{PV}(t)$	produced power of PV system at time t	Watt
$load_{rem}(t)$	remaining load of microgrid at time t	Watt
$E_{bat}(t)$	energy stored in batteries at time t	Wh
$E_{bat}(t-1)$	energy stored in batteries at time $t-1$	Wh
e_{max}	allowable maximum stored energy of batteries	Wh
$P_{dis-max}$	maximum allowable discharging power	Watt
η_{dis}	discharging efficiency	Dimensionless
E_{min}	minimum allowable stored energy of batteries	Wh
T	time horizon	h
$CL(t)$	curtailed load	Watt
$VOLL$	Value of lost load	$/MWh
$P_{ex}(t)$	exchanged power	Watt
$P_r(t)$	price of the electricity at each time	$

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Research Paper

1. INTRODUCTION

Due to accurate predictability, high potential and large capacity, barrage type tidal power plants can be used for providing required load of coastal regions and islands. These units can be integrated into microgrids containing other renewable and non-renewable generation plants. In addition to tidal barrages, potential of solar energy in different regions of world is high, and so, photovoltaic (PV) systems can be used in the microgrids to produce electricity. However, the produced power of tidal barrage and PV systems is dependent on tidal height and solar radiation intensity. Variation in solar radiation and tidal height results produced power of PV systems and tidal barrages changes over time. Thus, due to output variation of renewable generation plants, planning and operating studies of microgrids containing these units have challenges that must be studied. For this purpose, numerous researches are performed.

1.1. Literature review

To optimally schedule microgrids containing renewable resources such as tidal barrage, numerous researches related to microgrid scheduling and tidal barrage optimization are reviewed. In [1], optimal sizing and energy scheduling of a standalone microgrid is performed through firefly algorithm. The proposed hybrid microgrid is composed of wind units, photovoltaic modules, diesel generators and batteries. This research minimizes operating cost of standalone microgrid by economic scheduling of generation units considering optimal capacity of the battery. Paper [2] proposes a short-term planning of a microgrid containing renewable energies. It contains several objectives related to tidal generation units and energy storage systems. This paper suggests an efficient optimization algorithm for solving a problem with two objectives including environmental and economic aspects of understudied microgrid including PV units, micro-turbines, fuel cells, current type tidal turbines and energy storage systems. In [3], an efficient energy management system is proposed to optimally schedule a microgrid containing large pumps for industrial processes. The understudied microgrid is composed of diesel generators, batteries, PV systems, flexible and interruptible loads. The proposed optimal scheduling approach is done at two levels. At first level, the formula associated to pump planning and load interruption is developed and solved. At second stage, the solution of optimal power flow problem is obtained for verification feasibility of the method applied to understudied microgrid with network constraints. Paper [4] suggests a novel system for microgrid energy management that is suitable for use in sustainable power networks. This research develops an advanced framework for energy management to achieve a suitable structure of distributed units combined with economic dispatch. The proposed economic dispatch is based on optimal power flow containing single time interval. In [5], optimal power operation planning of microgrids for electricity market studies is done. This research suggests scenario-based approach for modelling uncertainties associated to renewable resources. In the proposed optimal scheduling of multiple-coupled microgrids, for maximizing expected profit of every microgrid and mitigate the distribution power losses, the local power trades among all microgrids are performed. Paper [6] proposes priority-based novel strategy for energy scheduling of isolated microgrids designed in event of disasters or attacks. In this research, the customers with higher priority must be reliable, and so, a model based on goal programming containing positive and negative variables is suggested. The proposed method is performed in four steps including data collection through smart meters, priority determination, energy planning and power generation or power consumption. Paper [7] proposes an optimization model used stochastic programming approach containing risk neutral and risk-averse states. This model can be used for day-ahead planning and operation control of the microgrid containing uncertainties. The proposed microgrid is composed of PV systems, wind turbines, generation units equipped to gas, energy storage systems, combined heat and electricity plants and integration into main network. Paper [8] suggests four approaches for enhancing produced energy of tidal barrage. In first stage, optimal design of tidal barrages is performed and optimum values for number and diameters of turbines, number and width of sluices are obtained by particle swarm technique. In second approach, the plant produces electricity in ebb state. In third stage, optimum number of turbines and gates at different times of operation is determined through particle swarm optimization method. In the last stage, produced energy of tidal barrage improves by hydro-pump. In [9], present and future status of tidal barrages and techniques for tidal units optimization are discussed. This research develops different types of tidal units such as lagoons, barrages and stream turbines. This paper suggests energy storage systems for reducing variability of produced power of tidal barrage. Besides, for improving produced power of tidal barrages, optimal value of start and stop times of pumping are calculated. In [10], simulation-based methods are proposed for operating tidal barrage in optimal manner to determine operation modes of tidal barrages, and start and stop times of gate and, also turbine operation time. To evaluate the suitability of proposed method, a practical case study is examined.

Paper [11] studies scheduling of microgrids containing renewable resources from environmental and economic points of view. In this research, direct search domain approach is proposed for computing combined environmental and economic dispatch in microgrids containing photovoltaic units, batteries, fuel cells, wind units and micro-turbines. Besides, for trade off among entire Pareto optimal points, fuzzy method is implemented. Paper [12] proposes energy management technique for microgrids containing renewable energies. In this research, a day-ahead energy management for microgrids with demand side response program is suggested for maximizing social welfare of the network. To this end, accelerated distributed optimization technique according to alternative direction approach of multiplier is suggested. Paper [13] suggests probabilistic power flow to minimize losses of balanced islanded microgrids. In this research, normal distribution is proposed to model uncertainty nature of load. In the proposed power flow analysis, the constraints including power balancing, droop control mode of generators, angular reference and probability of providing frequency limits of microgrid are considered. Paper [14] evaluates distributed cooperative resource management for microgrids. In this research, a distributed fixed-time consensus method is proposed for integrating economic dispatch and demand side response program. For satisfying proposed method, numerical results related to IEEE 30-bus and 6-bus are discussed. Paper [15] proposes an optimal framework for operation studies of a barrage type tidal power plant. In this research, number of turbines, number of gates and number of pumps are determined so that produced energy of tidal unit during time horizon of operation study is maximal. Paper [16] presents optimal design of hybrid microgrids considering demand side response program and statistical wind power estimation. In this research, renewable units including wind turbines, photovoltaic units and energy storage devices are considered in the hybrid microgrid. Besides, for modelling the behaviour of wind speed, Monte Carlo approach is utilized. In [17], demand side management of smart microgrids is proposed for improving economic and environmental issues of them. To this end, the economic and environmental indices of the microgrid as primary objective functions of suggested demand side management technique are optimized by combination of ant lion algorithm and analytical hierarchy process approach. Paper [18] studies energy management of microgrids including electric vehicles and renewable resources. In this research, the market price of energy, demand side response program, the prices quoted by distributed generation units and electric vehicles in the grid and responsive loads are considered. For solving resulted linear mixed-integer planning problem, GAMS software is implemented.

