Le 3ème Séminaire International sur les Energies Nouvelles et Renouvelables
The 3nd International Seminar on New and Renewable Energies
Unité de Recherche Appliquée en Energies Renouvelables, Ghardaïa – Algérie 13, 14 Octobre 2014

Cuckoo search algorithm for optimal energy management strategy of hybrid power system systems

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***Abstract* – This paper presents the optimal sizing and control strategy for stand-alone PV-battery-Diesel. The sizing method that is developed to establish the minimum capacity of the system components; however the optimal energy management strategy is developed to increase the reliability and the lifetime of system. The cuckoo search algorithm is introduced to minimize the cost of the system throughout its lifetime by finding the appropriate parameters off control.**

***Keywords*: energy power system, photovoltaic, energy management, Cuckoo search algorithm.**

I. Introduction

In south of Algeria, there are many communities live a hundreds of kilometers far from the electrical distribution network, generally they use the diesel generator to produce electricity for lighting or water pumping. However, this kind of generator is not a perfect solution if considering the high cost of electricity produced and environmental pollution. Hybrid power system based on photovoltaic is considered an effective option to electrify those remote and isolated areas benefited the good solar radiation throughout the year. For the south Algerian case, the average daily solar radiation intensity on a horizontal surface is about 5.73 kWh/m2 while the total annual sunshine hours amounts to about 3000 hours. These values are relatively considered high and very encouraging for using PV generators. The highest averages are in summer months (May to August). Their averages are about 7-8 kWh/m2

Although, the prices of PV modules have been reduced substantially in recent years, partly by improved efficiencies, partly by improved manufacturing techniques, and partly by economies of scale in production, the optimal sizing of PV panels within hybrid power system is very important step to reduce the whole investment cost. Sizing a PV-battery-Diesel is a complex task because different resources are employed moreover they have not same behaviors [1]. A properly sizing system is a system that responds to different energy requirements to reach a techno-economic hybrid power system. Oversized system components will certainly increase the system cost. However, undersized system components will cause the power blackouts [2].

The optimum photovoltaic size and battery capacity are calculated based on the total life cycle cost, for this aim, a methodology has been developed in this paper by which the PV panel number as well as the batteries bank can be optimized simultaneously.

The objective of PV-Battery-Diesel is to provide sufficient and reliable electricity to meet the end-use power demand, and store the excess energy into the batteries bank. The energy efficiency is significantly determined by the energy management strategy for the stand-alone PV-Battery-DG systems; moreover, diesel generator and battery Lifetime depend on the time and manner that we use them.

In PV-Battery-Diesel, the allowed minimum sates of charge of batteries bank are given by the manufacturer, as those may has an effect on the useful life of the battery, generally they are between 20% and 30%. However, higher values than those provided by the manufacturers may, in some cases give lower Net present cost (NPC) values [3].

The generator diesel has minimum power value provided by manufacturers because the diesel generator usually has high fuel consumption when supplying low levels of power, and therefore higher value than that provided by the manufacturers may also, in some cases give lower NPC values.

The meta-heuristics as genetic algorithm, particle swarm optimization and cuckoo search have been successfully used for solving some engineering design and optimization problems with promising results[4].

In this paper, we have used the cuckoo search algorithm

to search for possible values between the minimum power recommended by the manufacturer and the nominal power of the diesel generator and on another hand to search for possible values between the minimum SOC recommended by manufacturer and 100% of SOC of batteries bank.
Benefit the two search capabilities of CS algorithm:

Global search (explorative random walk) and local search (exploitative random walk) to reach the global solution of our optimization will be verified and discussed in next sections.

The hybrid PV-Battery-Diesel power plant that considered in this paper uses a real meteorological data as well as equipments costs in the market for showing its feasibility if will be planted in south of Algeria.

II. Mathematical model of the hybrid power system

In order to simulate the performance of the hybrid plant, mathematical models of all components have been taking based on electrical models to simulate their real behaviors.

