Optimal sizing design of stand-alone photovoltaic/wind generator systems using genetic algorithms

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Abstract — **nowadays, the photovoltaic and the wind energies are the most important energetic alternative resources; so far, a lot of researches are developed and must continue to be concerning the cost-optimally design for the stand-alone hybrid PV-wind systems, in this study a methodology for optimal sizing design of stand-alone PV-WG systems is presented. The purpose is to find the optimal number of units ensuring that the 20 years round total system cost is minimized subject to the constraint that the load energy requirements are completely covered. The optimization methodology and the formulation of the problem are detailed. Finally, an optimal configuration is obtained with a lifetime of 20 years. The optimized parameters are also given.**

Keywords — **Design, Genetic algorithm, Hybrid source, Optimization, Photovoltaic, Stand-alone, total system cost, wind energy.**

I. NOMENCLATURE

C_T	The total design cost
C_{cpt}	The total capital cost
C_{Mtn}	The total maintenance cost
P_{pv}^t	The power generated by solar panel
P_s^t	The power generated by wind turbine
P_{dmd}^t	The power (kW) demanded at time t
P_{inv}	Inverter's maximum power
P_{contr}	Controller's rated power
P_{load}	The maximum continues power load
N_{pv}	The number of the solar panels
N_{wind}	The number of wind turbines
N_{batt}	Bettery's number
N_{inv}	The number of the inverters required
N_{contr}	Controller's number
P_s^t	The power generated by each solar panel
P_w^t	The power generated by each wind turbine
S_{batt}	The rated capacity of each battery
ρ	Usage% of the battery's rated capacity
C_{conv}	Capital-recovery factor
qty	Quantity of the appliances

II. INTRODUCTION

Photovoltaic (PV) and Wind Generator (WG) power sources are widely used in order to supply power to consumers in remote areas. Due to their almost complementary power production characteristics [1] however, design of small-scale stand-alone power sources for use in remote or off-grid locations is yet to reach a commercially feasible stage [2].

A various researches have been performed for the optimal design of hybrid PV and wind power generating systems [3–4]. These alternative energy sources are clean, free and renewable. But the high capital cost made its growth a slow one .In recent years, and because of the advance materials, better manufacturing progressions have decreased their capital costs making them more attractive. Another way to try to decrease the cost of these systems is by using the hybrid designs that uses both wind and photovoltaic energies.

Actually, a various researches have been performed about optimization of the hybrid renewable energy systems [5–6, 7]; also a lot of techniques have been employed to reach the objective of the optimization [9-10, 11].so, the problem is which structure will be the most cost effective while supplying demand. This paper presents an optimization procedure capable to design hybrid PV-wind energy for the stand-alone systems using genetic algorithm (GA) approach in order to find the most effective way to use wind and solar energy at the lowest cost possible.

The GA which compared to conventional optimization methods, such as dynamic programming and gradient techniques, has the ability to attain the global optimum with relative computational simplicity [8], the GA approach is selected because of their ability to handle complex problems with linear or non-linear cost functions, also due to their probabilistic development of solutions providing the location of the global optimum. The objective of this paper is to provide a methodology for the sizing of the stand-alone hybrid PV-wind energies system using genetic algorithm, also intends to provide a better optimization formulation problem.

III. Architecture of the Hybrid System

The model of the hybrid PV–wind power generation system involves PV arrays, wind turbines, batteries bank, inverters, controllers, also other devices and cable. A representation diagram of the basic hybrid system is shown in Fig. 1. The PV array and wind turbine provide power to reach and satisfy the load demand by the consumer. Once the generated power by the PV-wind sources satisfies the load demand, this energy will be oriented to supply the batteries until it is full charged.in the other case, when energy generated by PV-wind sources is less than the load demand, the batteries will discharge that energy stored to supply the amount and support the power generated from the PV-wind source to cover the amount requirements until the storage is depleted.

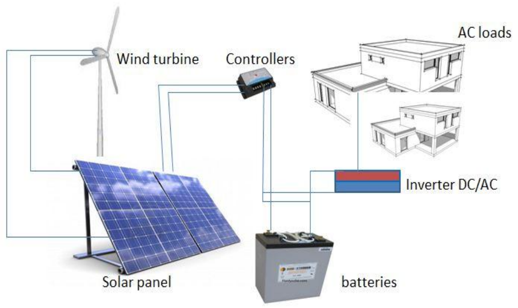

Fig. 1. PV–wind-batteries stand-alone hybrid system.

