

## Optimal Sizing of an Islanded Micro-grid for an area in north-west Iran Using Particle Swarm Optimization Based on Reliability Concept

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**Abstract:** In islanded micro-grid design, a proper Distributed Energy Resource (DER) selection, sizing and effective coordination between resources are important and challenging optimization tasks. The types and sizes of renewable energy sources such as wind turbines, photovoltaic panels, fuel cell and the capacities of battery bank and the other distributed generators must be optimized in islanded micro-grid design. In this paper, the problem is formulated as a nonlinear integer minimization problem which minimizes the sum of the total capital, operational and maintenance and replacement cost of DERs, subject to constraints such as energy limits of each DER. This paper proposes Particle Swarm Optimization (PSO) for solving this minimization problem. The proposed methodology was used to design micro-grid for northwest of Iran. The simulation studies have shown that the proposed methodology provides excellent convergence and feasible optimum solution for sizing of islanded micro-grids using particle swarm optimization. In this paper some notions of reliability are considered for micro-grid, and the effect of reliability on total cost of micro-grid is evaluated.

**Keywords:** Micro-grid, Optimal sizing, Particle swarm optimization, Reliability

### Nomenclature

$P_{wind}$ power generated by wind turbines..... kW	$E_{bat}$ stored energy in battery banks ..... kWh
$P_{PV}$ power generated by PV generators ..... kW	$R$ lifetime of project ..... year
$P_{FC}$ power generated by fuel cells ..... kW	$L$ lifetime of each component..... year
$P_{Load}$ ..... load power	$ir$ Interest rate ..... %

### 1. Introduction

The increase in penetration of distributed generation depth and the presence of multiple distributed generators in electrical proximity to one another have brought about the concept of the micro-grid [1, 2]. Micro-grids comprise low voltage distribution systems with distributed energy sources, storage devices, and controllable loads, operated either islanded or connected to the main power grid in a controlled, coordinated way. Refs. [3, 4] introduce the benefits of micro-grid, such as, enhance local reliability, reduce feeder losses, support local voltages, provide increased efficiency through using waste heat combined heat and power, voltage sag correction or provide uninterruptible power supply functions. Proper selection of distributed energy resources and optimal sizing of them are important and challenging tasks in the designing of islanded micro-grids [5] because the coordination among distributed energy resources is very complicated. The problem can be formulated as a nonlinear integer optimization problem which can be solved by a suitable optimizing methodology. Our aim is to minimize the total costs of the system such that the demand is met. For standalone hybrid wind/PV power systems, a typical tangent method is used to fix the size of wind generator and optimize the size of PV panels and the capacity of batteries [5, 7]. Several research works have been done for selecting the parameters such as the size of wind generators, the size of PV panels and the capacity of batteries but the decision variables collectively taken without any optimizing methodologies [5- 12]. Recently, a genetic algorithm for the concerned problem has been proposed by Xu et al. [13] where genetic algorithm optimizes the size of wind generators, the size of PV panels and the capacity of batteries as decision variables. Although this method provides a better performance in comparison to the previous literature,

it is necessary to find a flexible generalized methodology for any kind of micro-grid designing with higher computational efficiency.

In this paper, the optimal sizing of a wind-PV-fuel cell-battery bank in micro-grid is considered. The optimization is carried out via Particle Swarm Optimization (PSO) algorithm. Generation of hydrogen by the reformer causes a higher reliability for the system.

First, we consider the micro-grid. And then the cost of the system presented by an objective function. Finally some simulation results are presented. This study is performed for Ganje site in northwest of Iran. It is located in a village with a population of 800.