II.1. PV generator model

Photovoltaic conversion of the sun irradiation implies conversion of the energy of solar irradiation to the electrical energy. The power produced by the PV system is estimated by the following equation [5]:

$$P_{pv} = \eta_{pv} A_{pv} G \tag{1}$$

Where: A_{pv} is PV array area (m^2), G is solar irradiation (kWh/m^2) and η_{pv} represents the PV generator efficiency and is given by:

$$\eta_{pv} = \eta_{pv\_ref}\,\eta_{MPPT}[1-\beta(T_c - T_{c\_ref})] \tag{2}$$

Where η_{pv_ref} is the reference module efficiency, η_{MPPT} is the power conditioning efficiency which is equal to 1 if a perfect maximum power tracker (MPPT) is used. β is the generator efficiency temperature coefficient, it is assumed to be a constant and for silicon cells the range of β is 0.004-0.006 per ^oC, T_{c_ref} (is the reference cell temperature (^oC) usual it is taken as 25^oC and T_c is the cell temperature (^oC) and can be calculated as follows

$$T_c = T_a + [(NCOT - 20)/800]G \tag{3}$$

Where T_a is the ambient temperature (^oC) and NCOT is the nominal cell operating temperature (^oC)

II.2. Battery model

Currently, battery technology is being considered in research and development. The CIEMAT model presents a good performance to represent dynamic and complex battery operation. The equations are normalized with respect to the total ampere-hours that may be charged or discharged in 10 h at 25 ^oC (C10 capacity), and it considers the low current operation and temperature effects of the battery capacity. Equations (4) and (5) show the capacity equation [6].

$$C_T = 1.67 C_{10}(1 + 0.005\Delta T_a) \tag{4}$$

$$C = \frac{C_T}{1 + 0.67\left(\frac{|I|}{I_{10}}\right)^{0.9}} \tag{5}$$

Where $\Delta T_a = T_a - 25$ is the temperature variation from the reference of 25 ^oC, and Ta is the ambient temperature in ^oC, C_T is the maximum capacity of the battery (Ah), and C is the ampere-hours capacity at the charge or discharge constant current $I(A)$

II.3. Diesel generator fuel consumption

The fuel consumption of the diesel generator, ConsG (l/h) is modeled as dependent on the output power:

$$ConsG = B_G P_{N\_G} + A_G P_G \tag{6}$$

Where $P_{N\_G}(KW)$ is the nominal power, $P_G(KW)$ is the output power of the diesel generator, A_G and B_G are the coefficients of the consumption curve, defined by the user (l/kWh).

$A_G = 0.246 l / KWh$ and $B_G = 0.08145 l / KWh$

III. Sizing and allocation

III.1. Abstract PV panel sizing

To install the PV power, we have to optimize its size to achieve the desired output and consequently get the most economically viable solution. The PV power generated by an area without counting the losses in inverter is described as follows [7]:

$$P_{PV\_in} = A_{pv} G_{avg} \eta_{pv} \eta_{MPPT} \tag{7}$$

The PV power can be determined through the assuming that all the end-user load power P_L comes directly from solar power P_{pv}

$$P_{PV} = \frac{P_L}{G_{avg}\eta_{pv}\eta_{MPPT}\eta_{inv}} \tag{8}$$

Due to the mismatch between solar power P_{pv} and load power P_L as is shown in Fig. 2, the energy management strategy is applied in which during the intervals (t0, t1) and (t2, t3), the deficit load power will be provided by the battery; during the interval (t2, t3), the excess solar power will be converted to the battery energy. The difference of energy dE can be calculated by [7]

$$dE = dE_1 + dE_2 \tag{9}$$

Where:

$$dE_1 = \int_{t0}^{t1} (P_{pv} - P_L)\eta_{dis}\eta_{inv} \text{ if } P_{pv} < P_L \tag{10}$$

$$dE_2 = \int_{t1}^{t2} (P_{pv} - P_L)\eta_{ch} \text{ if } P_{pv} > P_L \tag{11}$$

Therefore, the required PV panel area A_{pv} can be calculated by:

$$A_{pv} = k\left(\frac{P_{pv\_in}}{G_{avg}\,\eta_{pv}\,\eta_{MPPT}} + \frac{dE}{G_{avg\_yearly}\,\eta_{pv}\,\eta_{MPPT}}\right) \tag{12}$$

Where k is the safely factor greater than one and P_{pv_in} is initial power generated by initial A_{pv} area before optimization. The global batteries bank capacity is given as following:

$$G_{bat} = \frac{P_L D_s}{V_{bat} DOC_{\max} T_{cf}\,\eta_{bat}} \tag{13}$$

Where P_L is the load in Wh; D_s is the battery autonomy or storage days; V_{bat} is the battery bank voltage; $DOD_{\max}$ is the maximum battery depth of discharge; T_{cf} is the temperature correction factor and η_{bat} is the battery efficiency.