1.2. Paper novelties

In the current paper, for reducing uncertainties associated to microgrids containing tidal barrage and PV systems, energy storage devices, fuel-based generation units and grid-connected mode of microgrid can be utilized. The produced power of tidal barrage is dependent on number of sluices, turbines and hydro-pumps. To maximize generated energy of tidal barrages, optimum number of turbines, sluices and hydro-pumps should be committed at each time of operation. The economic dispatch of turbines, sluices and hydro-pumps in a tidal barrage should be performed by an optimization approach. In this paper, a microgrid composed of barrage type tidal power plants, PV systems, batteries, fuel-based generation units and connection with main grid is considered and optimal operation of understudied microgrid is done in two stages. At first stage, number of turbines, sluices and hydro-pumps of tidal barrage at each time is determined for maximizing generated energy of tidal unit during time horizon of operation study. In second stage, the remaining load should be provided by PV systems, batteries, fuel-based plants and connection with main grid. If PV systems and batteries cannot provide the remaining load, generated power of fuel-based plants, power exchanged between main grid and microgrid and curtailed load can be determined using optimization approach. Thus, the main contributions of the paper are:

- For the first time, barrage type tidal power plant has been included in the microgrids and the operation of the microgrid with the presence of these power plants has been studied.
- Optimal operation of tidal barrage is performed to determine optimal number of turbines, number of sluices and number of hydro-pumps for maximizing generated energy of the power plant during time horizon.
- Three well-known optimization algorithms including imperial competitive algorithm, particle swarm method and artificial bee colony algorithm are implemented to select suitable optimization technique for optimizing the objective function of operation problem.
- Optimal operation of a grid-connected microgrid containing tidal barrages, PV units, batteries and fuel-based generation units is performed.

1.3. Paper organization

In the current paper, optimal scheduling of a grid-connected microgrid including barrage type tidal power plant, PV units, energy storage devices and fuel-based generation units is performed. For this purpose, the organization of the paper would be as follows: the second section discusses the topology and composed components of the understudied microgrid. Third section introduces proposed optimal scheduling of the understudied microgrid. To evaluate suitability of proposed technique, numerical results associated to optimal operation scheduling of understudied microgrid are given at fourth section. This research is summarized at fifth section.

2. The structure of the understudied microgrid

The structure of understudied microgrid that is suitable for coastal areas, is presented in Fig. 1. The main role in providing the required load of microgrid is played by renewable energy-based generation units including tidal units with barrage and PV systems. The produced power of tidal units with barrage and PV systems varies over time that is resulted from the variation of tidal height and solar radiation intensity. Thus, batteries can be used to reduce the associated uncertainties. When the produced power of renewable units is more than required load, excess power charges batteries. When the generation units of the renewable resources is less than the required load, the batteries are discharged and the power shortage is compensated. To increase the reliability of the microgrid and prevent from load curtailment, the dispatch-able fuel-based generation units can be committed and provides the remaining loads. In addition to renewable, non-renewable and energy storage units, the microgrid can be implemented in grid-integrated state to exchange the electricity with main network. The proposed scheduling approach is done at two levels: at first stage, the optimal operation plan of tidal unit with barrage is performed and the number of turbines, sluices and hydro-pumps is determined for maximizing generated energy of tidal unit with barrage during time horizon of operation studies. Then, PV systems and the batteries provide all or part of the required loads. In the renewable resources and the energy storage devices cannot provide all the required load, the second stage of the optimal operation approach is performed. In this stage, the generated power of the fuel-based plants and power exchanged between microgrid and main network are determined for minimizing operating cost of microgrid. Characteristics and associated equations of components of the understudied microgrid including tidal units with barrage and impact of hydro-pumps on generated power, PV systems, batteries and fuel-based generation units are described in this section.

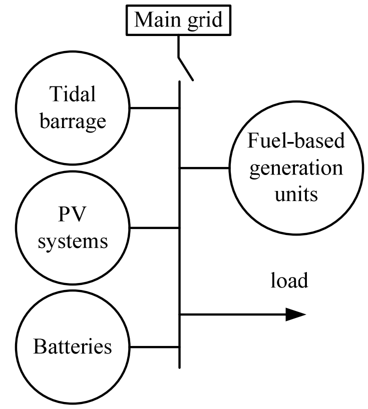

Fig. 1. Topology of understudied microgrid

2.1. Tidal units with barrage

Among different tidal power plants including tidal streams turbines, tidal barrages and tidal lagoons, high capacity barrage type tidal power plant can be implemented for electric power production in bulk power systems. In this technology, a dam is constructed between the sea and the reservoir, and the water can be transferred between the sea and basin through gates placed at barrage of dam. Several turbines are placed in sluices and water passing through turbines can produce the electricity. A tidal barrage can be implemented at three generation states including ebb production, flood production and two-way production states. In ebb production mode, the electricity is produced in ebb occurrence state. When the flood is occurred, the seawater is transferred to basin through turbine-free gates to fill basin. When ebb is occurred, reservoir water is transferred to sea through sluices equipped to turbines to generate the electricity. In this state, the basin is discharged. At flood production state, at flood occurrence mode, seawater is transferred to basin by gates equipped to turbines to fill basin and generate electricity. At ebb occurrence state, reservoir water is moved to sea by turbine-free sluices to discharge reservoir. At two-way production state, the electricity is produced in both ebb and flood occurrence states. In this mode, the basin is filled in the flood occurrence state, and discharged in the ebb occurrence state. It is deduced from [8], the annual generate energy of tidal units with barrages for ebb production state is more than other production states, and so, in the current research, the understudied tidal barrage is considered to be operated in ebb production state.

