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Optimal Sizing of an Islanded Microgrid based on PV, Wind and Battery Energy Storage System

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Abstract—**In this paper, to increase reliability and efficiency and to have a cost-effective system a standalone hybrid microgrid (PV/wind/Battery) Optimal sizing has been analyzed. For this propose implementation of different optimization Evolutionary algorithms (EA) are investigated. A comparative algorithm study is carried out with particle swarm optimization algorithm (PSO), Invasive Weed Optimization (IWO), Backtracking Search Optimization Algorithm (BSA) and hybrid IWO-PSA. The system's components optimal sizing has been studied under various performance conditions using real-time information and meteorological data of Rabat region located in Morocco. Net present cost (NPC) is considered as an objective function. Simulation results shows that the Hybrid IWO-PSO have more promising results than the other algorithms.**

Index Terms—**Islanded microgrid, Net Present Cost(NPC), particle swarm optimization, Invasive Weed Optimization, IWO-PSO Hybrid**

I. INTRODUCTION

In the modern world, the depletion of the fossil fuel resources, environmental problems, and the ever-increasing promotions in renewable energy technologies make the renewable energy resources one of the most efficient solutions for sustainable energy sources. The combination of wind and solar energy sources with battery storage improve the system efficiency and reliability. Renewable energy sources take advantage of clean sources comes from nature, solar irradiation for photovoltaic and velocity for the wind.

In previous studies, different methods have been presented for the optimal sizing, based on probability, analytical and heuristic methods. In [1] The system's components optimal size has been studied under various performance conditions using real-time information and meteorological data of one of three atypical regions. [2] is focused on the optimal sizing of hybrid grid-connected photovoltaic/wind power systems from real hourly wind and solar data and electricity demand. Using GA optimization methodology. It was able sizing the componenets with minimum life cycle cost with maximum trealiability. [3] have built an efficient method for integer recourse variables. an objective which is to minimize the cost of the worst scenario mixed integer first stage variables and continuous second stage variables. [4] In this research study, it was aimed to study the utilization of an optimized hybrid PV/Wind/Battery system for a three-story building, with an inclined surface on the edge of its roof. For this purpose, a hybrid FPA/SA algorithm was developed, in order to maximize systems reliability and minimize systems costs. [5] have presented the results of the investigations on the application of the wind, photovoltaic (PV), and hybrid wind/PV power generating systems as stand-alone systems. A simple numerical algorithm has been developed for generation unit sizing. It has been used to determine the optimum generation capacity and storage needed for a stand-alone, wind, PV, and hybrid wind-PV system for typical residential load. [6] have undertaken model a renewable energy system that meets an electric load with the combination of a photovoltaic (PV) array, a diesel generator, and batteries by using the HOMER software. [7] have presented a methodology for the optimal sizing of stand-alone PV/ wind systems using genetic algorithm. The proposed methodology is to suggest, among a list of commercially available system devices, the optimal number, and type of units. [8] have presented the optimal sizing model based on the iterative technique in order to optimize the capacity sizes of different components of the hybrid PV/wind power generation system, using a battery bank.

In this paper a hybrid microgrid of a farm is investigated based on photovoltaic and wind with a battery storage. This proposed system has DC structure supplying pumps and lamps for lighting given a total load of 43 kW. In order to have a cost effective system, a study is carried out to have an optimal sizing of the hybrid system. to accomplish this, EA (PSO, IWO, BSA and hybrid IWO-PSO) are applied in order to find the lower cost of electricity by considering the objective function as net present cost (NPC). It is a function that allows calculating the overall cost of the component, which include the cost of replacement and the cost of operation, maintenance and the cost of the component. Hence, the cost of PV depends on of the panel area [m^2], the Wind depends on the surface crossed by the wind [m^2] and the battery cost depends on its capacity [Ah].