IV. Optimization Formulation

As we mentioned in the section 2, the genetic algorithms guarantee global optimum, usually all the meta-heuristic algorithms find the better solutions [14]. In this study the objective function of the PV-wind system design is the total design cost Ctot which involves the total capital cost CCpt and total maintenance cost CMtn. to minimize the total capital cost CCpt using the genetic algorithm, the general form of the objective function should be expressed as follows:

Minimize: $f(x)$ (1)

Subject to: $g(x)=0$ (2)

$H(x)\leq 0$ (3)

Where, $f(x)$ is the objective function; $g(x)$ is the equality constraints and $H(x)$ is the inequality constraints.

According to the equations (1), (2) and (3), the optimization problem can be expressed as follows:

Minimize $C_T = C_{cpt} + C_{Mtn}$ (4)

Subject to:

$$\sum_1^{24}(P_{pv}^t \times \Delta t) + \sum_1^{24}(P_{wind}^t \times \Delta t) \geq \sum_1^{24}(P_{dmd}^t \times \Delta t) \quad (5)$$

$$\text{total wattage installed} \leq \sum_d P_{inv} \times N_{inv} \quad (6)$$

$$\text{photovoltaic maximum power STC} \leq \sum_e P_{contr} N_{contr} \quad (7)$$

Where, $P_{pv}^t = N_{pv} \times P_s^t$ (8)

And $P_{wind}^t = N_{wind} \times P_w^t$ (9)

N_{pv} a decision variable which is the number of the solar panels and P_s^t is the power generated by each solar panel at time t; can be obtained using insolation data and insolation-power characteristic curve [10].The P_{wind}^t which is the power generated by wind turbine, N_{wind} a decision variable which is the number of wind turbine and P_w^t is the power generated by each wind turbine can be obtained using wind speed data, turbine hub height correction function, and wind speed-power characteristic curve [10].

To calculate the total wattage installed we should sum all the power of all the loads.

$$\text{total wattage installed} = \sum P_{\text{loads}} \quad (10)$$

P_{inv} is the maximum power that can be supplied by the inverter and N_{inv} is a decision variable which represents the number of the inverters required.

A. *Photovoltaic panels sizing*

The initial capital cost (ICC) of PV system may vary from 6000 \$/kW to 10.200 \$/kW [15-16]. In this work, we have chosen the model of KYOCERA KD215-LPU for a cost of 322 \$/panel, where the photovoltaic maximum power is 33.2V under the Standard Test Conditions (STC: Irradiance 1000W/m2, AM1.5 spectrum, cell temperature 25°C). Operational and maintenance (O&M) cost for photovoltaic array is considered 0.5 cent/kW h and its lifetime is 20 years.

B. *Wind turbines sizing*

A vast range of wind turbines is available. Capital costs for a commercially available wind turbines range 1500\$ for the size of 1KW to 3 500 000\$ for the size of 1800 kW [17-18]. In this analysis wind turbine cost is taken as 17.681, 25\$/kW, we have used the model of API-10KW with blades diam 3-7.0m and height 16m.Operation and maintenance costs for the wind turbine is considered 2 cents/kW h. and its lifetime is 20 years.

C. *Converters sizing*

The cost of converter may vary from 200 \$/kW to 6500 \$/kW. Cost used in the current work was 3597 \$/kW, we have chosen the model of SET48/220-10KW; the life time was considered 20 years. The efficiency of converting the direct current to alternative current of most inverters nowadays is 90 percent or more. Many inverters claim to have higher efficiencies but for this study the efficiency that will be used is 90%.

In the case of stand-alone system the number of inverters can be calculated as follows

$$N_{inv} = \frac{P_{load}}{P_{inv}} \quad (11)$$

Where, P_{load} is the maximum continues power load, and P_{inv} is the maximum power that can be supplied by the inverter.