## 2. Description of the micro-grid components

### 2.1. Wind turbine

The power of the wind turbine is described in terms of the wind speed by Ref [16]:

$$\begin{cases} 0 & V < V_{cut-in}, V > V_{cut-off} \\ P_{rated} \times ((V - V_{cut-in}) / (V_{rated} - V_{cut-in}))^3 & V_{cut-in} \leq V < V_{rated} \\ P_{rated} & V_{rated} \leq V \leq V_{cut-off} \end{cases} \quad (1)$$

In which  $V_{cut-in}$ ,  $V_{cut-off}$ ,  $V$ ,  $V_{rated}$  and  $P_{rated}$  are cut-in wind speed [m/s], cut-out wind speed [m/s], wind speed [m/s], nominal wind speed [m/s] and the rated power of wind turbine [kW] respectively. In this analysis, each wind turbine has a rated capacity of 1 kW. Cost of one unit is considered 2500\$, while replacement and maintenance cost are taken as 1500\$ and \$75/year. Lifetime of a turbine is taken to be 20 years [14].

### 2.2. PV

The output power of the PV generator  $P_{PV}$ , can be calculated according to the following equation:

$$P_{PV} = \eta_g * N * A_m * G_t \quad (2)$$

Where  $\eta_g$  is the instantaneous PV generator efficiency,  $A_m$  is the area of a single module used in a system ( $m^2$ ),  $G_t$  is the global irradiance incident on the titled plane ( $W/m^2$ ) and  $N$  is the number of modules. In this analysis, each PV generator has a rated power of 1 kW. Cost of one unit considered is 6000\$ while replacement and maintenance cost are taken as 5000\$ and 0\$/year respectively. Lifetime of a PV generator is taken to be 20 years [14].

### 2.3. Fuel cell

Proton exchange membrane (PEM) fuel cell is an environmentally clean power generator which combines hydrogen fuel with oxygen from air to produce electricity.

The capital cost, replacement cost and operational cost are taken as 3\$k, 2.5\$k and 175\$/year for a 1-kw system, respectively. Fuel cell's lifetime is considered to be 5 years [14].

### 2.4. Battery storage

At any hour the state of battery is related to the previous state of charge and to the energy production and consumption situation of the system during the time from t-1 to t.

In all cases the storage battery capacity is subject to the following constraints:

$$E_{bat \min} \prec E_{bat}(t) \prec E_{bat \max} \quad (3)$$

Where  $E_{bat \max}$  and  $E_{bat \min}$  are the maximum and minimum allowable storage capacities.

$E_{bat \min}$  is determined by the maximum allowable depth of battery discharge (DOD) as follows:

$$E_{bat \min} = (1 - DOD) * E_{bat \max} \quad (4)$$

In this analysis, each battery bank capacity is 552Ah. Cost of each battery is considered 264\$ while replacement and maintenance costs are taken as 260\$ and 2.64\$/year. Lifetime of a battery is taken to be 3 years [14].

### 3. System modeling

The micro-grid consists of some wind turbines, PV arrays, fuel cells, reformers and battery banks (Fig. 1). Natural gas is used to produce fuel cells' required hydrogen.

It is desirable that the system meets the demand, the costs are minimized and the components have optimal sizes.

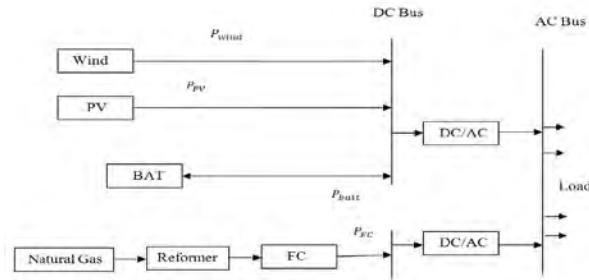


Fig.1. Schematic diagram of micro-grid

#### 3.1. Strategy

We consider three situations for the system: A. generation power produced by renewable energy (wind + PV) meets demand, B. over generation and C. over demand.

##### 3.1.1. Power generation produced by wind and PV meets demand

In this situation the power generated by the wind turbine plus the power produced by the PV array is equal to the demand ( $P_{wind}(t) + P_{PV}(t) = (P_{Load}(t) / \eta_{conv})$ ), hence:

$$E_{bat}(t) = E_{bat}(t-1), P_{FC}(t) = 0 \quad (5)$$

It is notable that the time steps  $\Delta t$  are taken to be 1 hour in this study.

##### 3.1.2. Over generation

The produced power of the wind turbine plus power produced by the PV array are more than the demand ( $P_{wind}(t) + P_{PV}(t) \succ (P_{Load}(t) / \eta_{conv})$ ).