II. SYSTEM DESCRIPTION

DC microgrids hold great promise, for ordinary residential and commercial buildings, where they could feed many electrical loads that use DC. It offers significant energy efficiency,

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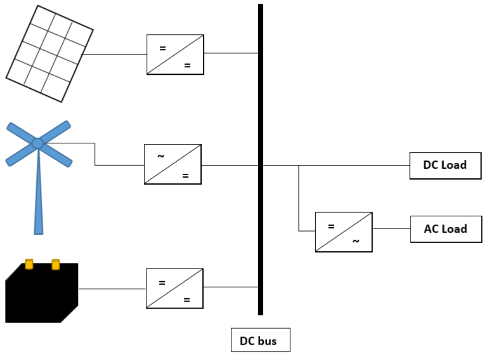

Fig. 1. DC microgrid architecture for stand alone system

cost, reliability, and safety benefits compared to conventional alternating current (AC) systems [8]. The dc-bus architecture has been widely used in small-scale microgrids for its convenient control and interface of renewable energy to the system. DC microgrid architecture for standalone system is shown in Fig.1. The PV panel and wind turbine are connected to the dc bus by the dc/dc converter with the maximum power point tracking (MPPT) function. The battery cells are connected to the dc bus via a bidirectional dc/dc converter in a concentrated location, which are used to control the dc bus voltage. The dc voltage is converted to ac voltage through an inverter to supply the AC loads.

The farm is located in Rabat region (Morocco) withe the metorological informations for Velocity and Irradiation are shown in Fig.2. According to operation loads Fig.3, power required to supply the farm per day is 46 kW; pumping is active in one hour per day. This means that, the daily energy required for irrigation unit is approximately 50 kWh.

A. Photovoltaic

Assuming that the PV array is equipped with a MPPT controller, thus, the output power of PV array can be expressed as [9]:

$$P_{pv} = f_{pv} P_{pv_r} \frac{G}{G_{STC}} [1 + \alpha_T (T - T_{STC})] \quad (1)$$

Where f_{pv} is the derating factor considering shading, wiring losses and PV shadow,etc. G_{STC} and T_{STC} are the solar radiation and temperature on PV cell under standard test conditions, respectively. G and T are the solar radiation and temperature, respectively, and α_T is the temperature coefficient of power.

B. Wind

To calculate the output power generated by the wind turbine generator [10].

$$\begin{cases} P_{WT} = 0 & V < V_{ci} \\ P_{WT} = a.V^3 - b.P_{WT,R} & V_{ci} < V < V_r \\ P_{WT} = P_{WT,R} & V_r < V < V_{co} \\ P_{WT} = 0 & V > V_{co} \end{cases} \quad (2)$$

a, and b calculated by (3):

$$\begin{cases} a = P_{WT,R}/(V_r^3 - V_{ci}^3) \\ b = V_{ci}^3/(V_r^3 - V_{ci}^3) \end{cases} \quad (3)$$

Where P_{WT},$P_{WT,R}$, V_{ci}, and V_{co} are the produced power, rated power, cut-in and cut-out wind speed respectively. Furthermore, V_r and V are the rated and actual wind speed.

The real electric power is calculted as:

$$P_{e,WT} = P_{WT}.A_{wind}.eff_w \quad (4)$$

Where A_{wind} is the total swept area and eff_w is the efficiency of the wind turbine generator.

C. Battery

The battery bank, which is usually of the lead-acid type, is used to store surplus electrical energy. Battery bank is treated as a constant voltage storage with some constraints such as capacity limit. it is usually measured by state of charge (SOC). The SOC of battery bank can be obtained by monitoring the charge and discharge power of the battery bank continuously.