Produced power of tidal unit with barrage in ebb production state is calculated as [19]:

$$P = \eta_{TUR}\eta_{GEN}\,\rho g(h_R - h_E)q_E \quad (1)$$

Where, P, η_{TUR}, η_{GEN}, ρ, g, h_R, h_E, and q_E are produced power of tidal unit, turbine efficiency, generator efficiency, seawater density, the gravitational acceleration, the reservoir level, sea height in ebb occurrence state and water flow rate of turbines in ebb occurrence state, respectively. Due to the good performance of the Kaplan turbines in the wide range of the water head and flow, in the understudied tidal barrage, the Kaplan technology is applied for turbines. Efficiency of Kaplan turbines can be determined as [19]:

$$\eta_{TUR} = R\left(1 - S\left|1 - T\frac{q_E}{q_{En}}\right|^U\right) \quad (2)$$

Where, R, S, T and U are the dimension-less parameters corresponding to the Kaplan turbines. For the Kaplan turbines used in the understudied tidal barrage, these parameters are 0.905, 3.5, 1.333 and 6, respectively. The q_{En} is nominal water flow rate passing through turbines in ebb occurrence state. Water flow rate of turbine in ebb occurrence state can be obtained as [19]:

$$q_E = \frac{\pi}{4}\sqrt{2g(h_R - h_E)}\big(d^2_{TIP-TUR} - d^2_{HUB-TUR}\big) \quad (3)$$

Where, $D_{HUB-TUR}$ and $D_{TIP-TUR}$ are the tip and hub diameters of the turbines, respectively. For filling the reservoir, water is moved from sea to basin by turbine-free sluices. Water flow rate of the sluices in flood occurrence state can be calculated as [19]:

$$q_F = h_R W_S\sqrt{2gh_F} \quad (4)$$

Where, q_F, h_F and W_S are the water flow rate of the sluices at flood occurrence mode, sea height in flood occurrence state and the width of the sluices. One of the effective methods to improve produced power of the tidal unit with barrage is use pumping to increase the water level of the basin. As can be seen in (1), produced power of tidal unit with barrage depends on water head moving through turbines. If water head moving through turbine is increased, generated power of the plant would be enhanced. For this purpose, the hydro-pumps are used to increase the water level of the basin at the end of flood period. If the water level of the basin wants to increase by Δh, the consumed power of the hydro-pumps would be as [8]:

$$P_{con-P} = \frac{\rho g q_P \Delta h}{\eta_P} \quad (5)$$

Where, P_{con-P}, q_P and η_P are the consumed power, water flow rate and hydro-pumps efficiency, respectively. Power consumption of the hydro-pumps is less than the increase in produced power of plant caused by hydro-pumps, therefore the hydro-pumps increase produced energy of tidal unit with barrage.

2.2. The PV system

A PV panel is composed of several solar cells that can directly convert the energy of sunlight to the DC electric energy. To increase the voltage and current produced by solar cells, series and parallel connections of them are used to construct the PV panels with higher voltage and current. A typical PV system contains numerous panels, and produced power of PV system can be determined as [20, 21]:

$$P_{PV}(r,\theta) = \frac{r}{r_0}NP_{P0}(1 + \beta(\theta - \theta_0)) \quad (6)$$

Where $P_{PV}(r,\theta)$ is the produced power of PV system when solar radiation and air temperature are r and θ, respectively. The r_0 and θ_0 are solar radiation intensity and air temperature associated to the test conditions, N is number of panels and P_{P0} is the nominal power of each panel at the test conditions and β is temperature coefficient associated to power parameter. In this research, the produced power of each panel at the ambient temperature of 25 degrees centigrade and the solar radiation of 900 w/m^2 is assumed to be 250 watts. The PV system is composed of 4000 PV panels and so, the nominal power of the PV system would be 1 MW.

2.3. The batteries

For reducing uncertainties of tidal barrage, PV system and load, the energy storage systems are implemented in microgrids. In the current research, batteries are used to store excess produced power of renewable units when produced power of renewable energy-based generation units is more than the required load, and compensate power shortage when generated power of renewable resources is less than the required load. To determine power and energy stored in batteries during time horizon of operation study, characteristics and constraints of batteries must be considered. In the current research, the following limitations are considered for batteries:

- The battery charging and discharging power cannot exceed the associated maximum allowable values.
- The stored energy of batteries must be placed in the allowable range between maximum and minimum values.
- Charging and discharging efficiencies of batteries are less than unity that is arisen from power losses of batteries in charging and discharging states.

