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Optimal Planning of Renewable Energy-Based Micro Grids Considering the Reliability Cost

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Abstract— *In recent years, the local feeding of the required loads in the micro grids has received much attention comparing to the extension of the large fuel-based power plants, which require the development of costly transmission lines. On the other hand, environmental constraints have led to the increasing development of renewable energy sources that can generate electricity in the form of small-scale generation units in micro grids. In this study, an appropriate mixture of renewable sources incorporating the wind turbines, current type tidal generation units and the photovoltaic systems is integrated to the micro grid connected to the energy storage systems. The proposed micro grid can be customized in the coastal regions and islands for supplying required loads. To optimally determine capacity and size of renewable power plants, different metaheuristic algorithms are applied, and among them, the particle swarm optimization methodology is used to minimize cost function of the system including the investment, operation and the reliability costs. To calculate reliability cost of micro grid, variable hazard rate of the assembled elements influenced by change in air and water temperature, wind velocity, tidal stream velocity and sun irradiance is taken into account. Load curtailment of the micro grid is occurred due to failure of the assembled elements and the change in renewable sources that both are addressed in the paper. For examining effectiveness of proposed approach, numerical results associated to the planning of a micro grid incorporating renewable sources considering the reliability cost are given.*

Keywords—Optimal planning, renewable energy-based micro grid, reliability cost, variable failure rate, particle swarm optimization algorithm.

NOMENCLATURE

Abbreviations

α, β and a	Constants parameters of the PV panels
E_a	Activation energy (Joule)
E_{max}	Maximum energy of the batteries (MWh)
E_{min}	Minimum energy stored in batteries (MWh)
k_d	Temperature factor
L_k	Hourly-curtailed load (MW)
n_r	Rotor velocity (rpm)
n_s	Synchronous velocity
P_0	Produced power of PV panel at test state (MW)
P_{dmax}	Maximum discharging power (MW)
P_{sc}	PV panels produced power (MW)
s_0	Sun irradiance associated to test requirements (w/m^2)
t_0	Useful lifetime of component (year)
T_a	Outside temperature ($^\circ C$)
T_F	Temperature of the gearbox and turbine (Fahrenheit)
t_k	Time horizon of the planning study or lifetime of the unit (year)
T_{a0}	Outside temperature under test state ($^\circ C$)
V_0	Voltage of MPP of PV panel in standard test states (V)
V_s	Tidal stream velocity related to synchronous velocity (m/s)
V_{sc}	Voltage of PV panel (V)
V_{tid}	Tidal current velocity (m/s)
η_{ch}	Charging efficiency of the batteries
η_{dis}	Discharging efficiency of the batteries
γ_P	Temperature coefficient of power parameter (K^{-1})
γ_v	Temperature coefficient of voltage parameter (K^{-1})
λ_0	Base capacitor hazard rate at test requirements ($Occ./\gamma r$)
λ_0	Base hazard rate of PV panel ($Occ./\gamma r$)
λ_t	Equivalent hazard rate ($Occ./\gamma r$)
μ_t	Equivalent repair rate ($Occ./\gamma r$)
π_A	Application coefficient
π_C	Capacitance coefficient
π_E	Environmental coefficient
π_R	Power coefficient
π_S	Electric stress coefficient
π_T	Temperature coefficient
π_V	Voltage-stress coefficient
π_{SR}	Series-resistance coefficient
$C_{ins,\,k}$	Installation cost ($)
$C_{inv,\,k}$	Investment cost ($)
$C_{main,\,k}$	Maintenance cost ($)
$C_{op,\,k}$	Operation cost ($)
F_k	Cost of the renewable generation units or energy storage system ($)
F_{PV}	Cost of PV units ($)
$F_{reliability}$	Reliability cost ($)
$F_{storage}$	Cost of energy storage systems ($)
F_{tidal}	Cost of tidal units ($)
F_{wind}	Cost of wind units ($)
n_k	Number of each units
$P_{battery}(h)$	Generated (stored) power of the battery associated to the hour h (MW)
$P_{charging}(h)$	Charging power in hour h (MW)

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P_{cmax}	Maximum charging power (MW)
$P_{discharging}(h)$	Discharging power in hour h (MW)
$P_{interrupted}(h)$	Interrupted load associated to the hour h (MW)
$P_{load}(h)$	Required load associated to the hour h (MW)
$P_{PV}(h)$	Produced power of PV systems associated to the hour h (MW)
$P_{ren}(h)$	Output power of renewable plants in hour h (MW)
$P_{tidal}(h)$	Produced power of tidal turbines associated to the hour h (MW)
$P_{wind}(h)$	Produced power of wind turbines associated to the hour h (MW)
d	Discount rate
E(h)	Energy stored in batteries in hour h (MWh)
E(h-1)	Energy stored in batteries in hour h-1 (MWh)
EENS	Average curtailed energy (MWh/year)
F	Cost of micro grid ($)
k	Boltzmann factor ($m^2kgs^{-2}K^{-1}$)
M	Number of years in the time span of the planning process
N	Repetitions number in Monte Carlo simulation approach
n	Number of series components
s	Slip
s	Sun irradiance (w/m^2)
t	Duration of the operation of the component (year)
VOLL	Interrupted energy assessment rate ($/MWh)

1. INTRODUCTION

The environmental problems of the large-scale fossil fuel-based power plants and the costly transmission networks lead the development of the micro grids to locally supply the required loads. One of the advantages of the micro grids is that it can be used from renewable energies such as wave, wind, tidal and solar for producing clean and pollutant-free electricity required for the loads. However, the investment costs of renewable power plants are high, and to economically generate the electricity, an optimization approach must be performed to determine the capacity and size of the renewable units installed in the micro grid. On the other hands, in recent years, the reliability of the micro grids has become very important and the consumers except the electricity delivered to them to be with minimum curtailment. Thus, for planning of micro grids incorporating renewable energies, reliability cost associated to the penalty of the interrupted loads must be taken into account. Due to the importance of the optimal planning of micro grids, a lot of research has been performed in this regard. In [1], a comprehensive review of optimization formulations associated to the management of energies isolated micro grids is performed. The optimization objectives, constraints, control variables, forecasting methods, socio-economic factors and suitable approaches for multiple criteria problems proposed in 120 past studies performed for operation and planning of isolated micro grids are reviewed in this paper. Paper [2] proposes an appropriate planning methodology used in remote hybrid micro grids to determine the locations and sizes of distributed generation units, energy storage systems and AC/DC converters. In this research, the formulation of planning studies is expressed through a mixed integer non-linear program to ensure reliable power flow with minimum deployment and operational cost. In the first stage of the proposed planning approach, the micro grid topology and the allocation and sizing of the components are determined using of a heuristic optimization method. In the second stage, the smooth and reliable operation of the micro grid over all possible operation scenarios is satisfied. In [3], the optimum size and placement of the distributed generation units in the micro grids are determined based on the reliability concept. In this study, the particle swarm optimization (PSO) methodology is proposed for minimizing non-linear integer minimization problem including the sum of the total capital, operational, maintenance and replacement costs of distributed plants. For studying system reliability, some important reliability indices of micro grid in both on-grid and islanded modes are calculated. Paper [4], proposes a novel approach based on the clustering process to optimally design the micro grids including multiple distributed generation units in on-grid and isolated operating modes. In the suggested planning approach, three objectives including maximizing the self-adequacy of the micro grid, maximizing micro grid islanding success probability and a combination of both targets are considered to be satisfied. In [5], optimal planning of the partially self-sufficient micro grids addressing restrictions of the annual electric power exchange with distribution network is performed. For this purpose, the models associated to capacity and power management are combined in a model and studied through polynomial form. In this research, K-means method is used for reducing the number of variables associated to the understudied year horizon by selecting a set of typical days. Paper [6] proposes a game theoretical technique including daily peer-to-micro grid exchanges to perform the long-term planning of the connected industrial micro grids. In this paper, two game theoretical frameworks are used to couple a short-term energy management performed in each day of the planning period to the long-term investments for modelling the different objectives of the stakeholders. In [7], the chance constrained stochastic conic programming is proposed to perform the planning of the networked micro grids. The proposed planning approach suitable for both on-grid and islanded states of micro grids is performed under a two-stage optimization framework including investment and operational problems. To address random nature of renewable energies and demands, stochastic scenarios are suggested for capturing the randomness and control the operational risks. In [8], the stochastic risk-constrained scheduling of the renewable energy-based micro grids in the isolated mode is executed. In this study, influence of demand response programs on the reliability and the economic issues of the autonomous micro grids are taken into account, and to address random nature of both supply and demand sides of the understudied micro grid, the conditional value-at-risk concept is proposed.