SOC at the time (t) of the battery bank is given by the following equation [11]:
battery charging

$$SOC(t) = SOC(t-1)(1-\sigma) + (E_{pv}(t) + E_{wind}(t) - \frac{E_{load}}{\eta_{inv}})\eta_B \quad (5)$$

battery discharging

$$SOC(t) = SOC(t-1)(1-\sigma) + (\frac{E_{load}}{\eta_{inv}} - E_{pv}(t) - E_{wind}(t)) \quad (6)$$

Where $SOC(t)$ and $SOC(t-1)$ are the states of charge of battery bank (Wh) at the time t and $t-1$, respectively; σ is hourly self-discharge rate; E_{pv}, E_{wind} are PV array and wind generators after energy loss of controller, respectively ; E_{load} is load demand at the time t; η_{inv} and η_B are the efficiency of inverter and charge efficiency of battery bank, respectively.

It is important that the SOC of the battery prevents the battery from overcharging or undercharging. The associated constraints can be formulated by comparing the battery SOC at any hour.

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (7)$$

D. Solar Radiation and Wind Speed Data

The traces of solar power output $s(t)$ and wind power output $w(t)$ are obtained from empirical data on solar radiation and wind speed at locations close to the Rabat. Hourly solar radiation and wind speed data in one year are obtained from [12]. We use the hourly data for a farm near to Rabat (longitude: 34.1, latitude: 6.50). The hourly solar radiation data are depicted in Fig.2.

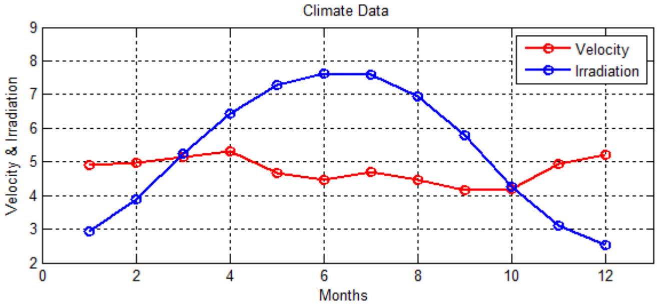

Fig. 2. Velocity and Irradiation data

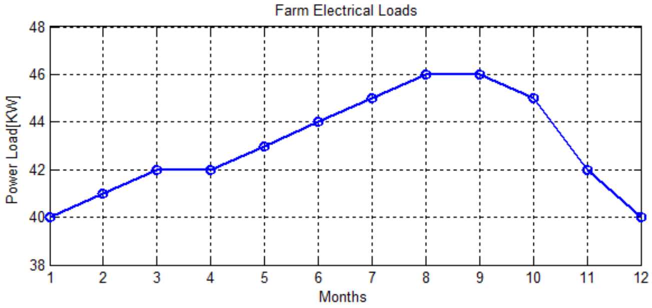

Fig. 3. Power Load data

III. PROBLEM FORMULATION

The objective function has been developed to find the optimal combination of components of various sizes that minimizes the total cost of the system.

A. *Economical model*

We choose net present cost for calculating the cost of microgrid. The objective must be minimized and can be calculated as follows for each component.

The Total Net Present Cost are calculated as follows [13]:

$$C_{NPC} = \frac{C_{Ann,tot}}{CRF} \tag{8}$$

The annual investment cost [\$/yr] of the system is expressed by:

$$C_{Ann,tot} = C_{Ann,com} + C_{Ann,rep} + C_{Ann,Op} + C_{Ann,Maint} \tag{9}$$

with:

$$C_{Ann,com} = C_{Ann,pv} + C_{Ann,wind} + C_{Ann,batt} + C_{Ann,Converter} \tag{10}$$

Where $C_{Ann,rep}$, $C_{Ann,Op}$, $C_{Maintenance}$ is the annual value of the replacement of part of the installation cost, the annual value of operation cost, the annual value of system life of maintenance costs; respectively.

In order to convert the initial cost to an annual capital cost, the capital recovery factor (CRF), defined by (11) is used.

$$CRF(ir, R) = \frac{ir(1+ir)^R}{(1+ir)^R - 1} \tag{11}$$

Where ir is Interest rate[%] and R project lifetime [year] for the project. Interest rate is fixed at 6% and Project life time is 20 years.