When hourly produced power of tidal barrage is determined, according to generated power of PV systems and remaining load, the power of batteries and stored energy of them are obtained. To obtain power and stored energy of batteries, associated limitations must be considered. When produced power of PV systems is more than remaining load, batteries are charged. However, to determine the charging power of batteries and stored energy of them, the maximum charging power and maximum stored energy of batteries must be taken into account. Thus, in charging state, battery power and stored energy of them are calculated as [1]:

$$P_{bat}(t) = -n_{bat} \times \min(P_{ch-\max}/\eta_{ch}, \frac{P_{PV}(t) - load_{rem}(t)}{n_{bat}}) \quad (7)$$

$$E_{bat}(t) = \min(E_{\max}, E_{bat}(t-1) - \eta_{ch}P_{bat}(t)) \quad (8)$$

Where, $P_{bat}(t)$, n_{bat}, P_{ch-max}, η_{ch}, $P_{PV}(t)$, $load_{rem}(t)$, $E_{bat}(t)$, $E_{bat}(t-1)$ and e_{max} are power of batteries at time t, number of batteries, allowable maximum charging power of batteries, battery charging efficiency, produced power of PV system at time t, remaining load of microgrid at time t, energy stored in batteries at time t, energy stored in batteries at time $t-1$ and allowable maximum stored energy of batteries, respectively. In charging state, battery power is negative, while in discharging state, battery power would be positive. In discharging state, the power and stored energy of batteries are calculated as [1]:

$$P_{bat}(t) = n_{bat} \times \min(P_{dis-\max}/\eta_{dis}, \frac{load_{rem}(t) - P_{PV}(t)}{n_{bat}}) \quad (9)$$

$$E_{bat}(t) = \max(E_{\min}, E_{bat}(t-1) - \eta_{dis}P_{bat}(t)) \quad (10)$$

Where, $P_{dis-max}$, η_{dis} and E_{min} are maximum allowable discharging power, discharging efficiency and minimum allowable stored energy of batteries, respectively.

2.4. The fuel-based generation units

The produced power of tidal units with barrage and PV systems depends on tidal height and solar radiation intensity, respectively. Due to variation of tidal height and solar radiation intensity, produced power of tidal barrages and PV systems changes over times. Due to the uncertainties of the mentioned renewable resources, to provide the required load of the understudied microgrid, the dispatch-able fuel-based plants must be committed in microgrid when produced power of renewable resources and energy storage system is less than required load. Operating cost of fuel-based plants is dependent of the generated power of them as [7]:

$$C_k(t) = a_k + b_k P_k(t) + c_k P_k^2(t) \tag{11}$$

Where, $C_k(t)$ is operating cost of k^{th} plant at time t, $P_k(t)$ is generated power of k^{th} plant at time t, a_k, b_k and c_k are constant coefficients associated to k^{th} generation unit. In the proposed optimal operation plan of understudied microgrid, generated power of each fuel-based generation units at each time is determined for minimizing operating cost of microgrid.

2.5. The grid-connected mode of microgrid

In the understudied microgrid, when generated power of renewable resources and the energy storage devices is less than the required load, in addition to the generated power of the fuel-based generation units, the exchange power from main network can be used to provide remaining load of microgrid. At this stage, an optimization approach is performed to determine whether electricity generation by the fuel-based plants is more economical or purchase electricity from main network. Besides, the connection to main network also allows microgrid to sell excess produced power of renewable resources to main network when produced power of tidal unit with barrage and PV systems is more than load while the batteries are full charged.

3. Optimal operation plans of understudied microgrid

In this section, proposed scheme for optimal operation plan of a grid-integrated microgrid containing tidal unit with barrage, PV system, energy storage system and the fuel-based plants is explained. Operation plan of understudied microgrid is performed in two stages. At first stage, optimal operation plan of a tidal unit with barrage and hydro-pumps is done through three well-known algorithms including imperial competitive algorithm, particle swarm method and artificial bee colony algorithm. For this purpose, following steps are performed:

Step 1. The input data of the understudied tidal unit is collected. Required data is:

- Hourly tidal level of the understudied site
- The characteristics of the basin such as minimum and maximum height of the basin and relationship between basin volume and water height
- The characteristics of the turbines such as tip and hub diameters of the turbines, the nominal water flow rate of the turbine, number of turbines, efficiency curve of turbine and the minimum water head required for power generation
- The characteristics of the sluices such as the number and the width of them
- The characteristics of the hydro-pumps such as the efficiency, water flow rate and number of them
- The generator efficiency,

Step 2. According to equations of tidal unit and input data, produced power of the tidal barrage at each hour of the time horizon of the operation study can be obtained. Using the heuristic optimization techniques, the hourly number of turbines, sluices and hydro-pumps are calculated for maximizing produced energy of tidal barrage during time horizon of the operation study as presented in (12). Among different optimization techniques, particle swarm method is implemented in this research for optimizing produced energy of tidal unit during study time [15].

$$f_1 = \sum_{t=1}^{T} P_{tid}(t, n_{TUR}(t), n_S(t), n_P(t)) \tag{12}$$

Table 1. The characteristics of the understudied tidal barrage [8–10]

The parameters	The values
Minimum water height of basin	2.5 m
Maximum water height of basin	4.5 m
Minimum turbine water head needed for power production	1 m
Number of turbines	60
Number of gates	60
Number of hydro-pumps	60
The tip diameter of the turbines	1.2 m
The hub diameter of the turbines	3 m
The width of the sluices	2 m
The water flow rate of hydro-pumps	100 m^3/s
Generator efficiency	90%
Hydro-pumps efficiency	95%

Where, $P_{tid}(t)$ is generated power of tidal barrage at time t that is dependent on number of turbines ($n_{TUR}(t)$), number of sluices ($n_S(t)$) and number of hydro-pumps ($n_P(t)$) at time t. According to equations of batteries, generated power of PV systems and remaining load, the battery power is obtained. If produced power of PV systems and batteries cannot provide all remaining loads, the fuel-based generation units and connection to main grid should be implemented and second stage of optimal operation is performed. In this stage, the following cost function must be minimized using suitable heuristic optimization techniques. Among different heuristic optimization techniques, particle swarm optimization (PSO) algorithm is utilized to minimize operating cost of microgrid as presented in (13) [5].

$$f_2 = \sum_{k=1}^{n}\sum_{t=1}^{T} C_k(t) + \sum_{t=1}^{T}[CL(t) \times VOLL) + \sum_{t=1}^{T}[P_{ex}(t) \times \Pr(t)] \tag{13}$$

In the suggested cost function, first term is operating cost associated to n fuel-based generation units during the time horizon T. The second term is penalty associated to curtailed load that is obtained by multiplication curtailed load (*CL(t)*) by value of lost load (*VOLL*). The third term is cost of electricity exchanged between main network and microgrid that is determined by multiplication of exchanged power (*P_{ex}(t)*) by the price of electricity at each time (*Pr(t)*). In the understudied microgrid, produced power of renewable and non-renewable units can transfer to the main grid when the exchange of power is economically viable. The flowchart associated to proposed two-stage method for optimal operation of understudied microgrid containing tidal barrage is presented in Fig. 2.