Paper [9] reviews recent researches associated with application of demand side management in the smart grids. In this research, different techniques and algorithms applied for demand side management of smart grids and their related challenges, operation mode of demand side management, energy production profile, storage and consumption and benefits of demand side program are studied. In [10], a comprehensive study on technology, energy management and planning methodologies used in hydrogen storage-based micro grids is performed. In this research, various challenges associated with traditional storage systems are studied to present the advantages of hydrogen-based storage device in the micro grid applications. In [11], a novel method based on the linear parameter varying technique is used to reduce the low frequency oscillations by enhanced power system stabilizer. In this paper, a single machine infinite bus system is considered and through proposed technique, low frequency oscillations are attenuated. Paper [12] introduces four novel methods for generated power enhancement of the barrage type tidal power plants. In this research, optimal dispatch of turbines and gates, electricity production in ebb state of the plant, application of hydro-pumps, optimal design of tidal plant to determine the characteristics of the plant including number of turbines, number of gates, turbine diameters and sluice width are proposed for power enhancement of the plant. For optimizing the plant, this paper proposes particle swarm optimization method. Paper [13] studies reliability evaluation of ocean current converters considering variation in the velocity of ocean currents. In this paper, both Monte Carlo simulation approach and analytical method are used to calculate reliability indices of power system containing these renewable resources.

In this paper, optimal planning for renewable unit-based micro grids incorporating the wind turbines, photovoltaic (PV) units and tidal turbines suitable for installation in the coastal and island regions is performed. Because of the change in output power of renewable resources, the energy storage systems must be utilized in the examined micro grid. For optimally determining capacity of renewable power plants and energy storage systems, objective function including sum of investment, operation, maintenance and reliability costs is minimized using of the PSO algorithm. The reliability cost of the micro grid is arisen from the penalty of the curtailed loads occurred because of change in renewable resources and failure of elements of power plants. In this paper, to determine the reliability cost of the micro grid, the impact of change of renewable energies including wind velocity, water and air temperature, tidal stream velocity and solar radiation on hazard rate of components is addressed. Accordingly, the major benefits of the proposed method over previous methods are:

- Considering variable failure rates in reliability studies of renewable energy-based micro grids will lead to more accurate results than considering a fixed failure rates.
- Considering the reliability cost in the planning studies of the renewable energy-based micro grids will lead to more accurate results.
- Application of appropriate metaheuristic method for optimizing the objective cost of the planning problem, i.e. particle swarm optimization algorithm, results in more optimal solution.

Thus, contributions of the paper would be:

- Through an appropriate optimization technique, i.e. particle swarm optimization algorithm, optimal planning of renewable unit-based micro grids including wind turbines, PV systems and tidal turbines that are suitable for installation in the coastal and islanded regions is performed.
- In the planning approach, the reliability cost of the micro grid arisen from the penalty of curtailed loads is considered. To determine the curtailed load of the micro grid, both change of generated power of renewable resources and failure of elements of generation plants are considered.
- To calculate the reliability cost of the micro grid, variable hazard rate of composed components is applied. In this study, the impact of change of renewable energies including wind velocity, water and air temperature, tidal stream velocity and solar radiation on components failure rate is addressed.
- To consider the impact of renewable resources and outside temperature on the reliability performance of the understudied micro grid, equations associated with hazard rate of composed components of the units are expressed versus variable parameters including wind velocity, tidal stream velocity, sun irradiance, air and seawater temperature.

According to the article aims, it organizes as follows: the characteristics of the examined micro grid is introduced in second section. Cost function of the problem and proposed optimization technique are proposed in third section. Reliability cost of the micro grid considering influence of renewable resource change on hazard rate of the elements of production plants is studied in fourth section. The numerical results associated to the planning studies of a renewable unit-based micro grid are given in the fifth section. The paper is summarized at the sixth section.

2. THE CONFIGURATION OF RENEWABLE UNIT-BASED MICRO GRID

In this paper, an appropriate combination of renewable sources incorporating wind turbines, PV systems and tidal turbines which can be installed in coastal regions and islands, is proposed for the understudied micro grid. The generated power of wind turbines, tidal units and PV arrays is relied on wind velocity, tidal stream velocity and sun irradiance. Due to the widely change of these quantities, generated power of the micro grid changes a lot. To reduce random nature of produced output of renewable energy-unit micro grid, energy storage devices connect to the renewable resources. When produced power of renewable plants is more than required load, energy storage system stores excess power. When the production capacity is not sufficient to supply the required load, the energy storage device can be applied for supplying remaining demand. In Fig. 1, structure of understudied renewable unit-based micro grid connected to energy storage device is presented.

In the wind turbines, kinetic energy of moving air can be used to rotate the wind turbines and generate the electricity. For extracting kinetic energy of wind resources, different technologies based on the applied generators are developed [14]. Among various generators, the permanent magnet synchronous generator (PMSG) due to the suitable performance in the installed wind turbines is selected to be applied in wind units, in this paper. The structure of a wind unit composed of PMSG is depicted in Fig. 2. This wind unit includes turbine, gearbox, PMSG, electrical converters including a rectifier, DC link and an inverter, transformer and cable. Generated power of a typical wind turbine at different wind velocities is determined via turbine power curve. The produced power of the wind unit for the velocities less than cut-in velocity and more than cut-out velocity is zero. The produced power of the wind turbine for velocities between the cut-in and nominal velocities is relied to the cube of wind velocity, and for wind velocities between nominal and cut-out velocities is constant and equal to nominal capacity.

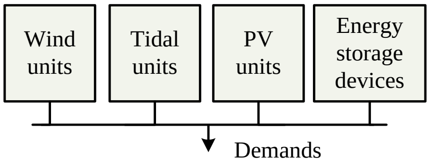


Fig. 1. The configuration of the renewable unit-based micro grid.

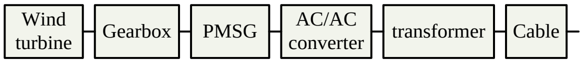


Fig. 2. The assembled elements of wind turbine equipped with PMSG technology.

Current type tidal generation units convert the energy of tides to electricity using of stream turbines in a methodology alike to wind turbines. The composed elements of tidal power plants incorporating tidal turbine, gearbox, generator, power electronic converters, transformer and cable, are presented in Fig. 3 [15]. Among various kinds of generators that can be implemented in tidal units, doubly fed induction generator (DFIG) is selected in this paper for extracting the mechanical energy of the tides. Thus, in this paper two well-known generator technologies, i.e. PMSG and DFIG are studied in wind and tidal turbines, respectively. Power curve of tidal turbines is alike to power curve of wind turbines. However, in tidal turbines, velocity of the tidal currents is small. It could not reach cut-out velocity.

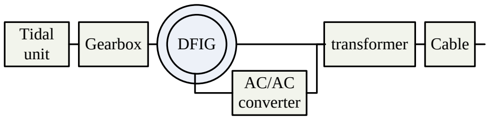


Fig. 3. The assembled elements of the tidal unit equipped with DFIG technology.

PV unit, directly converts sunlight energy to DC power via p-n junction of PV cells. The structure of typical PV units includes several parallel arrays attached to transformer and cable is presented in Fig. 4 [16]. Each array contains an inverter connected to the several parallel strings, that each string includes several parallel panels. Each panel is composed of several parallel PV branches, that each branch includes several series PV cells.

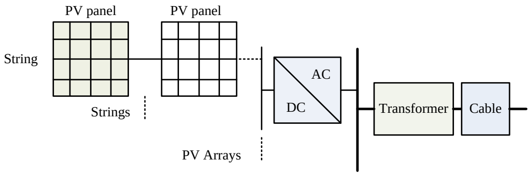


Fig. 4. Assembled elements of PV unit.