The excess power is utilized for charging the batteries:

$$E_{bat}(t) = E_{bat}(t-1) + (P_{wind}(t) + P_{PV}(t) - P_{Load}(t) / \eta_{conv}) * \Delta t * \eta_{cha}, P_{FC}(t) = 0 \quad (6)$$

### 3.1.3. Over demand

The demand is more than the power generated by the wind turbines and power produced by the PV array ( $P_{wind}(t) + P_{PV}(t) < (P_{Load}(t)/\eta_{conv})$ ).

In this situation we have two cases:

a. Available battery banks' energy and power generation of wind turbine plus PV array can meet demand ( $P_{wind}(t) + P_{PV}(t) + (E_{bat}(t) - E_{bat\ min}) * \eta_{dech} / \Delta t > (P_{Load}(t)/\eta_{conv})$ ).

$$E_{bat}(t) = E_{bat}(t-1) + (P_{wind}(t) + P_{PV}(t) - P_{Load}(t)/\eta_{conv}) * \Delta t / \eta_{dech}, P_{FC}(t) = 0 \quad (7)$$

b. Available battery banks' energy and power generation of wind turbine plus PV array can not meet demand:

In this situation the battery banks are completely discharged and the energy in the battery banks is equal to  $E_{bat\ min}$ . In this state, load requirements are supplied from the fuel cell:

$$E_{bat}(t) = E_{bat\ min}, P_{FC}(t) = (P_{Load}(t)/\eta_{conv}) - P_{PV}(t) - P_{wind}(t) - (E_{bat}(t) - E_{bat\ min}) * \eta_{dech} / \Delta t \quad (8)$$

## 3.2. System's cost

In this paper we consider the capital and replacement costs, the operation and maintenance costs of each component of micro-grid.

We choose Net Present Cost (NPC) for calculation of system's cost.

### 3.2.1. Net Present Cost

The Net Present Cost (NPC) of each component is defined as [15]:

$$NPC = N * (capital\_cost + replacement\_cost * K + operation \& maintenance\_cost * \frac{1}{CRF(ir, R)}) \quad (9)$$

$$CRF(ir, R) = \frac{ir * (1 + ir)^R}{(1 + ir)^R - 1}, K = \sum_{n=1}^y \frac{1}{(1 + ir)^{L*n}} \quad (10)$$

L is the lifetime and N is the optimal number of each component.

### 3.2.2. The objective function

The objective function is the sum of all net present costs [16]:

$$NPC = NPC_{wind} + NPC_{PV} + NPC_{battery} + NPC_{FC} + NPC_{ref} + NPC_{conv} \quad (11)$$

The objective function must be minimized, such as minimization is done by PSO algorithm in this paper.

## 4. Simulation results

Lifetime of the project is 20 years. In this article, the optimum combination of the micro-grid considered shown in Fig.1 is calculated. The system data consists of the annual wind data and

solar radiation which belong to a region in northwest of Iran. The load curve which is actually an IEEE standard curve with 500 kW peak, the yearly wind speed and solar radiation are showed in fig.2. For the sake of simplicity, we have considered the weekly mean in input data in our simulation. The data is the wind velocity and the demand in every one hour in a day. So, an average of the input data in each hour is calculated during a week. The power of the wind turbine and PV array could be derived by Eq. (1.2) from the wind speed and solar radiation data. The optimal size of wind turbine, PV array, battery bank and Fuel cell are shown in table.1. Fig.3. shows the output power of wind turbine, PV array, fuel cell and Energy of battery storages. We see that at the time 940, fuel cell injects power to the micro-grid. Where the available battery storage energy is equal to minimum allowable storage capacity and output power of PV array is equal to zero. Also output power of wind turbine does not satisfy the micro-grid's demand, so fuel cell injects power to the micro-grid in order to compensate load requirements. Fig.4. Shows the system costs in terms of the iterations.

Table 1. Optimal size of each component.