The annual capital cost for the photovoltaic sub-system can be formulated as:

$$C_{Ann,pv} = C_{Ipv} * CRF(ir, Rpv) \tag{12}$$

$$C_{Ipv} = \lambda_{pv} * A_{pv} \tag{13}$$

Where: C_{Ipv}, λ_{pv}, A_{pv} is initial cost, cost for each m^2 and area of installed pv. Similarly the wind turbine sub-system and battery bank annual cost can be formulated as:

$$\begin{cases} C_{Ann,wind} & = C_{Iwind} * CRF(ir, Rw) \\ C_{Ann,batt} & = C_{Ibatt} * CRF(ir, Rb) \end{cases} \tag{14}$$

with:

$$\begin{cases} C_{Iwind} & = \lambda_{wind} * A_{wind} \\ C_{Ibatt} & = \lambda_{batt} * A_{cap,Batt} \end{cases} \tag{15}$$

Where A_{pv},A_{wind} and $A_{cap,Batt}$ are the design parameters for calculating the NPC in this project.

Cost of Energy (COE) is the average cost per kWh of useful electrical energy produced by the system and can represented as:

$$COE = \frac{C_{Ann,tot}}{P_{Load}} \tag{16}$$

The levelized cost of energy is therefore the average cost per kilowatt hour of useful electrical energy produced by the system.

B. *constraints for optimization*

The operation of the various components is subject to several constraints, as is the islanded operation of the system. The strategy used is to ensure the minimum load with the photovoltaic and the wind turbine, the difference between the maximum power and the minimum power demanded by the consumer is ensured by the battery.

The balance between generation and demand has to be met at all time steps, so:

$$P_{pv} + P_{wind} + P_{batt} = P_{Load} \tag{17}$$

$$P_{batt} = Pl_{max} - P_{lmin} \tag{18}$$

The charge quantity of battery bank should satisfy the constraint of:

$$0.2 * P_{batt} < P_{batt} < 0.8 * P_{batt} \tag{19}$$

$$P_{wind} < P_{windmax} \tag{20}$$

$$P_{batt} < P_{PV} \tag{21}$$

$$P_{batt} < P_{wind} \tag{22}$$

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IV. OPTIMIZATION ALGORITHMS

In this section, we will present a hybrid algorithm based on Invasive Weed Optimization (IWO) and Particle Swarm Optimization (PSO), which named IWO-PSO. IWO is a relatively novel numerical stochastic optimization algorithm. By incorporating the reproduction and spatial dispersal of IWO into the traditional PSO, exploration and exploitation of the PSO can be enhanced and well balanced to achieve better performance. Based on the novel and distinct qualifications of IWO and PSO, we introduce IWO/PSO algorithm and try to combine their excellent features in this extended algorithm.

A. Particle Swarm Optimization

PSO is originally attributed to [14], it was first intended for simulating social behavior, as a stylized representation of the movement of organisms in a bird flock or fish school. The algorithm was simplified and it was observed to be performing optimization see Algorithm 1. PSO is an approach for evaluating optimal parameters of complicated search spaces.

```
initialization : particles population;
while $stopping\ conditions\ are\ not\ met$ do
    for $each\ particle\ P\ with\ position\ x_p$ do
        calculate fitness value $f(x_p)$;
        if $f(x_p) > Pbestp$ then
            $Pbestp \leftarrow x_p$
        end
    end
    Define $Gbest_p$ as the best position found;
    for $each\ particle\ P$ do
        calculate fitness value $f(x_p)$;
        if $f(x_p) \sup Pbest_p$ then
            $v_p \leftarrow$ compute velocity $(x_p, Pbest_p, Gbest_p)$;
            $x_p \leftarrow$ update position $(x_p, v_p)$;
        end
    end
end
```

Algorithm 1: Pseudo-Code of PSO

B. Invasive Weed Optimization

IWO algorithm was introduced by [15]. IWO algorithm is inspired by the colonial behavior of invasive weeds. Invasive weeds are very adaptable to the environment; the more effort that agriculturists take to eradicate them, the stronger and fitter they become. The performance of IWO algorithm is examined in some cases, but it has not been examined in sizing of Microgrid, which is one of the purposes of this research. The basic steps of IWO algorithm can be summarized by flowchart as depicted in Algorithm 2.