3. OPTIMAL PLANNING APPROACH

In this section, the objective function, constraints, optimization variables and suggested optimization algorithm associated to the proposed optimal planning of renewable unit-based micro grid are introduced. For determining capacity of renewable generation units and also energy storage systems, the following objective function Eq. (1) should be minimized. In this paper, the batteries are used as the energy storage systems to store the excess energy of the renewable resources.

$$F = F_{wind} + F_{tidal} + F_{PV} + F_{storage} + F_{reliability}. \quad (1)$$

Where, F_{wind}, F_{tidal}, F_{PV}, $F_{storage}$ and $F_{reliability}$ are the cost of wind, tidal, and PV units, energy storage systems and reliability cost, respectively. The cost of renewable generation units and the energy storage system (ESS) can be calculated as:

$$\begin{aligned} F_k = n_k[C_{inv,k} + C_{ins,k} + \\ (\tfrac{1-(1-d)^{t_k}}{d(1-d)^{t_k-1}})(C_{op,k} + C_{main,k})]. \end{aligned} \quad (2)$$

Where, F_k, n_k, $C_{inv,k}$, $C_{ins,k}$, $C_{op,k,}$, $C_{main,k}$, t_k and d, are the cost of the renewable generation units or energy storage system, the number of each units, investment cost, installation cost, operation cost, maintenance cost, the time horizon of the planning study or the lifetime of the unit and the discount rate. In the cost function of the generation units or energy storage devices, based on discount rate and units lifetime, operation, maintenance and reliability costs should be converted to the present value. The reliability cost of micro grid is determined via penalty associated to load curtailment arisen from change of renewable resources or failure of assembled elements of micro grid. To calculate the reliability cost of the micro grid, the interrupted energy should be multiplied by the value of the lost load (VOLL) as:

$$F_{reliability} = (\frac{1-(1-d)^{t_k}}{d(1-d)^{t_k-1}})EENS \times VOLL. \quad (3)$$

Where, EENS and VOLL are average curtailed energy with unit of MWh per year and interrupted energy assessment rate with unit of $/MWh. Constraints of understudied planning problem are:

- The power balance: at each hour of the time horizon, produced power of renewable plants and energy storage systems must be equal to the required load. If produced power of power plants and the battery is less than require load, load curtailment is occurred. Thus, the power balance equation of the understudied micro grid can be written as:

$$\begin{aligned} P_{wind}(h) + P_{tidal}(h) + P_{PV}(h) + P_{battery}(h) \\ = P_{load}(h) - P_{\text{interrupted}}(h). \end{aligned} \quad (4)$$

  Where, $P_{wind}(h)$, $P_{tidal}(h)$, $P_{PV}(h)$, $P_{battery}(h)$, $P_{load}(h)$ and $P_{interrupted}(h)$ are produced power of wind turbines, tidal turbines, PV systems, the generated (stored) power of the battery, the required load and the interrupted load associated to the hour h, respectively. Produced power of PV unit decreases over time based on the amount of the associated de-rating factor. If the battery is discharging at the hour h, the $P_{battery}(h)$ is considered positive and if the battery is charging, the $P_{battery}(h)$ would be negative.
- The generation units limit: produced power of renewable plants should be in range between minimum and maximum power.
- The battery state-of-charge limit: the state-of-charge (SOC) of batteries should be in range between maximum and minimum values.
- Battery current limit: charging and discharging currents associated to batteries should be less than the maximum values.

To optimal planning of the renewable energy-based micro grid, the optimization variables including the installed generation capacity of the renewable energy-based generation units including wind turbines, tidal turbines and PV systems and also the capacity of the energy storage systems are determined using of the minimization of the objective function presented in Eq. (1). In the proposed optimal planning process, all limitations associated with batteries including the battery SOC limit, efficiencies of charging and discharging states of the batteries, maximum and minimum stored energy of batteries, battery current limit and maximum charging and discharging rate of batteries are considered. At each hour of simulation, according to the hourly demand and hourly generated power of renewable units, SOC of batteries is calculated. For optimizing the objective function of planning problem, among different heuristic algorithms, imperial competition algorithm, artificial bee colony and particle swarm optimization technique are utilized. Among these algorithms, particle swarm optimization method has the best performance. This algorithm optimizes the objective function by iteratively searching to improve a candidate solution with regard to a given index of quality. According to the particle swarm optimization method, the problem is solved by having a population of candidate solutions and moving these particles around in the search space based on the simple mathematical formula over the particles position and velocity. The movement of each particle is affected by its local best known position, but is also guided toward the best known positions obtained in the search space, which are updated as better positions are found by other particles. Thus, the swarm is expected to move toward the best solutions.

4. THE RELIABILITY COST

To analysis the influence of the reliability on renewable unit-based micro grid planning, this paper performs a comprehensive reliability evaluation of the understudied micro grids. Because of the random nature of renewable resources including wind turbines, tidal turbines and PV systems, that makes produced power of these pants changes widely, generated power of the micro grid may be less than the required load. Thus, it makes load curtailment in the micro grid. To reduce values of the load curtailment, energy storage devices are placed in micro grid to reduce the uncertainty nature of the renewable resources. Another factor that may cause the load curtailment in the micro grid is failure of plants or energy storage systems that must be considered in the planning studies. For this purpose, in this part, hazard rates of assembled elements considering change of renewable plants and duration of operation, and the impact of them on produced power of the micro grid are addressed.

4.1. Reliability of Wind Turbine

A common wind unit with PMSG incorporates turbine, gearbox, generator, power electronic converters, control systems, transformer and cable. With failure of any of these components, the whole system will also fail and the transmitted power from wind unit to micro grid will be zero. Thus, in terms of reliability, all assembled elements of wind plant are series. Thus, equivalent hazard rate of wind unit is computed by adding hazard rates of composed components [17]. In Eqs. (5) and (6), the equivalent hazard rate (λ_t) and equivalent repair rate (μ_t) of a system incorporating n series components are presented, respectively [17].

$$\lambda_t = \sum_{k=1}^{n} \lambda_k, \tag{5}$$

$$\mu_t = \frac{\lambda_t}{\sum\limits_{k=1}^{n} \frac{\lambda_k}{\mu_k}}, \tag{6}$$

Where, λ_k and μ_k are hazard and repair rates of the composed components of wind unit. Due to change of wind velocity, outside temperature and duration of operation of the elements, hazard rate of elements and, consequently, hazard rate of wind unit changes, too. It is concluded from [18–21], the unavailability of the gearboxes used in the wind units is linearly relied on wind velocity. According to temperature-dependent studies performed in [22] about the fatigue strength of the carbon and alloy steels materials, hazard rate of gearbox and turbine of wind units that are usually made of carbon and alloy steels, is computed as:

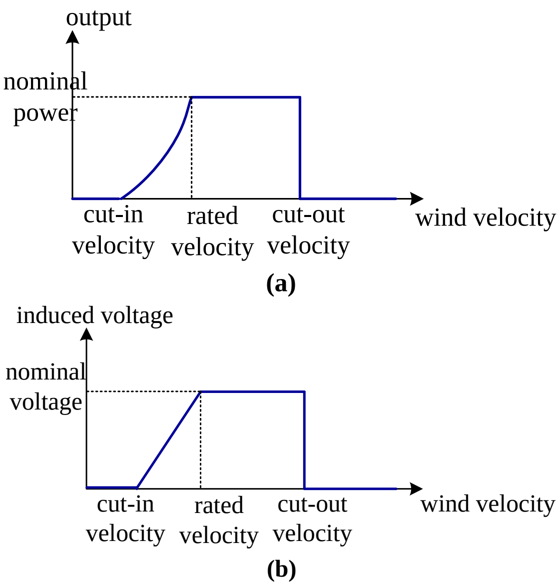


Fig. 5. (a)- Wind turbines power curve and, (b)- Stator windings induced voltage.

$$\lambda(T_F) = \frac{k_d(T_F)}{k_d(T_{F0})}\lambda(T_{F0}). \tag{7}$$

Where, T_F and T_{F0} are the temperature of the gearbox and turbine in Fahrenheit (between 70 and $1000^\circ F$), and k_d is the temperature factor that is calculated as [22]:

$$\begin{aligned} k_d &= 0.975 + 0.000432T_F - 0.115 \times 10^{-5}T_F^2 \\ &+0.104 \times 10^{-8}T_F^3 - 0.595 \times 10^{-12}T_F^4. \end{aligned} \tag{8}$$

In [23], dependency of hazard rate of wind plant, PMSG, power electronic converters, transformer and cable on wind velocity is studied. The hazard rate of turbine considering change of wind velocity and outside temperature can be computed using of limit state function [23] and Eq. (7), respectively. For computing hazard rate of PMSG, based on Eq. (9), the hazard rates of electrical and mechanical parts should be determined.