4. Numerical results

In this section, a grid-connected microgrid located in the coastal region is considered and the proposed two-stage optimal operation approach is implemented on it. The hourly tidal level of the understudied site during 24h and volume of basin considering water height of basin obtained from the bathymetric studies are presented in Figs. 3 and 4, respectively. The characteristics of understudied tidal unit with barrage including the characteristics of reservoir, turbines, sluices, hydro-pumps and the generators are presented in Table 1.

In this part, the first stage of the optimal operation approach is performed and using three well-known algorithms including particle swarm method (PSO), imperial competitive algorithm (ICA) and artificial bee colony algorithm (ABC), the number

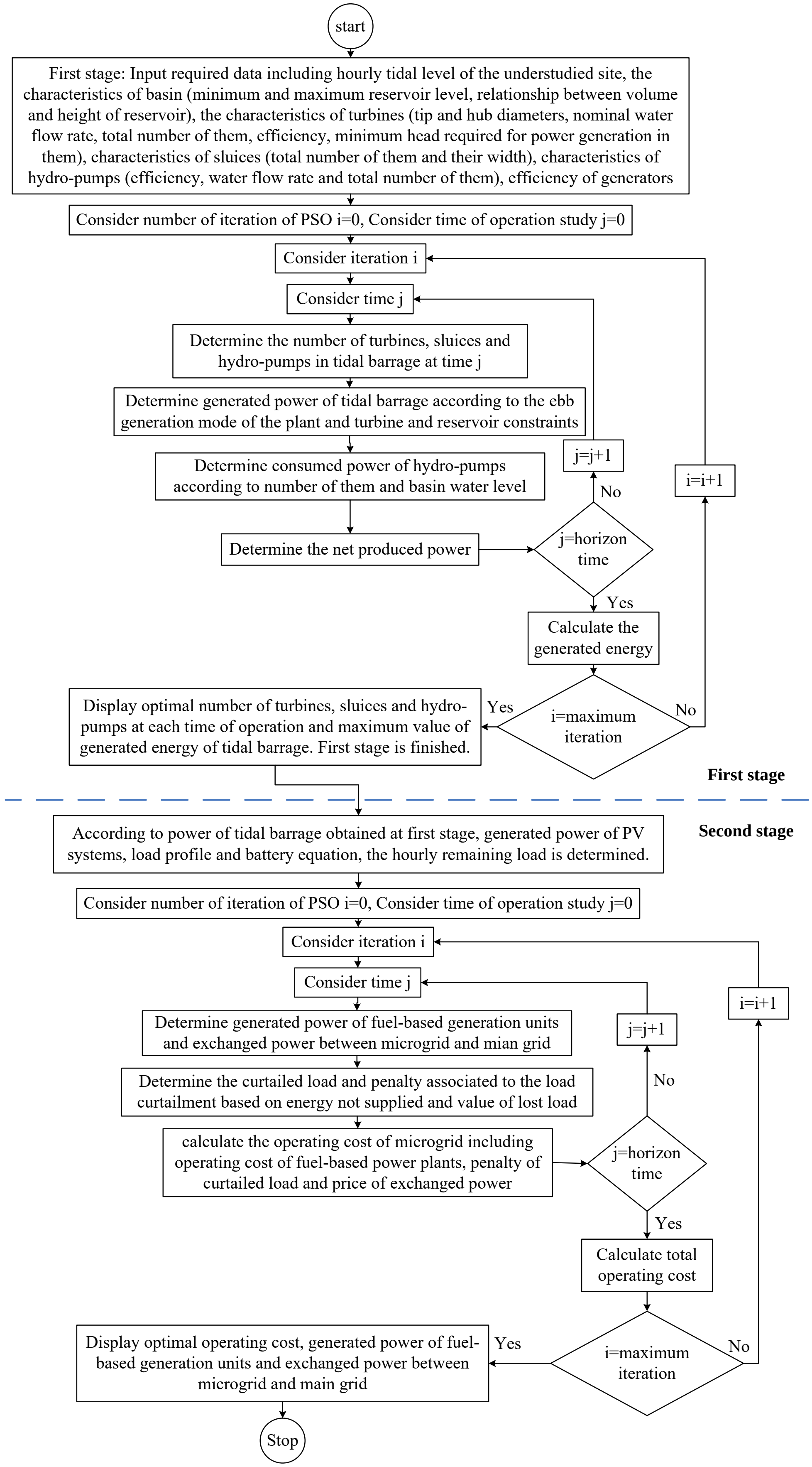

Fig. 2. Flowchart of proposed two-stage method for optimal operation of microgrid