C. Backtracking Search Optimization Algorithm

BSA is an EA developed by [16] for solving real-valued numerical optimization problems. It has only one tuning parameter and it uses the three basic operators that are selection, mutation and crossover. The general structure of the BSA is given in Algorithm 3.

```
initialization : generate random population of weeds $W$;
while $max\ itaeration\ are\ not\ met$ do
    compute maximum and minimum fitness in the
      colony for $each\ weed\ w \in W$ do
        Compute the number of seeds for $w$ depending of
          its fitness;
        Select the seeds from the feasible solutions;
        Add seeds produced to the populations $W$;
        if $|W| > Max\_SizePop$ then
            Sort the population $W$ according ti their
              fitness;
            $W \leftarrow MAX(weed, seed, Max\_SizePop)$
        end
    end
end
```

Algorithm 2: Pseudo-Code of IWO

D. IWO-PSO Hybrid

IWO offers good exploration and diversity, while PSO is very simple compared with the other developing calculations. In this section, we mix the two algorithms and present a hybrid algorithm IWO-PSO [17].

In the hybrid algorithm, the IWO algorithm plays the role of guiding the evolution and the PSO algorithm works as an assistant. The interaction between the dispersion method of the IWO algorithm and the velocity of the PSO algorithm controls the balance between local exploitation and global exploration in the problem space. The process of the hybrid algorithm is formulated in detail in Algorithm 4.

V. RESULTS AND DISCUSSIONS

A farm located in Morocco (Rabat) is used to investigate the optimization of sizing a small stand-alone Hybrid Microgrid. From the existing data, the yearly average wind speed

```
Data: N, D
Result: $bestfitness, bestindividual$
initialization : current population $P$, $oldP$,
  $bestfitness, bestindividual$;
while $stopping\ conditions\ are\ net\ met$ do
    -Selection 1: replace the whole $oldP$, with probability
      $0.5$. Then, permute all individuals of $oldP$ ;
    -Mutation: generate new population $Mutant$ from $P$
      and $oldP$;
    -Crossover: generate new population $Trial$ from
      $Mutant$ and $P$;
    -Boundary control: for each dimension of each
      individual of $Trial$, randomly regenerate if outside
      the search space;
    -Selection 2: evaluate $Trial$ and, for $i = 1$ to $N$,
      update individual $i$ of $P$ with individual $i$ of $Trial$
      if better;
    -Update $bestfitness$ and $bestindividual$;
end
```