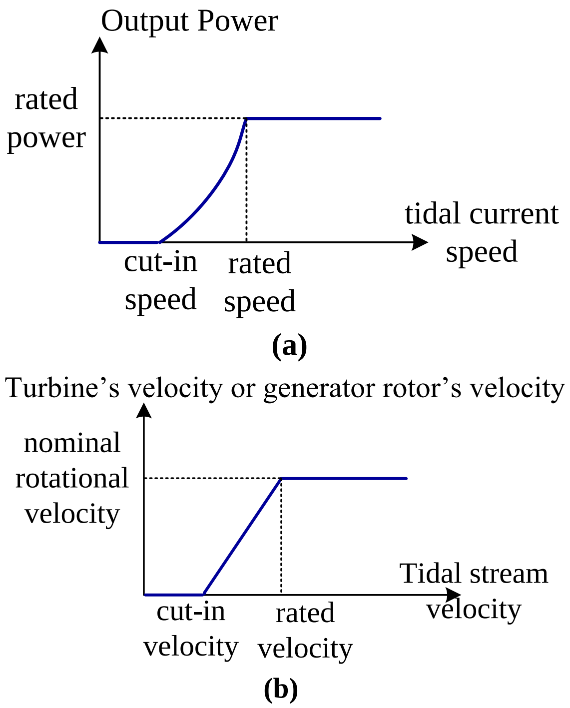


Fig. 6. (a)- Power curve of tidal turbines and, (b)- The speed of the tidal turbines.

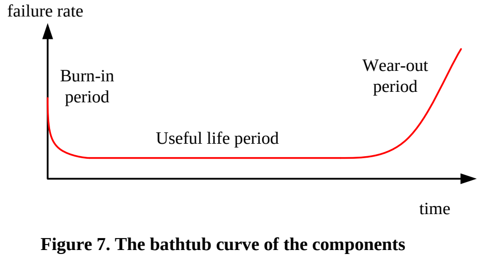


Fig. 7. The bathtub curve of the components.

$$\lambda_{PMSG} = \lambda_{PMSG-e} + \lambda_{PMSG-m}. \tag{9}$$

To calculate hazard rate of electrical devices, the temperature-rise of generator caused by current passing through stator winding is determined and using of Arrhenius law, hazard rate is obtained as [26]:

$$\lambda(\theta) = \lambda(25^0C)e^{\frac{-E_a}{k}\left(\frac{1}{\theta+273}-\frac{1}{298}\right)}. \tag{10}$$

In Eq. (10), $\lambda\,(25^\circ C)$ is generator hazard rate at $25^\circ C$, E_a is activation energy and k is Boltzmann factor. According to wind units power curve, output power of wind unit considering wind velocity is determined. The induced voltage in the stator windings is relied on rotational velocity of generator rotor, and consequently relied on wind velocity. Produced power of wind turbine and stator induced voltage considering the wind velocity are presented in Fig. 5. According to output power of wind turbine and associated stator windings voltage, current passing through stator windings is calculated. According to the current and value of stator windings

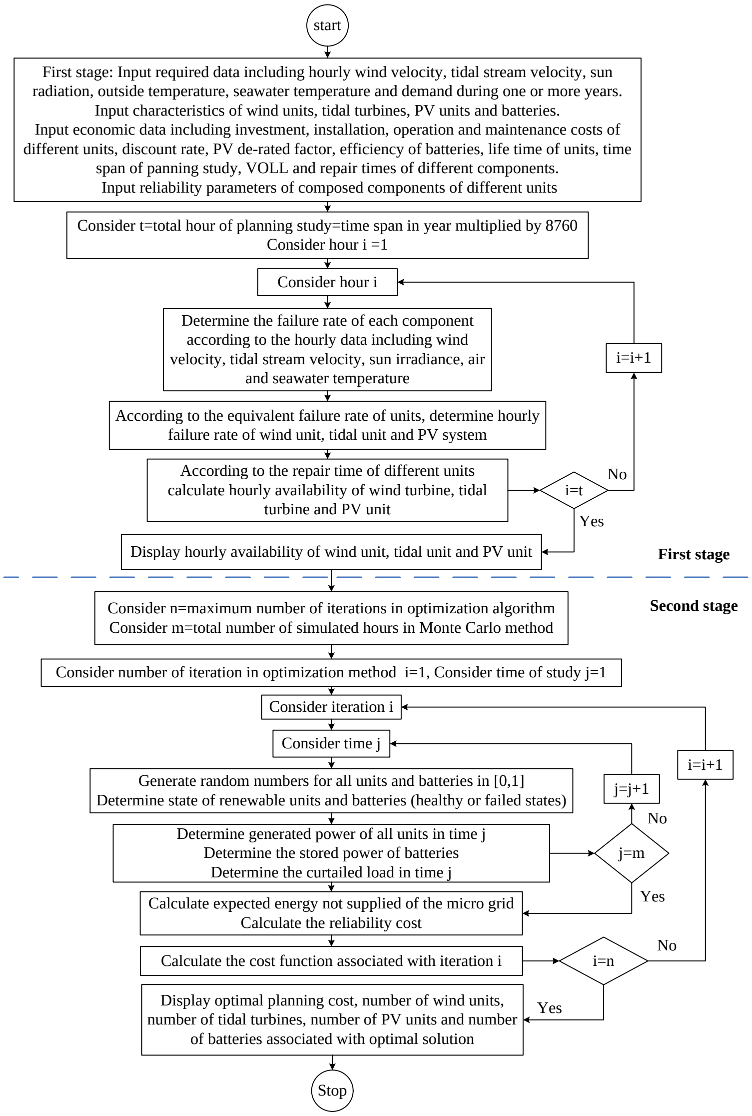


Fig. 8. The proposed flowchart associated with optimal planning of renewable energy-based micro grid considering reliability cost.

resistance, power loss is calculated. Then, according to the thermal modelling of generator, the operating temperature of the generator (θ) replaced in Eq. (10) is obtained.

To determine hazard rate of mechanical parts of PMSG, impact of change of wind velocity and outside temperature are considered. Due to the fatigue stress arisen from wind velocity analysed in [18–21], failure rate of the rotating part of the generator, i.e. the rotor is relied on wind velocity. In addition, Eqs. (7) and (8) are used for computing hazard of PMSG at different outside temperature.

In [23, 26], hazard rate of a typical back-to-back converter attached to the PMSG addressing the change of generated power of generator caused by change of wind velocity and tidal height are determined. However, to consider influence of change of outside temperature, ambient temperature used in the Arrhenius law should be modified. In [23, 26], hazard rate of capacitor installed between rectifier and inverter is considered constant. However, to consider influence of wind velocity and outside temperature variations on capacitor hazard rate, Eq. (11) is used [29].

$$\lambda_C = \lambda_0 \pi_T \pi_C \pi_V \pi_{SR} \pi_E. \tag{11}$$

Where, λ_0, π_T, π_C, π_V, π_{SR} and π_E are base capacitor hazard rate at test requirements, temperature coefficient, capacitance coefficient, voltage-stress coefficient, series-resistance coefficient and environmental coefficient. Hazard rate of oil-type transformer and XLPE cable, widely applied in wind and tidal units, considering variation in the current passing through the windings and cable conductors is determined in [23, 26]. However, to consider influence temperature change, ambient temperature used in the Arrhenius law should be modified.

4.2. The Reliability of Tidal Turbine

A procedure alike to wind turbine performed in the previous part is followed to determine hazard rate of elements of current kind tidal plant. Main elements of DFIG-based tidal turbine are turbine, gearbox, DFIG, power electronic converters, control systems, transformer and cable. With failure of any of these components, the entire tidal unit is failed, and thus, in terms of reliability, the components are in series. Equivalent hazard and repair rates of tidal unit are calculated by Eqs. (5) and (6). Hazard rate of turbine, gearbox, transformer and cable applied in tidal plants can be determined as the equations mentioned in Subsection 4.1. However, instead of wind velocity and ambient temperature, tidal current speed and seawater temperature are replaced, respectively.