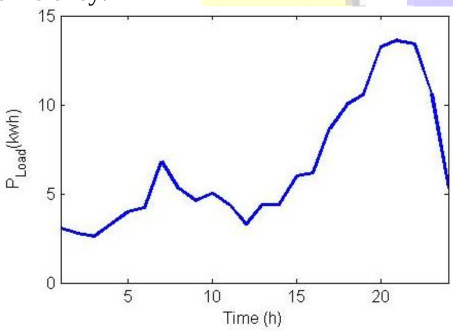

Fig. 1. Hourly load demand

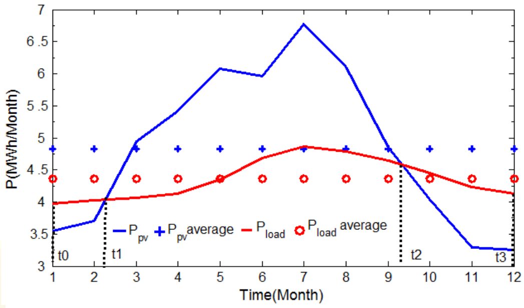

Fig.2. PV profile and Load demand

IV. Control strategy of the hybrid power system

The fundamental control rule is the power produced by renewable source P_{PV} should be preferentially used to supply the residential load. However, one of the PV system's disadvantages is the unexpected fluctuation of generated electric power caused by the unstable solar radiation. It can make the output of the diesel engine fluctuate; therefore it decreases its efficiency and increases the exhaust gases [9].

The optimized designing of the system is very important for a cost-effective energy supply system. The objective function to minimize in the optimization process is the total net present cost (NPC) of the system. The NPC represents the investment costs plus the discounted present values of all future costs during the lifetime of the system. To estimate the NPC of the system, we have to simulate the PV-Battery-Diesel throughout its lifetime, obtaining the energy produced and consumed by the components, their own lifetimes, the number of times in which the components must be replaced, the operating and maintenance costs, the fuel costs. The cost escalation of the fuel and maintenance are included in this optimization with the lifetime of all the important components to determine the optimum sizes.

The lifetime of PV-battery-Diesel is assumed the life of the PV panels, which are the elements that have the greater lifetime [10]. Diesel generator and battery lifetime depend on the time and manner that we use them.

The lifetime of battery is typically given in a datasheet and it is related to the stage at which the battery is considered to have a remaining capacity of 80% compared with the nominal capacity. There are many different methods to calculate the lifetime consumption of battery[11], which depends on the conditions of operation, on the charge/discharge regime and on temperature. Calculating the expected lifetime of battery is important, as it influences the total cost of the system. In literature, we can find two popular methods: the first is cycle counting [12]. It is based on counting the charge/discharge cycles of battery in order to estimate its lifetime. This method is used by the HYBRID2 program [13]

The second is Ah-throughput model [14]; it counts the amount of charge through the battery while the amount of energy that can be cycled through the battery is assumed fixed, independently of the depth of the individual cycles or any other parameters.
The Equivalent Full Cycle (EFC) in whole lifetime is constant. However, the total number of cycles in total lifetime depends on the depth of discharge. The battery manufacturers usually recommend that the SOC should not fall under a certain percentage of their Capacity Cn (Ah).The optimization of the hybrid system shows that the total net present cost depends on the minimum SOC allowed. For example, if the minimum state of charge SOC_{min} recommended by the manufacturers should not be under 20% of Cn, it is maybe better to build the system to prevent SOC_{min} not lower than 50%.
The estimated throughput of battery is calculated using the depth of discharge versus the cycles to failure curve provided by the manufacturer. Eq. (14) shows the calculation of the throughput:

$$\text{Throughput} = \frac{1}{N_p}\sum_{i=1}^{N_p} C_{Nom} * DOD_i * C_{F,i} \quad (14)$$

Where C_{Nom} is nominal batteries bank capacity , DOD_i is specific depth of discharge being considered , $C_{F,i}$ is cycles to failure to the specific depth of discharge, N_p is the total number of points considered and i represents each depth of discharge measurement provided by the manufacture.