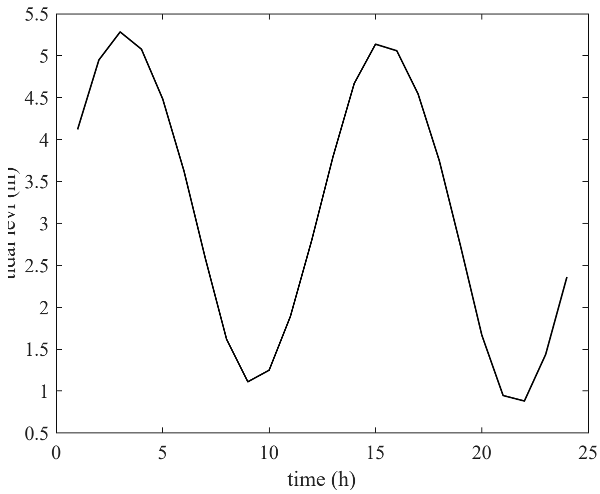

Fig. 3. The hourly tidal level during 24h

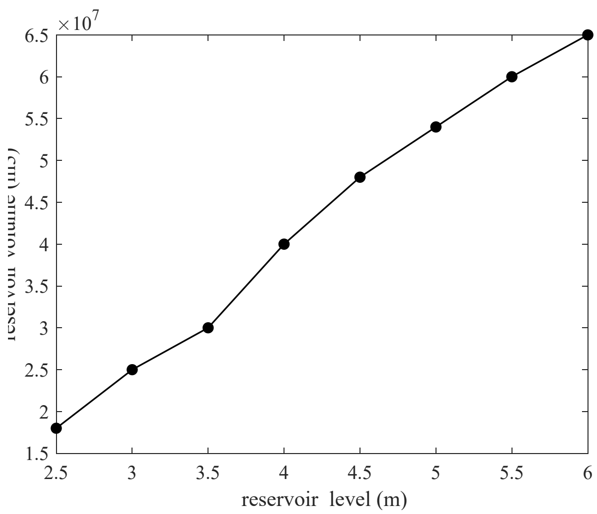

Fig. 4. The volume of the basin considering basin level

of turbines, sluices and hydro-pumps at each 6 minutes of 24h are determined for maximizing generated energy of tidal barrage during 24h. The setting parameters of these algorithms are presented in Table 2. The convergence diagram of the optimization algorithms is illustrated in Fig. 5. As can be seen in the figure, the convergence speed of PSO algorithm is better than others. Besides, optimal generated energy of understudied barrage type tidal power plant is achieved by PSO algorithm. The generated energy of tidal barrage obtained by PSO, ICA and ABC algorithms are 25.052, 25.016 and 24.953 MWh, respectively. The optimization results including the optimal number of turbines, gates and hydro-pumps and produced power of understudied tidal unit every 6 minutes for the optimum case obtained by PSO algorithm are presented in figures 6, 7 and 8. It is deduced from figure 5 that after 400 iterations the PSO algorithm has converged to the optimum solution with high velocity.

Hourly load of microgrid is presented in Fig. 9. In this paper, a PV system composed of 4000 panels with 1MW capacity is considered. Hourly solar radiation intensity and air temperature are presented in Figs. 10 and 11, respectively. According to hourly solar radiation intensity and air temperature, produced power of PV unit is obtained and illustrated in Fig. 12.

Characteristics of understudied battery are presented in Table 3. According to the hourly remaining load or generated power and

Table 2. The setting parameters of algorithms [8–10]

Algorithm	**PSO**	**ICA**	**ABC**
Number of decision variables	480	480	480
Maximum iterations	400	400	400
Number of population	50	100	100
Inertial weight damping ratio	1	–	–
Number of imperialists	–	10	–
Beta and zeta	–	2–0.1	–