D. Batteries sizing

The Surrette 12CS11Ps (12 V, 375 Ah) storage batteries are utilized in the system. Cost of one battery is 1300 $ with a replacement cost of 900 $. The battery stack may contain a number of batteries (0, 4, 6, 8, 10, 15, 20, 25, 30 or 32). The usage% of the battery rated capacity is 80% and the battery's rated capacity is 4.28KW/h. The life time of the Surrette 12CS11Ps is 10 years.

We can determinate the numbers of the batteries by the following function [10]:

$$N_{batt} = Roundup\left[\frac{S_{req}}{\rho \times S_{batt}}\right] \quad (12)$$

Where, S_{batt} is the rated capacity of each battery and ρ is usage% of rated capacity which guarantees battery's life span.

S_{req} is the required storage capacity, which can be calculated by the following equation:

$$S_{req} = \sum_{t=1}^{\max t}\left(P_{pv}^{t} + P_{wind}^{t} - P_{dmd}^{t}\right)\times \Delta t - \sum_{t=1}^{\min t}\left(P_{pv}^{t} + P_{wind}^{t} - P_{dmd}^{t}\right)\times \Delta t \quad (13)$$

Where $\max t$ the time when the energy generated is in the maximum; $\min t$ is the time when generated energy is lowest; and Δt is the unit of time (in this word it's considered 1 hour). P_{dmd}^{t} is the power (kW) demanded at time t.

E. Controller sizing

MPPT controller sizing consist in calculating the number of MPPT controllers necessary for the PV system. In small PV system one controller may be sufficient to supply the demand, but for larger PV system more controllers may be needed for supply the demand. The controller output voltage rating must be equal to the nominal battery voltage. Also the Maximum PV voltage should be less than the maximum controller voltage rating.

The number of the MPPT controller required can be calculated by the following function:

$$N_{contr} = \frac{P_{\max\, pv}}{P_{\max\, cntr}} \quad (14)$$

Where,

$$P_{\max\, pv} = \text{photovoltaic maximum power STC} \times \mathrm{N_{pv}} \quad (15)$$

And $P_{\max\, cntr}$ is the controller maximum power.

Also the controller maximum power can be calculated by the following function:

$$P_{\max\, \mathrm{contr}} = V_{batt} \times I_{contr} \quad (16)$$

Where V_{batt} is the voltage of the battery bank.

And I_{contr} is the max current the controller can handle from the PV system to the battery bank.

However, the total capital cost take place in the establishment of a project at the beginning, contrary the maintenance cost occurs along the project life. Therefore, costs at different times cannot be directly compared, and we will use a discount factors that convert a monetary cost at one time to an equivalent value at another time [12, 13]. The initial capital cost I is converted into annual capital cost A using the following capital-recovery factor:

$$C_{conv} = \frac{i(1+r)^{L}}{(1+r)^{L} - 1} \quad (17)$$

Where, (L) is the life span of the system and (r) is the annual interest rate.

The total capital cost in eq. (1) can be expressed by the following function:

$$C_{cpt} = C_{conv} \times \sum_{a} C_{pv} \times N_{pv} + \sum_{b} C_{w} \times N_{w} + \sum_{c} C_{batt} \times N_{batt} + \sum_{d} C_{inv} \times N_{inv} + \sum_{e}\left(C_{contr} \times N_{contrv}\right) + C_{BG} \quad (18)$$

Where, $C_{pv}, C_{w}, C_{batt}, C_{inv}, C_{contr}, C_{BG}$ are the costs of solar panel, wind turbine, battery, inverter, MPPT controller and the buck up generator respectively.

Also, the maintenance cost in the eq. (1) can be:

$$C_{Mtn} = \left(C_{mtn}^{pv} \times \sum_{t}^{24}(P_{pv}^{t} \times \Delta t)\right)\times 365 + \left(C_{mtn}^{wind} \times \sum_{t}^{24}(P_{wind}^{t} \times \Delta t)\right)\times 365 \quad (19)$$

Where, C_{mtn}^{pv} is the maintenance cost (kW h) for PV array; and C_{mtn}^{wind} is the maintenance cost (kW h) for wind turbine.

V. ENERGY CONSUMPTION

Energy consumption is the electrical power that the loads consume in a period of time (kWh). Loads are generally the largest single influence on the size and cost of a PV and wind turbine system. In order to reduce the cost of the PV and wind turbine system it is needed to use more efficient, lower demand appliance and to eliminate, partially or completely, the use of other loads.