Algorithm 3: Pseudo-Code of BSA

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```
initialization : generate random population of weeds $W$;
while $max\ itaeration\ are\ net\ met$ do
    compute maximum and minimum fitness in the
      colony set $Pg$ as the best position of all individual
    for each weed $w \in W$ do
        Set $P_i$ as the best position of individual $w$ in
          comparison with $P_{i-1}$ ;
        Compute number of seed of $w$, corresponding to
          its fitness;
        for each seed do
            Calculate the velocity;
            Update the position;
        end
        Randomly distribute generated seeds over the
          search space with normal distribution around the
          parent plant $(w)$;
        Add the generated seeds to the solution set,$W$;
    end
    if $|W| > p_{Max}$ then
        Sort the population $W$ according to their fitness;
        $W \leftarrow p_{Max}$;
    end
end
```

Algorithm 4: Pseudo-Code of IWO-PSO

TABLE I
TECHNICAL AND ECONOMICAL DATA OF THE COMPONENTS USED IN PROPOSED HYBRID SYSTEM

Components	PV	Wind	Battery	Converter
C_{rep}[\$]	1200	1500	67	0
$C_{Ann,rep}$[\$/yr]	104.62	130.77	15.9	0
$C_{Ann,OandM}$[\$/yr]	4	2	1.67	1
$C_{Ann,capital}$[\$/yr]	f(A_{pv})	f(A_{wind})	f(A_{Batt})	762
λ	450	100	100	-
Life time[yr]	20	20	5	20

of this location is $4.76m/s$, while average solar radiation is $5.3075kWh/m^2/day$.

Economical and technical parameters associated with components used in this study have been presented in TABLE.I. The lifetime of the project and the interest rate are considered to be 20 years and 6% respectively.

The results were simulated using MATLAB program. The control parameters for PSO, IWO, BSA and IWO-PSO algorithms are shown below in Table III. The microgrid size in this project is defined as an area of PV in m^2, area of Wind in m^2 and battery capacity in Ah. The size of the inverter has not been included as the decision variable.

TABLE II shows complete optimized results obtained for the case study by PSO, IWO, BSA and IWO-PSO algorithms. It is inferred from the results that IWO-PSO algorithm predicts minimum NPC of the system with least LCOE. The IWO-PSO algorithm predicts the best cost is 49656.7544 which results in an LCOE of $0.023/kWh$. The performance of IWO-PSO algorithm is satisfactory as compared to PSO, IWO and BSA in terms of computational time and results. Moreover, The LCOE obtained by four algorithms shows that the proposed system provides energy to the farm with an acceptable cost.

According to the Fig.4, Fig.5, Fig.6, Fig.7 we see that PSO and IWO-PSO converge very fast, PSO in the second

TABLE II
PARAMETERS OF THE IWO,PSO,BSA AND IWO-PSO ALGORITHM.

IWO	PSO