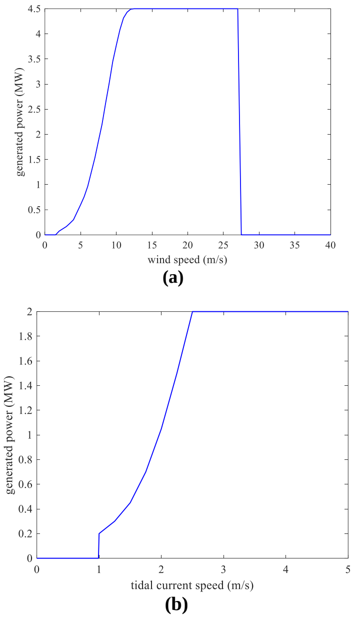


Fig. 9. power curves of understudied: (a)- Wind and, (b)- Tidal turbines [24, 25].

In this stage, hazard rate of DFIG addressing change of tidal current speed and seawater temperature is computed. Tidal units generated power considering tidal stream velocity is calculated via tidal turbines power curve. Power curve of a typical current type tidal turbine and turbines velocity at different tidal stream velocity are presented in Fig. 6.

In the DFIG, the powers of the rotor and stator windings can be obtained by multiplying the output power by $(-s/(1-s))$ and $1/(1-s)$, respectively. Slip presented by s is computed as [30]:

$$s = \frac{n_s - n_r}{n_s} = \frac{v_s - v_{tid}}{v_s}. \tag{12}$$

In Eq. (12), n_s, n_r, v_s and v_{tid} are synchronous velocity expressed in rpm, rotor velocity expressed in rpm, tidal stream velocity related to synchronous velocity expressed in m/s and tidal current velocity. Rotor windings induced voltage is computed by multiplying the stator voltage by the slip and rotor to stator winding turn ratio. According to the powers and currents of rotor and stator windings, rotor and stator windings currents, and consequently, based on the windings resistance, power losses related to rotor and stator windings are calculated. Using of thermal modelling of DFIG, and based on calculated generators power losses, the temperature of the DFIG is determined. In this stage, Arrhenius equation is applied to obtain hazard rate of electrical devices of DFIG. For computing hazard rate of mechanical devices of DFIG, similar approach used in the PMSG of the wind turbines, is followed. To determine hazard rate of back-to-back converter applied in tidal plants equipped with the DFIG technology, the approach explained in [30] is used.

4.3. The Reliability of PV Unit

The configuration of a common PV unit is depicted in Fig. 4. In this plan, with failure of the transformer or the cable, the transmitted power of PV unit to micro grid would be zero. With failure of any inverter, failure of related PV array occurs, and so the transmitted power from PV unit to micro grid is reduced as much as output power of a PV array. With failure of any PV panel, output power of related PV string is zero and so, output of PV unit is reduced as much as output of a PV string. Impact of change of sun irradiance and outside temperature on generated power of PV panel is presented in Eq. (13) [31]:

$$P_{panel} = \frac{s}{s_0} P_0 [1 + \gamma_P (T_a - T_{a0})]. \tag{13}$$

In Eq. (13), s, s_0, P_0, γ_P, T_a and T_{a0} are sun irradiance, sun irradiance associated to test requirements, produced power of PV panel at test state, temperature coefficient of power parameter, outside temperature and outside temperature under test state. Besides, PV panel voltage considering temperature variation can be determined as [31]:

$$V_{panel} = V_0 [1 + \gamma_V (T_a - T_{a0})]. \tag{14}$$

In Eq. (14), V_0 and γ_v are voltage associated to maximum power point of PV panel in standard test states and temperature coefficient of voltage parameter. Hazard rate of semiconductor elements such as PV panels can be determined as [29]:

$$\lambda = \lambda_0 \pi_T \pi_S \pi_A \pi_R \pi_E. \tag{15}$$

Where, $_0$, π_T, π_S, π_A, π_R and π_E are base hazard rate of PV panel, temperature coefficient, electric stress coefficient, application coefficient, power and environmental coefficients. For obtaining PV panels hazard rate considering variation in outside temperature and produced power, temperature coefficient can be determined as Arrhenius law, and electric stress and power coefficients are calculated as [29]:

$$\pi_s = \alpha e^{\beta V_{SC}}, \tag{16}$$

$$\pi_R = {P_{sc}}^a. \tag{17}$$

Where, α, β and a are the constants parameters of the PV panels, V_{sc} and P_{sc} are the voltage and the PV panels produced power. In this paper, PV system is placed in the coastal area, and so, the application and environmental factors are considered to be 1.5 and 15, respectively [29]. The failure rates of the inverters, transformers and cables used in the PV systems are computed in a procedure alike to that of wind and tidal units. However, in the PV system, current passing via elements can be calculated based on output power and voltage of PV panels addressing change of sun irradiance and air temperature.

4.4. The Impact of Operations Duration of Components on Hazard Rates

The hazard rate of each component can be presented as bathtub curve depicted in Fig. 7. Accordingly, each component experiences three stages including burn-in or childhood, useful life and wear-out periods. In the burn-in period, due to the improper design, the manufacturing problems and improper installation, hazard rate of elements may be high. In useful life period, hazard rate of elements is low and using of periodic proper repair and maintenance operations, the value of the failure rate remains in the permissible range. However, after the expiration date of the useful life period, due to the wear and tear of the components, the failure rate would be high. In [32], an exponential function named aging fault rate function as presented in Eq. (18) is introduced for computing hazard rate of the transformer in old age. This function with modified parameters can be applied for computing hazard rate of other elements.

$$\lambda = \lambda_0 e^{\alpha (t - t_0)} \quad for \;\; t > t_0. \tag{18}$$

Where, λ_0 is the component failure rate during the useful life period, α is a constant parameter, t is the duration of the operation of the component, and t_0 is useful lifetime of component.