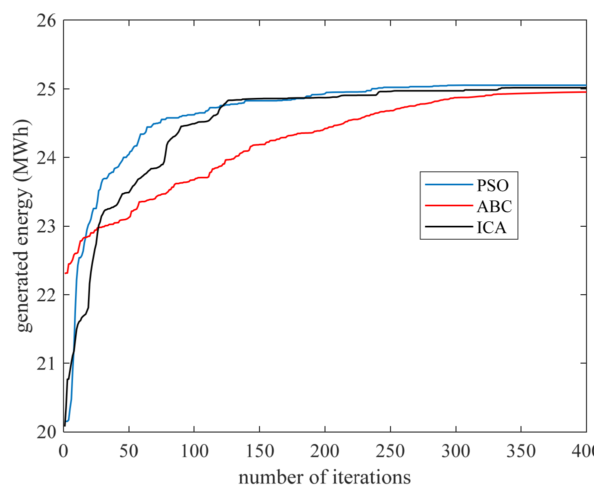

Fig. 5. The convergence diagram of the PSO algorithm

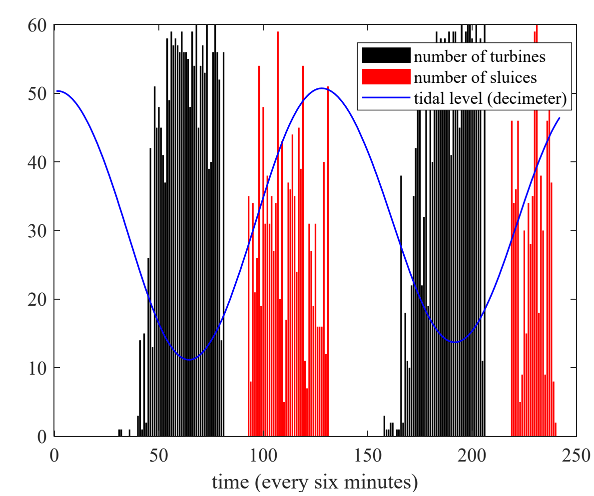

Fig. 6. Optimal number of turbines and gates at every 6 minutes

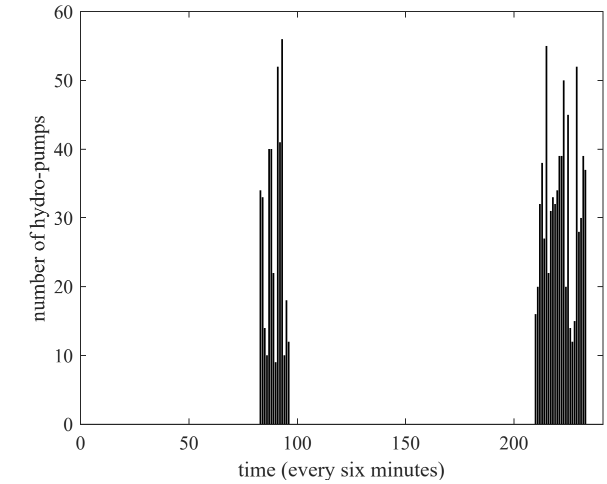

Fig. 7. The optimal number of hydro-pumps at each 6 minutes

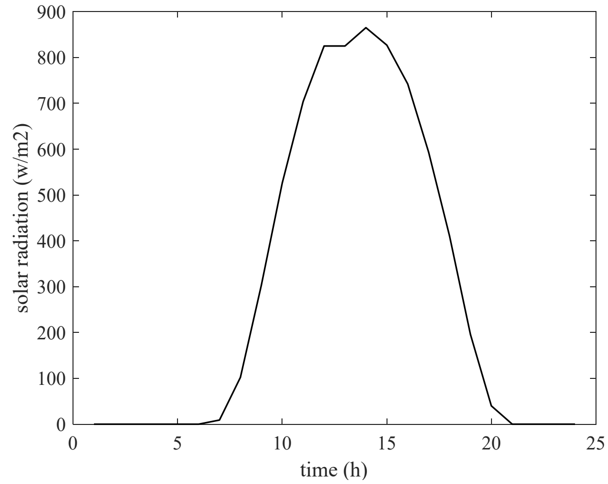

Fig. 10. Hourly solar radiation intensity

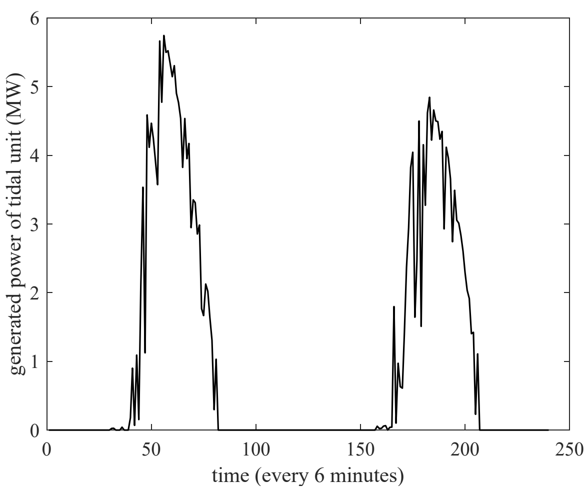

Fig. 8. Generated power of tidal unit with barrage

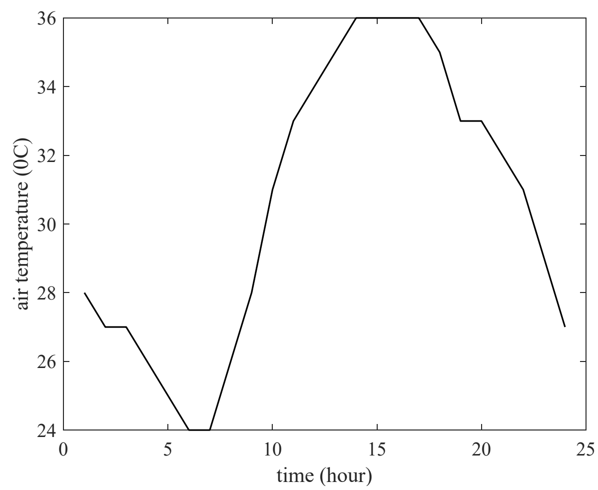

Fig. 11. Hourly air temperature

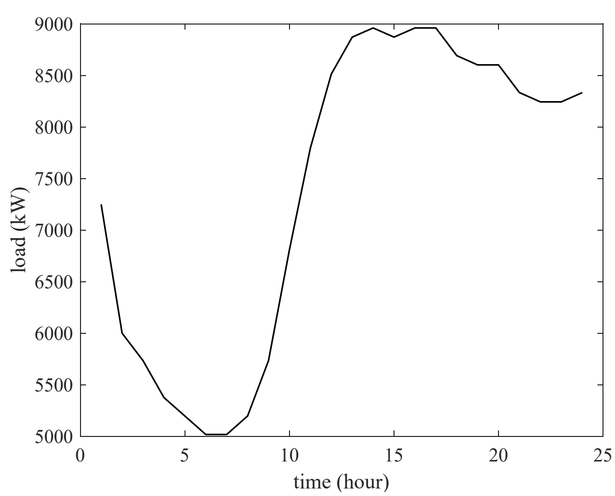

Fig. 9. Hourly load

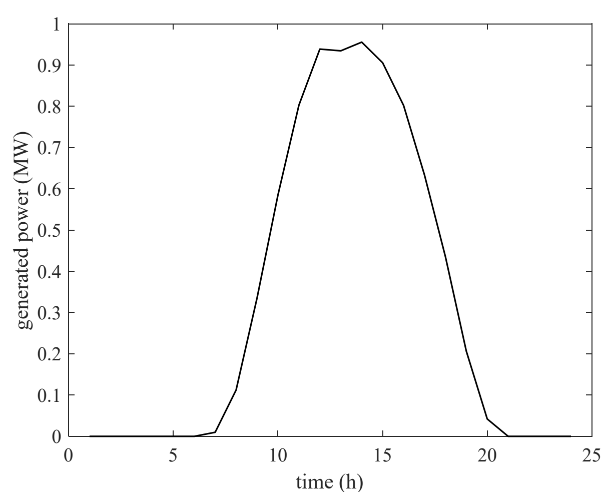

Fig. 12. Hourly generated power of PV unit

Table 3. The characteristics of the battery

Parameters	Values	Parameters	Values
Maximum charging power	600 kw	Maximum discharging power	600 kw
Maximum stored energy	1800 kwh	Minimum stored energy	180 kwh
Charging efficiency	93%	Discharging efficiency	93%

Table 4. The characteristics of the fuel-based generation units

Units	Capacity (MW)	a ($)	b ($/MW)	c ($/MW^2)
1	3	80	30	1
2	3	200	60	2
3	3	1000	50	3

the battery characteristic the power of the battery considering the associated constraints can be calculated.