A. Loads power estimation

To estimate energy consumption we need to determine the average daily electrical energy use in watt hours as well as the total power demand in watts. The system will be more economical if high efficient, low power consumption loads are used.

To calculate the kWh that a type of load consumes in a day [19]:

$$\frac{Kwh}{Day} = \frac{N \times P_{Load} \times H_{day} \times D_{week}}{7} \quad (20)$$

Where n signify the quantity of that type of load, and P_{Load} is the power consumption of the type of load, H_{day} is the number of hours the load is consuming power and

TABLE 1: ENERGY CONSUMPTION ESTIMATION FOR A TYPICAL ALGERIAN HOUSE.

individual loads (appliances)	***qty × volts × amps = watts × use × use / 7 = watt.***							
	qty	volts	amps	ac-watt	hrs/day	day/week	days	ac-watt
microwave oven	1	220	9	1980	0,08	7	7	158,4
refrigerator (16 cubic feet)	1	220	1,3	286	8	7	7	2288
laptop computer	2	220	0,42	184,8	8	7	7	1478,4
TV flat screen lcd 46"	2	220	1,02	224	4	7	7	897.6
music home theater	1	220	3,47	763	1	4	7	436,2
clothes washer	1	220	1,92	422.4	1	4	7	241.3
lights	14	220	0,17	37,4	4	7	7	149,6
printer	1	220	0,9	198	0,2	7	7	396
cable modem	1	220	0,08	17,6	12	7	7	211,2
hair dryer	1	220	10	2200	0,25	7	7	550
air conditioner	1	220	2,41	5302	6	7	7	3181
cellular charge	2	220	0,11	24,2	4	7	7	96,8
other things	/	/	/	/	/	/	/	200

D_{week} is the number of days the load is used during a week.

In this study we'll estimate the energy consumption of a proposed house located in Algeria, The house has three bedrooms, one bathroom, a living room, and a kitchen.

Table 1.shows the electrical loads and total Watt and kWh that the home consumes.

The estimated energy of the proposed house in Table 1. will be considered as the load that should be supplied by our PV-wind system.

VI. OPTIMIZATION MODEL WITH GENETIC ALGORITHM

In the sizing design optimization a lot of variables and parameters that have to be considered, therefor the sizing of the hybrid PV–wind system is much more complicated than the single source power generating system. This type of optimization includes economic objectives, so in order to reach the optimal system configurations for the minimization of a cost objective function we are employing the genetic algorithm (GA).

A. Genetic algorithm

The basic algorithm by which GAs operate is reasonably well established. GA is inspired by the evolutionary theory explaining the origin of species. In nature, weak and unfit species within their environment are faced with extinction by natural selection.

The strong ones have greater opportunity to pass their genes to future generations via reproduction. In the long run, species carrying the correct combination in their genes become dominant in their population. Sometimes, during the slow process of evolution, random changes may occur in genes.

If these changes provide additional advantages in the challenge for survival, new species evolve from the old ones. Unsuccessful changes are eliminated by natural selection. These algorithms encode a potential solution to a special problem on a simple chromosome like data structure and apply recombination operators to these structures so as to preserve critical information.

B. The GA's sizing optimization methodology

A general block diagram representing the cost optimization methodology with (GA) is shown in Fig. 2. Wherever, the optimization algorithm have a database containing the technical and economical (prices) characteristics of the commercially devices used in the system with their associated per unit maintenance costs. The type of PV module and WG, battery with nominal capacity, inverter type etc., are stored in the input database.

The next step of the optimal sizing procedure consists of a method employing GAs, which dynamically searches for the system configuration, usually; the GA uses three operators (selection, crossover and mutation) to imitate the natural evolution processes. The first step of a genetic evaluation is to determine if the chosen system configuration passes the functional evaluation, provides service to the load where the constraints of the system are satisfied by the initial configuration. a population of strings (called chromosomes or the genotype of the genome), which encode candidate solutions (called individuals, creatures, or phenotypes) to an optimization cost problem, is evolved toward better solutions. The evolution usually starts from a population of randomly generated individuals, and happens in generations. In this work we have chosen to determinate an initial population, where all the decision variables have been defined with specified values. In each generation, the cost fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population (based on their cost fitness), and modified (recombined and randomly mutated) to form a new population. The new population is then used in the next iteration of the algorithm. The lowest cost fitness value obtained at the previous iterations is considered to be the optimal solution for the minimization problem in this iteration.