Number Wind turbine	Number PV array	Number Battery bank	Number Fuel cell	Total cost \$
351	1758	4217	187	17.838M

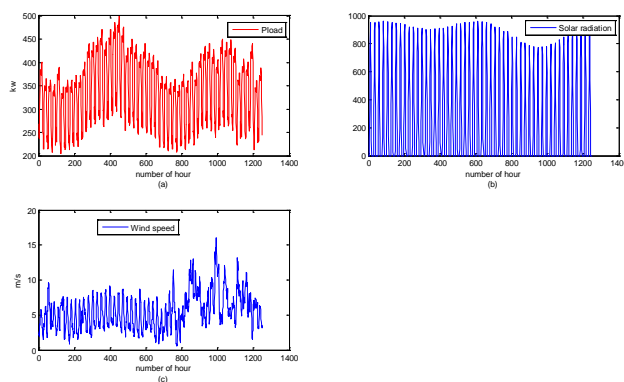


Fig. 2. (a). Load information. (b) Solar radiation information. (c) Wind speed information.

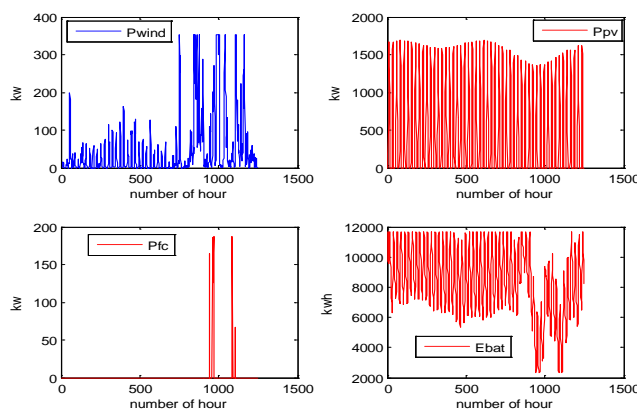


Fig. 3 (a) Output power of wind turbine. (b) Output power of PV array. (c) Output power of fuel cell. (d) Energy fluctuate of battery banks.

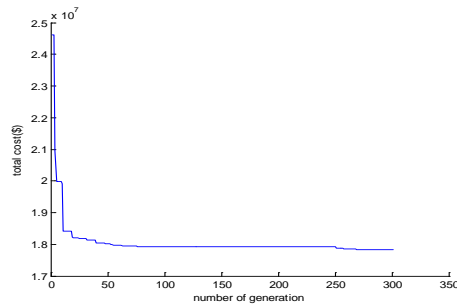


Fig. 4. The optimal cost of micro-grid in terms of the iterations

#### 4.1. Effect of the capital cost of PV arrays on simulation results

In this section, the effect of capital cost of PV arrays, on the optimal size of each component and total cost of micro-grid is regarded. Table.2 shows that increasing the capital cost of the PV array causes the micro-grid costs to increase and the optimal size of PV array to reduce.

Table 2. Effect of capital cost of PV array.

Capital cost of PV unit	Wind turbine	PV array	Battery bank	Fuel cell	Total cost \$
5000	337	1787	4154	193	16.149M
6000	351	1758	4217	187	17.838M
7000	383	1748	4263	172	19.558M
8000	523	1603	4732	106	20.646M

## 5. Reliability

Some notions of reliability are commonly used for systems with hourly demand and supply data. Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOEE), Loss of Power Supply Probability (LPSP) and Equivalent Loss Factor (ELF) are some of them considered in this paper. ELF is described by:

$$ELF = \frac{1}{N} \sum_{t=1}^N \frac{Q(t)}{D(t)} \quad (12)$$

Where  $D(t)$  is the total energy demand,  $Q(t)$  is the loss-of-load and  $N$  is the number of hours. The  $ELF$  contains information about both the number of outages and their magnitude. In this paper we regard that  $ELF$  should be lower than 0.01 [17].