In this part, the second stage of optimal operation plan of understudied microgrid is performed to determine the hourly generated power of the fuel-based plants and power exchanged between microgrid and main network. Characteristics of the fuel-based plants are presented in Table 4. Hourly electricity price of main grid is presented in Fig. 13. In this research, value of lost load is 7.5 $/kwh. In the optimization process, the generated power of the fuel-based generation units at each hour cannot be exceed the associated maximum capacities. Besides, the power exchanged between main network and microgrid is limited based on the capacity of tie line. In the current research, electric power exchanged between main network and microgrid cannot be exceed 1MW.

Using the PSO algorithm, the second stage of the operation of the understudied microgrid is performed and the associated results are obtained. In this stage, number of decision variables, number of population and maximum number of iterations are 96, 50 and 50, respectively. The convergence diagram of the proposed optimization algorithm for this stage is presented in Fig. 14. It is deduced from this figure that the PSO algorithm has converged to the minimal solution with high velocity. As can be seen in the figure after 25 iterations, the algorithm is converged to the best solution. The minimum value of the cost obtained from the proposed approach is 39868 $. The generated power of each fuel-based plants and electric power exchanged between main grid and microgrid are presented in Table 5.

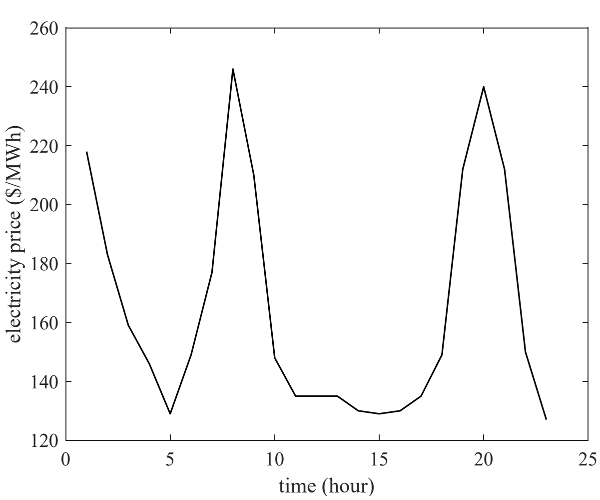

Fig. 13. The hourly electricity price of the main grid [22]

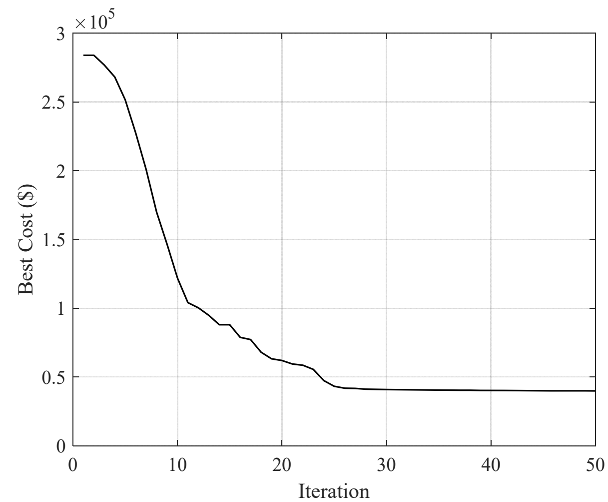

Fig. 14. The convergence of the PSO algorithm

Table 5. The results of the optimal operation performed by PSO algorithm

Time	Power of plant1 (kW)	Power of plant2 (kW)	Power of plant3 (kW)	Exchanged power (kW)
1	1427	2978	2444	620
2	2481	2366	1315	-156
3	1231	2749	1469	742
4	2293	1216	1828	549
5	1979	1147	309	-979
6	1992	1173	2198	-6
7	1445	568	2708	-88
8	2178	289	2065	268
9	2553	1737	2508	-479
10	850	2470	2740	94
11	2381	2525	2750	329
12	2719	1396	2597	803
13	2964	2489	2883	828
14	2692	3000	1619	614
15	2713	2227	2716	294
16	2914	2716	2780	-95
17	2658	1891	2463	750
18	2013	1571	630	37
19	2721	248	2668	-44
20	1630	2313	1729	552
21	2644	2169	2814	876
22	2744	2424	2867	409
23	2288	2982	2865	198
24	2605	2505	2396	734

5. CONCLUSION

In this paper, optimal operation plans of a grid-connected microgrid containing tidal barrage, photovoltaic system, battery and fuel-based generation units are performed. The proposed technique is performed in two independent stages. At first stage, the operating parameters of tidal barrage including number of turbines, number of sluices and number of hydro-pumps at each time are determined to maximum generated energy of tidal barrage is obtained. In this stage, three heuristic methods including particle swarm approach, artificial bee colony method and imperial competitive algorithm are implemented for maximizing produced energy of tidal barrage. It is concluded from numerical results that among these optimization methods, particle swarm algorithm has the best performance and results in optimal response after 400 iterations. The optimal value for generated energy of understudied tidal barrage is 25.052 MWh.

At second stage, remaining load of microgrid should be provided by photovoltaic systems, batteries, fuel-based generation units and main grid. In this stage, to determine the generated power of fuel-based generation units, the exchanged power between microgrid and main grid and curtailed load, operating cost of the microgrid is minimized by particle swarm optimization method. The operating cost of microgrid includes operating costs of fuel-based power plants, the price of purchased power and penalty associated to the curtailed load. According to the proposed method, operating cost of the understudied microgrid is minimized using PSO algorithm. Numerical results of this stage present that the proposed algorithm with high velocity converges to the best solution and produced power of fuel-based power plants and exchanged power between microgrid and main grids at each time are determined. The PSO algorithm converges after 25 iterations and the optimal value of operating cost of understudied microgrid is 39868 $. However, low convergence rate, falling into local optimum, computational complexity and long calculation time in high-dimensional space are some drawbacks of heuristic algorithms implemented for optimization of operation problems. To optimize the generated energy of understudied tidal barrage, the required time of simulation for PSO, ICA and ABC algorithms are 14.3746, 28.4519 and 127.7882 seconds, respectively.

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