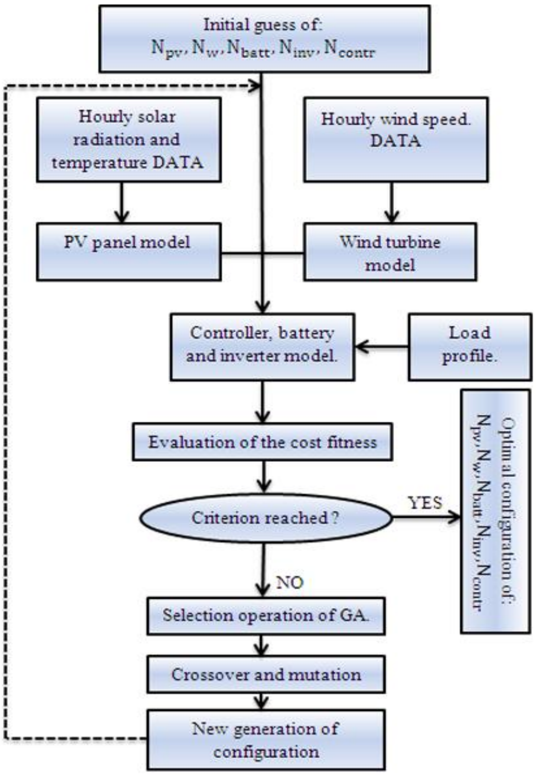

Fig. 2. Flowchart of the optimal sizing design PV-wind using GA.

This optimal solution will be replaced by better solutions, if any, produced in subsequent GA generations during the program evolution. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory cost fitness level has been reached for the population.

VII. RESULTS AND DISCUSSION

The proposed method has been applied to the design of a stand-alone hybrid PV-WG system in order to power supply an AC load. The parameters of GA method proposed for the system is detailed as follow:

TABLE 2: THE GA'S PROPOSING PARAMETERS.

Crossover probability	0.9
Mutation probability	0.08
Selection method	"Roulette"
Generation number	100
Population size	80
Crossover method	Two-points
Variables type	Integer

The distribution of the consumer power requirements during a day is shown in Fig. 7.

The beam solar irradiation on horizontal plane during a year, as well as the average hourly power generated by a solar panel in a day and the average hourly power generated by the wind generator, plotted in Fig.3.5.6 respectively.

Hybrid solar–wind systems usually meet load demands well because of the good complementary effect of the solar radiation and wind speed.

In the first case, when the example was solved with wind generator resources limitation constraints, the optimal solution for the cost of the system was US$14,022.99, with $N_{wind} = 0$. Therefore, in the second case; in order to use some wind turbines, the following constraints can be added to the formulation:

$$N_{wind} = 1 \quad (21)$$

With Eq. (21), Resulting in a minimum cost of system US$12,806.93. and the vectors corresponding to the optimal configurations shown as follow:

TABLE 3: THE OPTIMAL SIZING RESULTS FOR THE PV-WIND SYSTEM

Variable type	***Value(1st case)***	***Value(2nd case)***
PV	158	46
WG	0	2
MPPT.controller	47	14
Battery	40	43
Inverter	1	1
Total cost US$	14,022.99	12,806.93

In the third case, the example was solved with PV generator resources limitation constraints, the optimal solution $(N_w = 4 \quad N_{batt} = 62 \quad N_{inv} = 1)$ was found with the optimal cost of US$18,102.77.

It is obvious that in both cases (first and the third), the optimal configurations result in a higher annualized cost of system compared to the hybrid solar–wind system given in the second case.

Also, in order to make a more realistic optimization for the system problem, the output wind power was reduced into 75% of its original power as follows:

$$P_w^t = 0.75 \times P_w^t \quad (22)$$

The optimal solution vector was as follow:

TABLE 4: THE OPTIMAL SIZING RESULTS- PV-WIND SYSTEM (WIND GENERATOR ENERGY REDUCED).