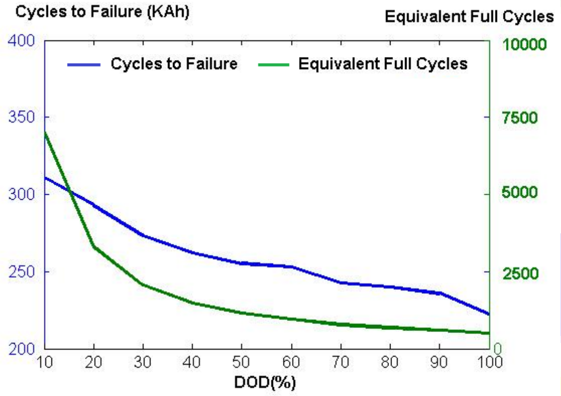

Fig. 3. Battery cycle life vs. depth of discharge

The cost of operation and maintenance of the Diesel generator throughout the life of the system (the number of hours the Diesel generator will run depending on the control strategy. The manufacturers usually recommend that the P_{min} should not descend under a certain percentage of its Capacity, the manufacturer of the DG used in the system that should not be run lower than 30% of nominal power, it is maybe better to build the system to prevent P_{min} higher than recommended by manufacturer.

The NPC is given as following:

$$NPC = C_{DG} + C_{Bat} + C_{inst} \quad (15)$$

Where: C_{DG} , C_{Bat} are hourly operating and maintenance cost of diesel generator and battery bank . The C_{inst} is hourly installation which is giving as following:

$$C_{inst} = C_{PV} + C_{inv} + C_{cc} \quad (16)$$

The C_{PV} is costs of installation of PV array area. C_{inv} , C_{cc} are the costs of installation and replacement of inverter and charge controller.

V. Cuckoo Search Algorithm

Cuckoo Search (CS) algorithm represents a new optimization metaheuristic algorithm, which was inspired by the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of host birds. Some cuckoos have evolved in such a way that female parasitic cuckoos can imitate the colors and patterns of the eggs of a few chosen host species. Cuckoos usually choose the nest of a bird that has just laid its eggs so that they can be sure that their eggs would hatch first because cuckoo eggs hatch earlier than their host eggs birds. A cuckoo chick can mimic the call of host chicks. If the host birds realize that a cuckoo egg has been laid in, they either remove the egg or abandon the nest. In this optimization algorithm, each nest represents a potential solution [15].
The simplest approach of using new metaheuristic CS algorithm can be done through three ideal rules, which are: 1) Each cuckoo lays one egg at a time, and dump its egg in randomly chosen nest; 2) The best nests with high quality of eggs will carry over to the next generations; and 3) The number of available host nests is fixed where the egg laid by a cuckoo is discovered by the host bird with a measured fraction probability, pa ∈ [0, 1].

The general system-equation of the CS algorithm is based on the general system-equation of the random-walk algorithms, which is given in Eq.17:

$$X_{g+1,i} = X_{g,i} + \alpha \otimes levy(\lambda) \quad (17)$$

Where g indicates the number of the current generation (g =1, 2, 3,…, max-cycle and max-cycle denotes the predetermined maximum generation number). In the CS algorithm, the initial values of the j^{th} attributes of the ith pattern, Pg=0;i =[xg=0;j,i], have been determined by using Eq.18:

$$X_{0,i} = rand(up_i - low_i) + low_i \quad (18)$$

Where low_i and up_i are the lower and upper search-space limits of j^{th} attributes, respectively. The CS algorithm controls the boundary conditions in each computation steps. The iterative evolution phase of the pattern matrix begins with the detection step of the by using Eq.19:

$$\varphi = \left(\frac{\Gamma(1+\beta).\sin(\pi.\beta/2)}{\Gamma((\frac{1+\beta}{2}).\beta.2^{(\frac{\beta-1}{2})})} \right)^{1/\beta} \quad (19)$$

The required stepsize value has been computed by using Eq.20

$$stpesize_j = 0.01 \left(\frac{u_j}{v_j} \right)^{1/\beta} .(v - X_{best}) \quad (20)$$