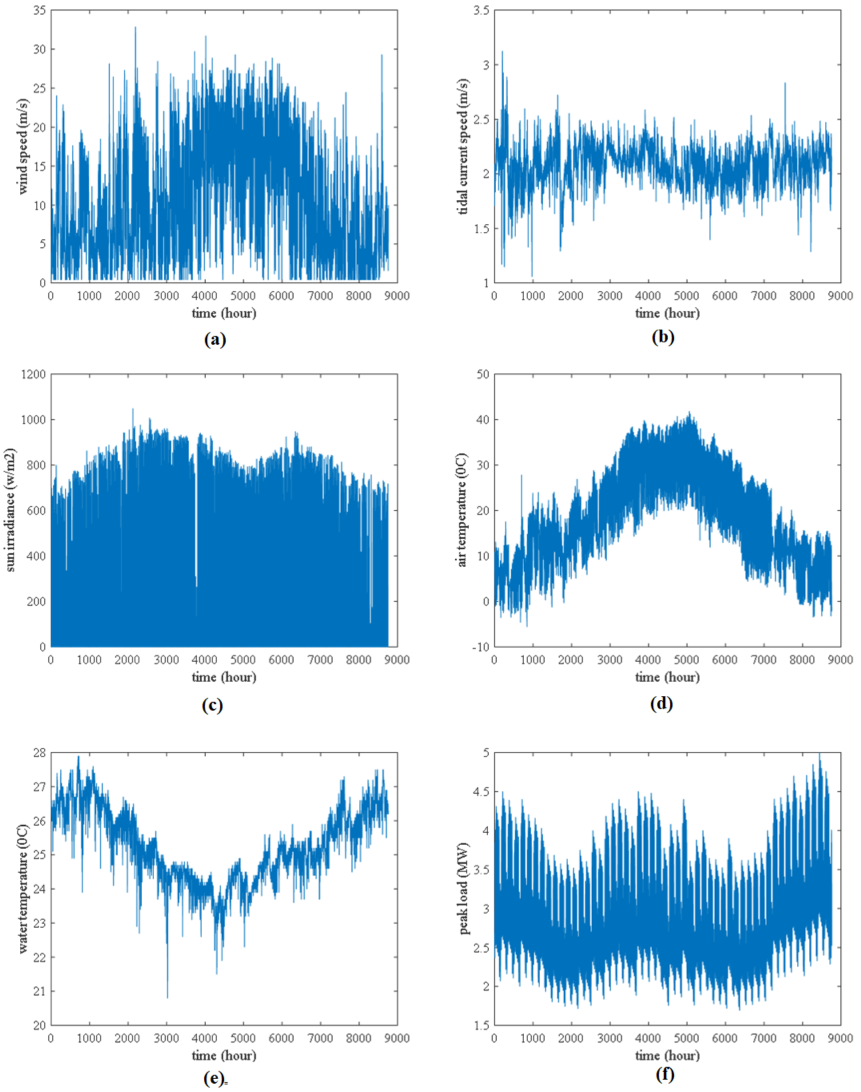


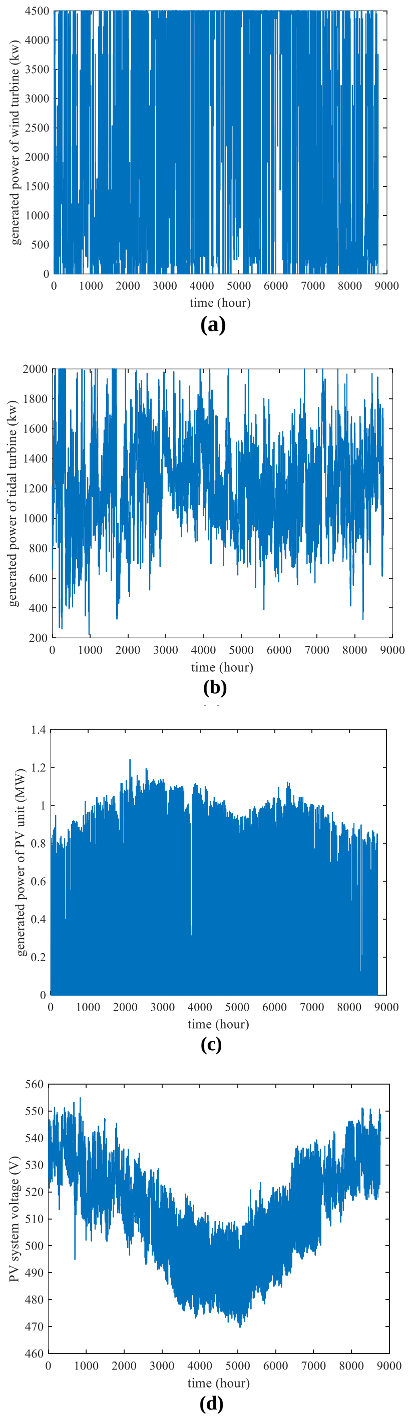
Fig. 10. Hourly: (a)- Wind velocity, (b)- Tidal stream velocity, (c)- Sun radiation, (d)- Outside and, (e)- Water temperature and, (f)- Peak demand [27, 28].

4.5. The Reliability Assessment Technique

For reliability assessment of the renewable unit-based micro grid, addressing variable hazard rate of assembled elements, Monte Carlo simulation methodology is proposed. Accordingly, hourly input data including wind velocity, tidal stream velocity, sun radiation, outside temperature, sweater temperature and demand for one or more years should be available. According to the equations derived in this section associated to the hazard rate of all assembled elements of renewable resources, addressing the change of wind velocity, tidal stream velocity, sun irradiance, and air and sweater temperature, hourly components failure rate during one or more years is determined. In addition, by Eq. (18), hourly hazard rate of all assembled elements during the time span of the planning process is obtained. Using of the repair rate of these components, the hourly data associated to the availability of all components is calculated. At every time or hour, for each component, a random number in [0,1] is customized. If customized number is in [0,Availability] or [Unavailability,1], component is healthy, and if the generated number is in [Availability,1] or [0,Unavailability], the component is failed. According to the states of all composed components, hourly data, and the characteristics of renewable sources, generated power of renewable plants is determined. Besides, based on hourly load and output power of renewable sources, and states (up or down) of batteries, stored energy of batteries, and consequently charging/discharging power of batteries are determined. In simulation process of the renewable energy-based micro grid containing the batteries, the charging/discharging power and stored energy of failed batteries are considered equal to the zero and minimum energy, respectively. If the hourly load is equal to output power of plants, stored energy of the healthy batteries remains constant. If the load is less than output power of renewable sources, stored energy of the healthy batteries increases as much as the charging power of the healthy batteries. In this state, the charging power of each healthy battery would be minimum value of maximum charging power with divided power on healthy batteries considering the charging efficiency.

$$P_{ch\arg ing}(h) = \min(P_{c\max}/\eta_{ch}, \frac{P_{ren}(h) - load(h)}{number\ of\ healthy\ batteries}). \tag{19}$$

Where, $P_{charging}(h)$, P_{cmax}, η_{ch} and $P_{ren}(h)$ are the charging power, maximum charging power and charging efficiency of the batteries, and output power of renewable plants in hour h. However, the stored energy in the batteries should not exceed the maximum value of the stored energy.



(a)

(b)

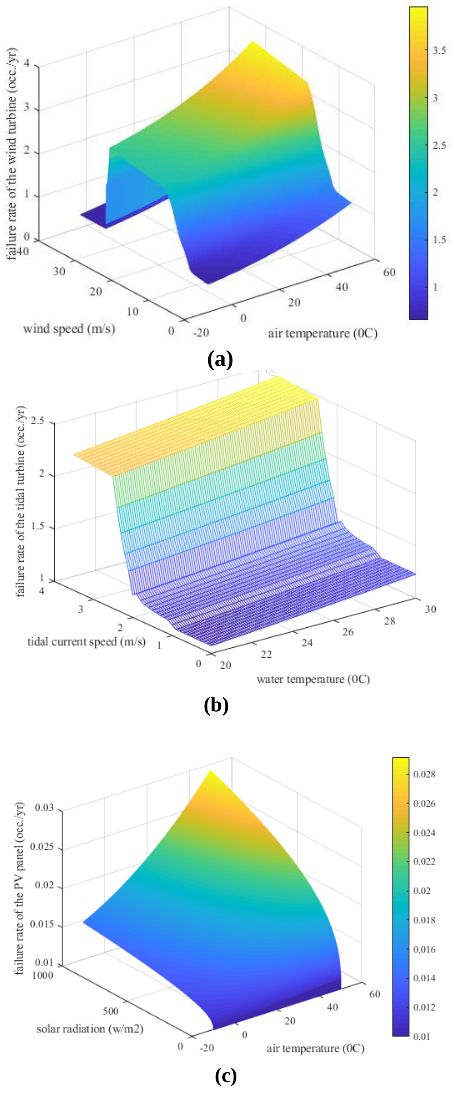
(c)

(d)

Fig. 11. The hourly: (a)- Wind power, (b)- Tidal power, (c)- PV power and, (d)- PV voltage.

$$E(h) = \min(E_{\max}, E(h-1) + \eta_{ch} P_{ch\arg ing}(h)). \tag{20}$$

Where, $E(h)$, $E(h-1)$ and E_{max} are energy stored in batteries in hour h, energy stored in batteries in hour $h-1$ and the maximum energy of the batteries. If the load is more than output power of renewable plants, stored energy of the healthy batteries decreases as much as the discharging power of the healthy batteries. In this state, the discharging power of each healthy battery would be minimum value of maximum discharging power with divided power on healthy batteries considering the discharging efficiency.



(a)

(b)

(c)