Variable type	***Value***
PV	12
WG	3
MPPT controller	4
Battery	37
Inverter	1
Total cost US$	12,220.15

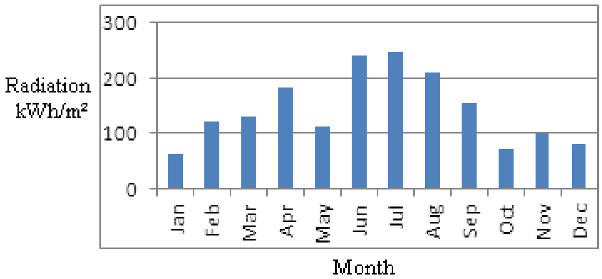

Fig. 3. Beam radiation on horizontal surface kWh/m² for city of Biskra [20].

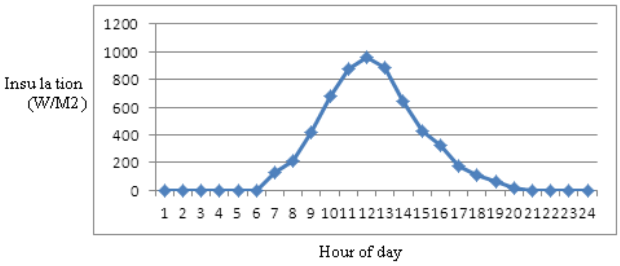

Fig. 4. Solar radiation in 24 hour

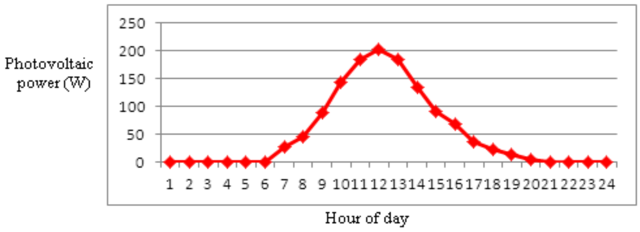

Fig. 5. Average hourly power generated by a solar panel in a day.

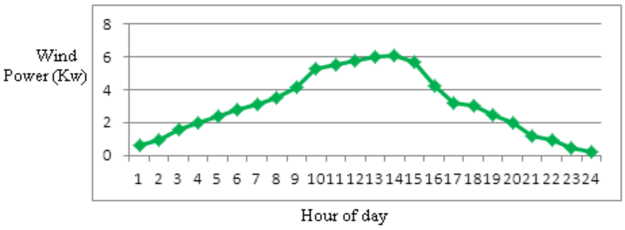

Fig. 6. Average hourly power generated by a wind turbine in a day.

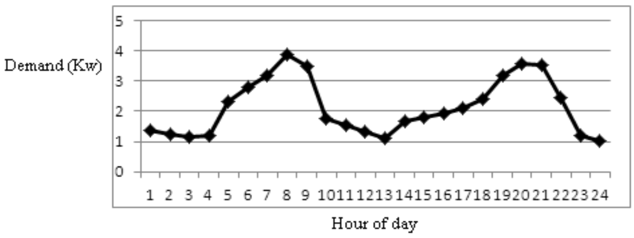

Fig. 7. Average hourly electrical demand in a day.

VIII. CONCLUSIONS

In this paper, a methodology for the optimal sizing of hybrid, stand-alone PV-WG systems with genetic algorithm, has been presented. The purpose of the proposed methodology is the selection of the optimal number of PV modules, WGs and batteries, the PV modules MPPT controllers and the inverters.

The optimal number of each system component is calculated such that the 20-year round total system cost is minimized subject to the constraint that the load power requirements are completely covered, thus resulting. The 20-year round total system cost is equal to the sum of the respective components capital and maintenance costs. The cost function minimization is implemented using genetic algorithms, which compared to conventional optimization methods, such as dynamic programming and gradient techniques, have the aptitude to attain the global optimum with relative computational simplicity. The proposed method has been applied to the design of a hybrid PV-wind power generation system in order to supply a residential household.

The results verify that hybrid PV-WG systems result in lower system cost compared to cases where either only WG or only PV sources are used.

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