#### 5.1. Simulation Result considering reliability parameters

In this micro-grid when the power of fuel cell to support the demand is greater than the optimal size,  $Q(t)$  is described by:

$$Q(t) = P_{FC}(t) - N_{FC} * P_{Fuel-Cell} \quad (13)$$

Where  $N_{FC}$  is the optimum size and  $P_{Fuel-Cell}$  is the rated power of fuel cell. The cost of electricity interruptions has been estimated. The value we use in our model is 5.6 \$/kWh. Fig.5. depicts the flowchart of the algorithm simulating the micro-grid considering reliability. The optimal size of wind turbine, PV array, battery bank, fuel cell and the total cost of micro-grid are shown in table. 3.

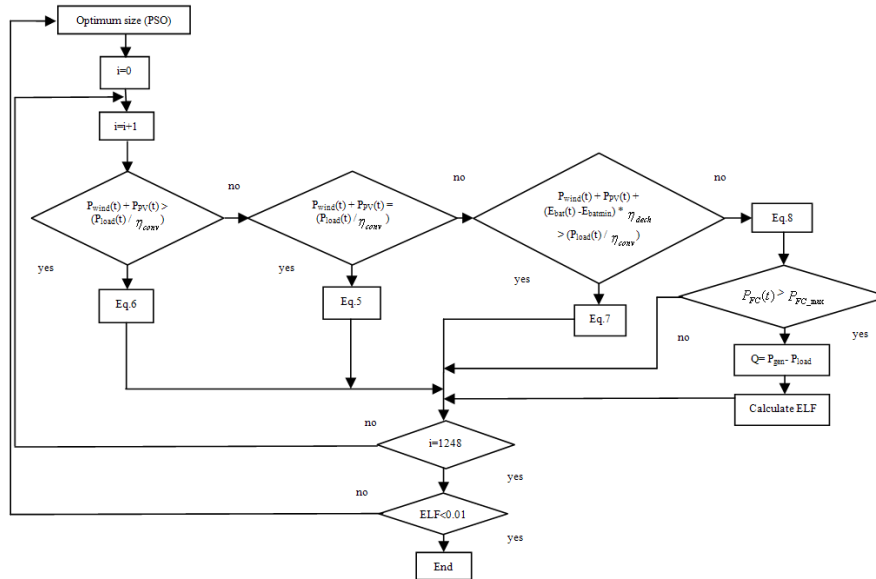


Fig.5. The flowchart of the algorithm simulating the micro-grid considering reliability.

Table.3. Optimal size of each component considering reliability parameters.

Wind turbine	PV array	Battery bank	Fuel cell	Total cost \$
515	1660	3150	14	15.33M

Table.3 shows that considering reliability parameters such as ELF for micro-grid (some of loads in some hours are not satisfied) reduces the total cost of micro-grid. Figure 6 shows the loss of energy in each hour.

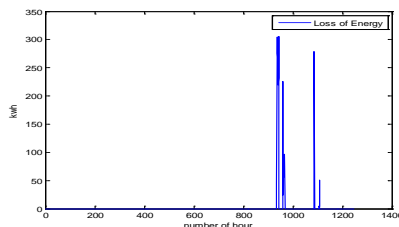


Fig. 6. Loss of energy in each hour.

We see that maximum loss of energy appears at the time between 900-1000. Where the available battery storage energy and output power of PV array to inject to the micro-grid is equal to zero. The value of some notions of reliability is shown in table. 4. Table 4 shows that ELF is in the acceptable confine.

Table 4. The amount of some notions of reliability

LOLE (hr/yr)	LPSP	LOEE (MWh/yr)	ELF	Penalty
24	$9.1098 \times 10^{-3}$	3.8623	$9.999 \times 10^{-3}$	0.21235M

## 6. Conclusion

In this paper the optimal sizing and operation strategy of micro-grid are considered. The system consists of wind turbines, PV arrays, fuel cells, battery banks, reformers and DC/AC converters. The micro-grid used in this study has high reliability because fuel cells are as a backup for wind turbines and PV arrays. The main problem of renewable energy source is that they are dependent on environmental conditions. So they could not cover the demand

perfectly. Entering storage component solves this problem significantly. In this study battery bank is used to cover the demand desirably. We assumed that in each hour micro-grid can interrupt loads subject to reliability constraint such as ELF. In this situation total cost of micro-grid reduces.

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