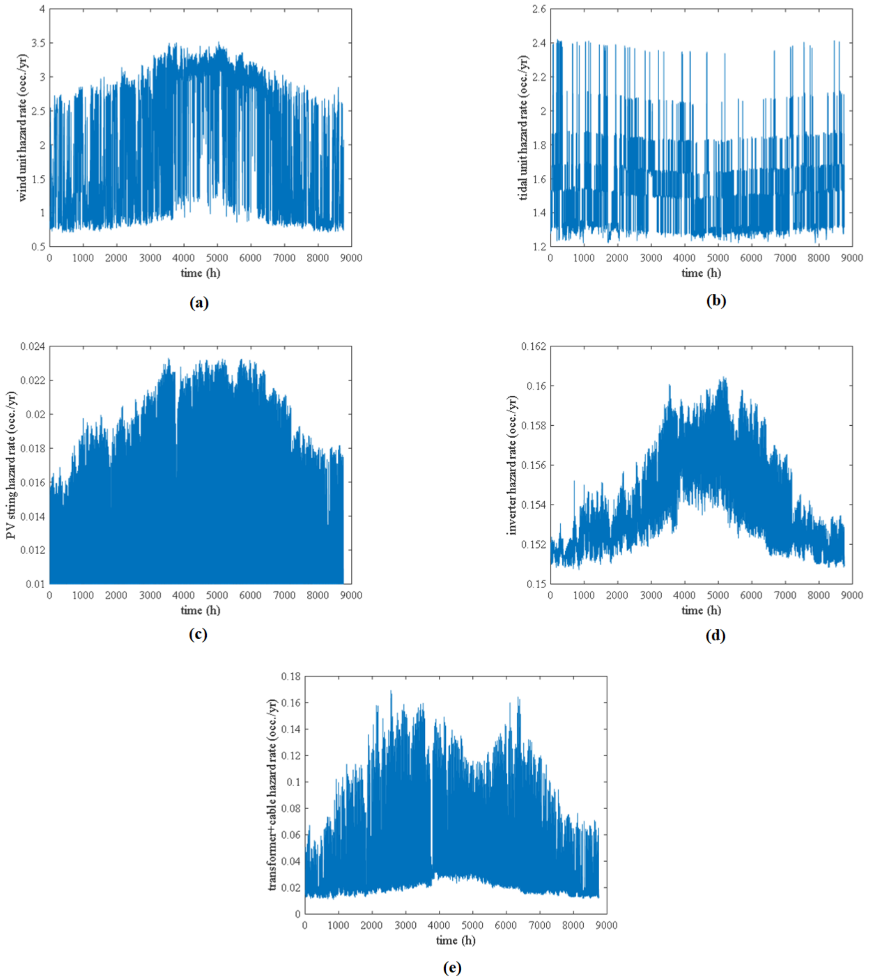
Fig. 12. Hazard rate associated to the: (a)- Wind turbine, (b)-Tidal turbine and, (c)- PV system considering resource variations.

$$P_{disch\arg ing}(h) = \min(P_{d\max}/\eta_{dis}, \frac{load(h) - P_{ren}(h)}{number\ of\ healthy\ batteries}). \tag{21}$$

Where, $P_{discharging}(h)$, P_{dmax} and η_{dis} are the discharging power in hour h, maximum discharging power and discharging efficiency of the batteries. However, energy stored in batteries should not be less than minimum value of stored energy.

$$E(h) = \max(E_{\min}, E(h-1) - \eta_{dis} P_{disch\arg ing}(h)). \tag{22}$$

Where, E_{min} is the minimum energy stored in batteries. The energies stored in all batteries in the first hour of the batteries installation (h=1 and h=12.5 × 8760+1) are considered minimum energy of batteries. With determination the hourly power of the batteries, the value of the hourly curtailed load during the time span of the planning process is calculated. An important reliability index, i.e. average curtailed energy (EENS) expressed in MWh or kwh at year can be calculated as:



(a)

(b)

(c)

(d)

(e)

Fig. 13. The hourly hazard rate: (a)- Wind turbine, (b)- Tidal plant, (c-e)- PV plant components.

$$EENS = \frac{1}{NM}\sum_{k=1}^{N\times M\times 8760} L_k. \tag{23}$$

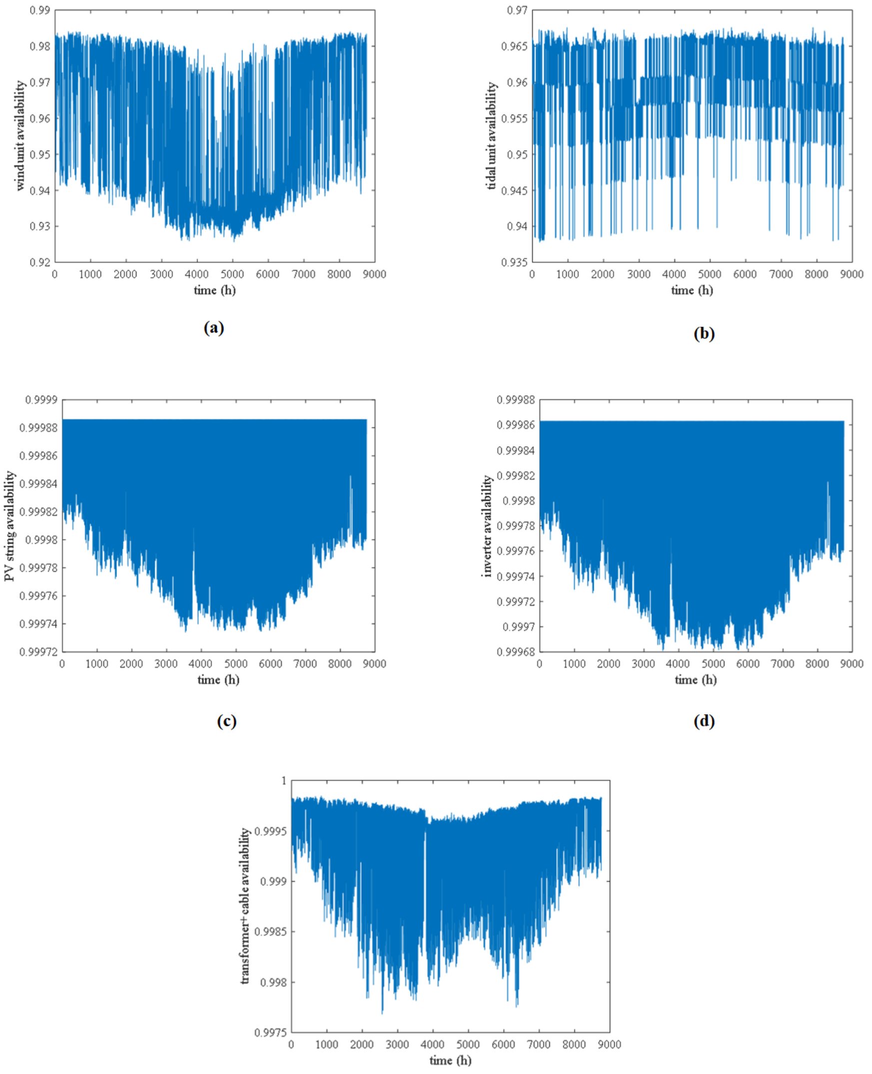
Where, N, M and L_k are repetitions number in Monte Carlo simulation approach, the number of years in the time span of the planning process and the hourly-curtailed load, respectively. The flowchart associated with optimal planning of the understudied micro grid is presented in Fig. 8. In this flowchart, for optimal planning of the renewable energy-based micro grid considering reliability cost, two stages are considered. In the first stage, according to the characteristics of different units, hourly wind velocity, tidal stream velocity, sun irradiance, air and seawater temperature and demand, hourly failure rate and consequently hourly availability of different units is determined. In the second stage, through Monte Carlo simulation technique and optimization algorithm, optimal planning of the understudied micro grid is performed to optimally determine the number of wind turbines, tidal turbines, PV units and energy storage devices.

5. NUMERICAL RESULTS

In this section, the optimal planning associated to a renewable unit-based micro grid installed in the coastal region, considering the reliability cost is performed. The 4.5MW wind turbine, 2MW current type tidal turbine, 1MW PV unit with 4000 250kW panels and 600kW energy storage system are considered in the understudied micro grid. Fig. 9 depicts power curves of wind and tidal turbines [24, 25]. The hourly data associated to the wind velocity, tidal stream velocity, sun radiation, outside and seawater temperature and demand at a year are depicted in Fig. 10 [27, 28].

The understudied PV unit is incorporated of 10 PV arrays and every array includes 25 parallel PV strings. In the sun irradiance radiation of 900 w/m^2 and outside temperature of $25°C$, the generated power of each panel would be 250kW. The hourly output power of wind plant, tidal turbine and PV plant and the generated voltage of PV plant are depicted in Fig. 11. As can be seen in the figure, due to the variation in the wind velocity, tidal stream velocity, sun irradiance and air temperature, the generated power of wind turbine, tidal turbine and PV panel varies largly over times. Thus, to accurately study the reliability and planning of the renewable energy-based micro grid, this variation must be addressed.

According to the equations derived in Section 4, hazard rate of understudied wind plant, tidal turbine and PV system considering variations in the wind speed, air and seawater temperature, tidal stream velocity and sun irradiance are presented in Fig. 12. To calculate failure rate of the understudied micro grid containing renewable resources, the required data are collected from [18–32]. As can be seen in the figure, the dependency of hazard rate of wind unit on wind speed is similar to the power curve of wind turbine. Because, the hazard rate of electrical components of the wind unit depends on the current passing through them, that is proportional to the generated power of wind unit. With increase in the air temperature, according to the Arrhenius law, the operating



(a) (b) (c) (d) (e)

Fig. 14. The hourly availability: (a)- Wind turbine, (b)- Tidal plant, (c-e)- PV plant components.

temperature of the wind unit components increases that results in higher hazard rate of wind unit. Similar results are extracted from the figure for tidal stream unit, i.e. the dependency of hazard rate of tidal unit on the tidal stream velocity is similar to the power curve of tidal unit. Also, with increase in seawater temperature, the hazard rate of tidal unit increases. For PV panel, increase in sun irradiance and air temperature results in the increase in the operating temperature of the panel that makes the hazard rate of PV panel increases.