Here u=φ·randn[D] and v=randn[D]. The randn[D] function generates a uniform integer between[1 D]. In the next step of the CS algorithm, the donor pattern υ is randomly mutated by using Eq.21:

$$v = v + stepesize_j .randn[D] \quad (21)$$

The update process of the best nest X_{best} pattern in the CS algorithm is defined by Eq.22:

$$X_{best} \leftarrow f(X_{best}) < f(X_i) \quad (22)$$

Where: $f(X_{best})$ is the fitness function $f(X_i)$

The unfeasible patterns are manipulated by using the crossover operator given in Eq.23:

$$v_i = \begin{cases} X_i + rand(X_{r1} - X_{r2}) \longleftarrow randn_i > pa \\ X_i \longleftarrow else \end{cases} \quad (23)$$

In this paper, β=1.50 and pa=0.25 have been used as in [15].

VI. Results and discussions

The PV sizing is based on monthly average of Load; the algorithm used starts to search the optimal area of PV (using equation 1) with A_{PV} equals zero and it then increases the area of PV using equation 12 until the yearly energy produced will be higher than the yearly energy required by the load, the safety factor has been included to ovoid the power outages which was taken 1.25. The total area obtained by the method developed before is only 289 m^2

The batteries bank is sized to supply the load only for one day without PV system and diesel generator. Using equation 13, the number of batteries obtained is 44 arranged on 11 branches in parallel and each branch has 4 batteries in series.

The size of diesel generator has been given at more than the maximum power required of load to avoid any probability of not satisfying.

Using the cuckoo search algorithm to give the optimal DOD_{bat} and $P_{DG\_\min}$ is based on forecasting of all next costs and load demand throughout the lifetime of system using Eq15 as fitness function. The CS is implemented in Matlab, depending on the problem of interest. The following parameters have been used in simulation: population size (50 individual), Lévy exponent $\beta = 1.5$, and discovery probability $p_a = 0.25$.

The CS simulates the PV_battrey_DG using the lifetime cycles of each component, the inflation rate of replacement and operation costs.

The results demonstrate that $DOD_{bat} = 20\%$ and $P_{DG\_\min} = 30\%$ given by manufacturers are not the good parameters for low value of net present cost. The optimal value are $DOD_{bat} = 52.82\%$ for the battery and $P_{DG\_\min} = 100\%$. The total NPC has been reduced by 30.77% which represents all total costs of investment and expenditure throughout the lifetime system (shown in Fig4).The parameters of simulation and results is given on table1.

TABLE I

Simulation parameters and results

	Name	Value
η_{pv}	PV efficiency	0.1%
η_{MPPT}	MPPT efficiency	0.95%
η_{ch}	Charge battery efficiency	0.85%
η_{dis}	Discharge battery efficiency	0.95%
η_{inv}	Inverter efficiency	0.95%
A_{PV_op}	PV area after optimisation	289(m^2)
C_{bat}	Nominal battery capacity	444(Ah)
N_{bat}	Battery number after optimisation	44
DOD_{bat}	Manufacturer depth of discharge	20%
DOD_{bat_opti}	Optimised depth of discharge	52.82%
$P_{DG\_\max}$	Maximal power of diesel generator	15kw
$P_{DG\_\min}$	Minimal power of diesel generator	30%
$P_{DG\_\min\_opti}$	Optimal power of diesel generator	100%
NPC	Net present cost without optimisation	926(k£)
NPC_{opti}	Net present cost with optimisation	641(k£)

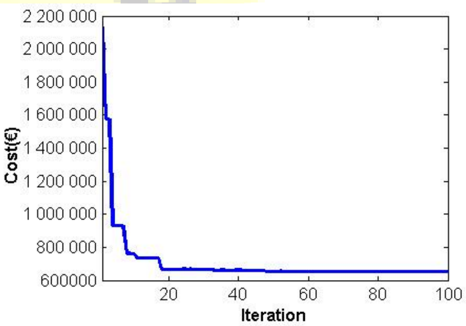

Fig.4.Net present cost optimized by cuckoo search

VII. Conclusion

In this work, the optimal sizing of PV_battery_DG is given in this paper. Using the PV in south of Algeria is very promising for low costs as well as CO_2 emission by decreasing the participation rate of diesel to produce energy. The net present cost is decreased by optimized the minimum state of charge of batteries bank and the minimum power of diesel generator where the system should not go under them.

The cuckoo search gives an optimal value of net present cost with small number of iteration.

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