Dimension of the problem (D): 3 Initial Population Size : 5 Maximum Population Size: 25 Minimum Number of Seeds: 0 Maximum Number of Seeds: 25 Maximum iterations (Itmax): 40 Initial Value of Standard Deviation: 0.1 Final Value of Standard Deviation: 0.0015 Variance Reduction Exponent: 3	Dimension of the problem (D): 3 population size (N) : 10 weight : 1 Maximum iterations (Itmax): 40 Weighting factors (C1 and C2): 2
BSA	IWO-PSO
Dimension of the problem (D): 3 Initial Population size : 20 Maximum iterations (Itmax): 40 DIM-RATE: 2	Dimension of the problem (D): 3 population size (N) : 10 Initial weigh : 0.2 Final weigh : 0.45 Maximum iterations (Itmax): 40 Weighting factors (C1 and C2): 2 Minimum Number of Seeds: 0 Maximum Number of Seeds: 5 Initial value of standard Deviation: 0.1 Final value of standard Deviation: 0.15 Variance Reduction Exponent : 3

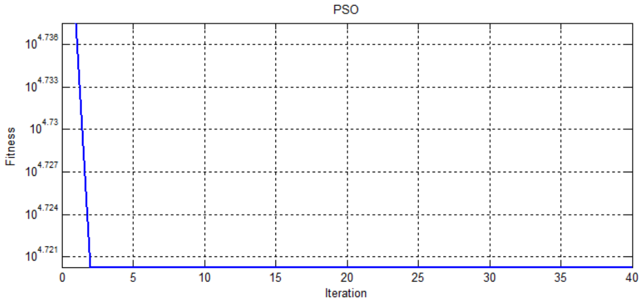

Fig. 4. PSO

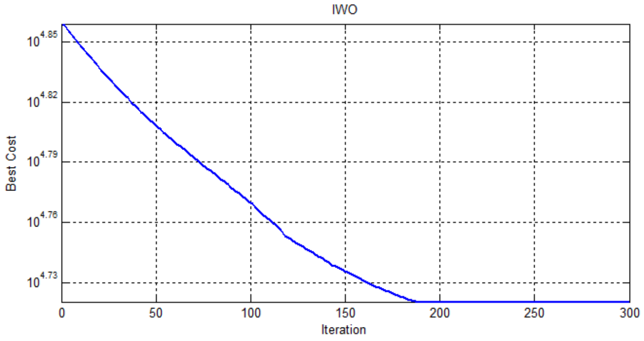

Fig. 5. IWO

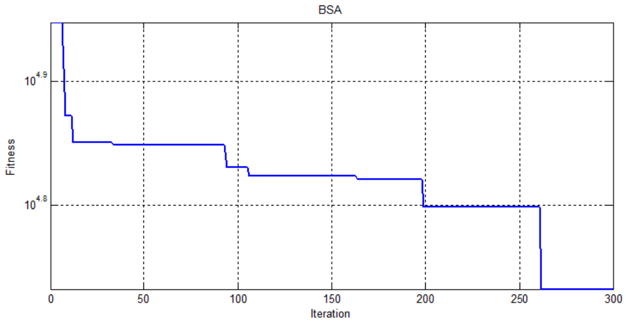

Fig. 6. BSA

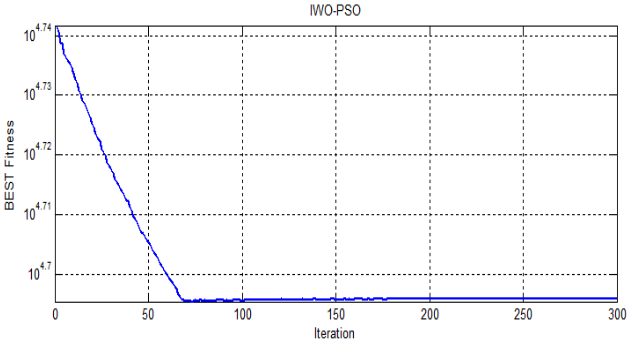

Fig. 7. IWO-PSO

iteration and IWO-PSO in iteration 70, whereas IWO waits until iteration 180, finally BSA converge slowly of iteration 265. The convergence time of PSO is 0.10707 second and IWO-PSO in 1.9937 seconds, IWO is 7.6016 second and BSA is too long is 576.2309 seconds. These results show that the optimum sizing solution is to take the IWO-PSO algorithm with $34,997m^2$ of PV area and $34,997m^2$ of wind turbine surface which means a blade of 3.3376 meters long and the battery capacity is $34.9992462Ah$.

TABLE III
TECHNICAL AND ECONOMICAL DATA OF THE COMPONENTS USED IN PROPOSED HYBRID SYSTEM

Comp	APV[m^2]	AWind[m^2]	CBattery[Ah]	Total[$]
PSO	35	35	35	52513.962
IWO	35	35	35	52513.962
BSA	35	98.539	100	54037.255
IWO-PSO	34.997	34.997	34.999	49656.7544

VI. CONCLUSION

Implementation of micro-grids can be considered as the most promising solution for rural electrification by decreasing the installation costs and increasing the supply quality. Depending on meteorological data, hybrid energy system is more reliable, economical and suitable source of electricity. In this paper, to obtain the best configuration of the system an evolutionary algorithm optimal sizing of a hybrid microgrid (PV-wind-battery) is proposed. net present cost (NPC) is defined as an objective function. a comparison study between PSO, IWO, BSA and IWO-PSO algorithms has been presented. The efficiency of IWO-PSO, both in the case of speed of convergence and best COE of the results are compared with IWO, PSO and BSA. The results show that the proposed algorithm can be successfully employed as a fast and global optimization method for a variety of theoretical or practical purposes. To overcome some of the technical barriers for distribution of micro-grid projects, the utilization of the proposed method can help. It can be also used as a support tool to promote electrification projects and design efficient projects faster.

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