According to the hourly wind velocity, tidal stream velocity, air and seawater temperature and sun irradiance, hourly hazard rate of wind turbine, tidal turbine, PV components including PV string, inverter and the series connection of transformer and cable is calculated and presented in Fig. 13. As can be seen in the figure, due to the variation in wind velocity, tidal stream velocity, air and seawater temperature and sun irradiance, the hazard rate of these units varies in time.

The economic data and properties of wind plants, tidal plants, PV plants and batteries integrated to renewable energy-based micro grid are presented in the following tables [2–7]-[33].

Table 1. The economic data of generation units and batteries [2–7]-[33].

Units	Investment and installation cost (in $/kW)	Cost in operation and maintenance (in $/kW/year)	Lifetime (years)
Wind turbines	1600	40	25
Tidal turbines	2500	10	25
PV systems	2000	35	25
Batteries	450	5	12.5

To determine hourly availability of wind turbine, tidal plant and elements of the PV plant incorporating PV string, inverter and transformer connected to the cable, the repair time of these systems are considered to be as presented in Table 4 [23, 26]. According to hourly hazard rate of these systems and the associated repair time, the hourly availability of them during the first year is calculated and presented in Fig. 14. As can be seen in the figure, the availability of the units varies over time that affects the reliability performance of the renewable energy-based micro grid. Thus, for accurate optimal planning of renewable energy-based micro grid considering reliability cost, variation in the availability of units should be considered.

For optimally determining the number of wind plant, stream

Table 2. The characteristics of the batteries [2–5].

Parameters	Values	Parameters	Values
Maximum charging power	600 kw	Maximum discharging power	600 kw
Maximum energy can be stored in batteries	1800 kwh	Minimum energy can be stored in batteries	180 kwh
Charging efficiency	93%	Discharging efficiency	94%

Table 3. The economic data of the planning study [2–5].

Planning time span	VOLL	PV de-rating factor	Discount rate	Battery availability
25 years	7.5 $/kwh	0.8% in year	5%	0.99

Table 4. The repair time of the components [23, 26].

Wind unit	Tidal unit	Elements of PV plant		
		PV string	inverter	Transformer and cable
200 h	240 h	100 h	120 h	120 h

Table 5. Setting parameters of metaheuristic algorithms [34–38].

Algorithm	PSO	ICA	ABC
Number of decision variables	4	4	4
Maximum iterations	100	100	100
Number of population	50	100	100
Inertial weight damping ratio	1	-	-
Number of imperialists	-	10	-
Beta and zeta	-	2-0.1	-
Optimal cost ($)	73168627	73252243	73518976

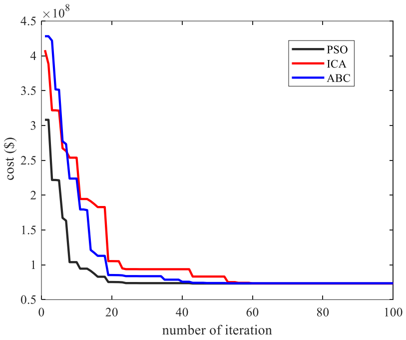


Fig. 15. The convergence diagram of metaheuristic algorithms.

kind tidal turbines, photovoltaic plants and batteries, proposed cost function is optimized via three metaheuristic algorithms including particle swarm optimization (PSO) technique, imperial competitive algorithm (ICA) and artificial bee colony algorithm (ABC). The setting parameters of these metaheuristic methods are presented in Table 5. These parameters are selected from [34–38]. In this paper, the suggested algorithms are repeated 100 times and the convergence diagrams of them are depicted in Fig. 15. This figure presents among different metaheuristic algorithms applied in the optimal planning of proposed micro grid, PSO method has converged at a high speed and results in the optimal solution. The optimal solution including the optimal number of wind turbines, optimal number of tidal turbines, optimal number of PV systems and optimal number of batteries is presented in Table 6. According to optimal resort, minimal cost would be 73168627 $.

By comparing the results obtained through PSO algorithm with other two well-known metaheuristic methods, the effectiveness of the proposed algorithm is satisfied. As can be seen in Fig. 14, the convergence speed of the PSO is higher than two other methods. Besides, the planning cost of the micro grid illustrated in Table 5 presents that the planning cost resulted from PSO method is less than the costs obtained by ICA and ABC methodologies.

The energy balance of the generation units and batteries associated with the optimal plan during time span of planning study is calculated and given in Table 7. As can be seen in the table, the energy balance of the micro grid during 25 years is established. According to the energy balance of the micro grid, the following equation is established: (Energy of demand) (curtailed energy) = (generated energy of wind turbines + generated energy of tidal units + generated energy of PV units [stored energy in batteries] / [efficiency of charging process of batteries]) + (efficiency of discharging process of batteries) × (stored energy in batteries)

Table 6. Optimal solution obtained by PSO method.

Number of wind turbines	1
Number of tidal turbines	1
Number of PV systems	3
Number of batteries	2

Table 7. Energy balance of the micro grid during 25 years (in MWh).

Energy of demand	672920
Generated energy of wind turbines	224040
Generated energy of tidal turbines	164035
Generated energy of PV units	286536
Stored energy in batteries	105124
Curtailed energy	12501

Unlike operation studies of power system or micro grid, which have a short study time, in planning studies, the time span is several years. Therefore, the proposed method is practical for real-time applications. In other words, there is enough time to carry out the simulation proposed in this research to optimally determine the number and size of renewable units and batteries so that the cost of the micro grid is minimized. However, there are several limitations of the method presented in this paper, including the unavailability of reliability parameters associated to composed components of renewable energy-based units, unavailability of hourly data associated to wind velocity, tidal stream velocity and seawater temperature for some coastal regions, and high volume of calculations when the number of units in the micro grid is large.

6. CONCLUSION

In this paper, optimal planning of renewable unit-based micro grids suitable for installation in the coastal areas or islands is performed. The proposed micro grid includes wind plants, stream kind tidal turbines, PV systems and batteries. Because of the variation in wind velocity, tidal currents velocity and sun irradiance, generated power of these renewable generation units varies that affects the reliability and planning of the micro grid. To reduce change in output power of micro grid, batteries are utilized. In this research, reliability analysis of different generation units is performed and influence of resource change on hazard rate and availability of wind plants, tidal turbines and PV plants is analysed. Numerical outcomes performed by MATLAB software presents change in the resources results in change of hazard rate and availability of these renewable resources. Thus, to exactly study the planning of renewable unit-based micro grid, variable hazard rate of composed elements should be considered. Then, for optimally determining the capacity and size of batteries and different renewable resources installed in the understudied micro grid, the cost function that includes reliability cost and the investment, installation, operation and maintenance costs of generation units and batteries is minimized. To calculate the reliability cost of the micro grid, the curtailed loads at different times are determined based on the penalty that the micro grid must pay for the interruption of the load. To determine the curtailed load, hazard rate of assembled elements and variation in generated power of renewable resources are addressed. For considering variable failure of composed components, Monte Carlo simulation methodology for 1000 repetitions is implemented. Optimal planning scheme of micro grid is determined by different metaheuristic algorithms including PSO, ICA and ABC methods. Among these optimization methodologies, due to the higher convergence speed and more optimal result, PSO algorithm with 100 iterations is selected to perform the optimal planning of the understudied micro grid. Numerical outcomes present suggested algorithm has converged after 30 iterations. Thus, the proposed algorithm has been able to lead to optimal solutions at short time.

As future works, the micro grid with the presence of other renewable energy resources such as wave power plants can be studied to investigate the effect of changes in the height and frequency of waves on the failure rate of composed components of the wave power plant. Besides, other metaheuristic algorithms such as Differential Evolution and Quantum Approximate Optimization Algorithm can be used in optimal planning of the renewable energy-based micro grids.

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