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Optimal sizing of small isolated hybrid power systems using tabu search

Y. A. KATSIGIANNIS*, P. S. GEORGILAKIS
Department of Production Engineering and Management, Technical University of Crete, GR 73100, Chania, Greece

The optimal sizing problem of a small isolated power system that contains renewable and/or conventional energy technologies belongs to the field of combinatorial optimization. Due to the large number of available technologies and their wide range of possible technical characteristics, the solution of this problem following the traditional method of exhaustive enumeration can be extremely time-consuming. In this paper, a tabu search algorithm is proposed for the solution of the above optimal sizing problem. Tabu search is an iterative metaheuristic method that has been successfully applied mainly in combinatorial optimization problems. The results prove the performance of the proposed method in terms of solution quality and computation time.

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1. Introduction

A small isolated power system (SIPS) provides electricity supply in remote areas that cannot be economically connected to the electrical grid. In such areas, renewable energy sources (RES) are usually present in large amounts, so a number of renewable power sources can be used. However, since these technologies are dependent on a resource that is not dispatchable, there is an impact on the reliability of the electric energy of the system, which has to be considered. The basic ways to solve this problem are the parallel operation of renewable power sources with conventional generators, as well as the use of storage as a type of energy-balancing medium. Due to the large variation and the different characteristics of the available renewable, conventional and energy storage technologies, the optimal sizing of a SIPS is a difficult task as it belongs in the category of non-linear combinatorial optimization problems.

Problems of this type are difficult to be solved by classical optimization methods. However, a number of new methods, called metaheuristics, have been developed mainly in the last two decades, such as genetic algorithms (GAs), simulated annealing (SA) and tabu search (TS). Metaheuristics are solution methods that orchestrate an interaction between local improvement procedures and higher level strategies to create a process capable of escaping from local optima and performing a robust search of a solution space 0. These methods are preferred for solving many types of complex problems, particularly those of a combinatorial nature.

For the optimal sizing of SIPS, several methods have been proposed. The most direct method is the complete enumeration. This approach is used by HOMER software (Hybrid Optimisation Model for Electric Renewables) 0 and ensures that the best solution is obtained, but it is time consuming, especially if it is combined with sensitivity analysis due to uncertainties of input data (e.g. load demand, weather data). Heuristic methods have been also applied in the design of hybrid isolated renewable energy systems, as stated in 0 and 0. In the area of metaheuristics, GAs have been used for the optimal design of an isolated hybrid system 0.

This paper proposes the application of tabu sarch for the optimal sizing of SIPS. TS is a powerful iterative optimization procedure that has been successfully applied to a number of combinatorial optimization problems. It starts from an initial feasible solution and attempts to determine a better solution in the manner of a greatest-descent algorithm. However, TS is characterized by an ability to escape local optima (which usually cause simple descent algorithms to terminate) by using a flexible memory system, in contrast to “memoryless” systems, such as SA and GAs.

2. Problem formulation

2.1 Objective function

The objective function to be minimized is system’s cost of energy (COE in €/kWh):

$$COE = \frac{C_{tot,ann}}{E_{tot,ann}} \quad (1)$$

where $C_{tot,ann}$ (€) is the total annualized cost and $E_{tot,ann}$ (kWh) is the total amount of annual energy to be served. $C_{tot,ann}$ is computed by:

$$C_{tot,ann} = C_{cap,ann} + C_{rep,ann} + C_{o\&m,ann} + C_{fuel,ann} \quad (2)$$

where $C_{cap,ann}$ is annualized capital cost, $C_{rep,ann}$ is the annualized replacement cost, $C_{o\&m,ann}$ is the annual operation and maintenance (O&M) cost, and $C_{fuel,ann}$ is the annual fuel cost (if applicable).

2.2 Constraints

1. SIPS component size range:

$$x_i^{\min} \leq x_i \leq x_i^{\max} \quad \forall\, i \tag{3}$$
$$x_i^{\min} \geq 0 \quad \forall\, i$$

where x_i is the size of each system's component i, x_i^{min} and x_i^{max} are the minimum and maximum acceptable values for x_i.

2. Satisfaction of load demand:

$$\sum_{j=1}^{N} P_{j,t} \geq D_t \quad \forall t \tag{4}$$

where $P_{j,t}$ is the power output of generator unit j at time interval t, and D_t is the load demand at t.

3. Overview of tabu search

TS was first proposed by Fred Glover in an article published in 1986 0, although it borrowed many ideas suggested before. TS is a powerful optimization procedure that has been successfully applied to a number of combinatorial problems. It uses an operation called *move* to define the neighbourhood of any given solution. TS can be viewed as an iterative technique that explores a set of problem solutions by repeatedly making moves from one solution to another, in the manner of a greatest-descent algorithm 0.

TS is characterized by the ability to escape from local optima and the occurrence of cycles, which usually cause simple descent algorithms to terminate. This goal is obtained by using a finite-size list of forbidden moves, called tabu moves, derived from the recent history of the search. The basic underlying assumption is that the suboptimal points, where the simple greatest-descent algorithm stops, can be better starting points with respect to random restarts, provided that care is taken so that the local minima do not become attractors of the dynamics included by the algorithm, and that limit cycles do not arise 0.

The two main components of the TS are the *tabu list restrictions* and the *aspiration criteria* of the solution associated with these restrictions. The tabu list restrictions could be stated directly as a given change of moves or indirectly as a set of logical relationships or linear inequalities. The tabu list is also referred to as the adaptive memory in a sense that some attributes are temporarily fixed as long as they are in the tabu list. Tabu lists are managed by recording moves in the order in which they are made. If a new attribute enters into the tabu list, the oldest one is released from the tabu list. The proper choice of the tabu list size is critical to the success of the algorithm and it depends on the specific problem.

Aspiration criteria can override tabu restrictions. That is, if a certain move is forbidden, the aspiration criteria, when satisfied, can reactivate this move. The appropriate use of such criteria can be very important for enabling a TS method to achieve its best performance levels. The most widely used aspiration criterion removes a tabu classification from a trial move when a move yields a solution better than the best obtained so far. However, other aspiration criteria have been also proposed 0.

Two highly important components of the TS are intensification and diversification strategies. Intensification strategies are based on modifying choice rules to encourage move combinations and solution features historically found good. On the other hand, diversification strategies encourage the search process to examine unvisited regions and to generate solutions that differ in various significant ways from those seen before. The simplest intensification and diversification strategy is the tabu list size. A short size allows the exploration of solutions close to a local optimum (intensification), while a long size can help to break free from a vicinity of a local optimum.

4. Proposed methodology

4.1 Description of system

The considered SIPS has to serve electrical load and can contain five component types:

1. Wind turbines (WTs).
2. Photovoltaic (PV) modules.
3. Diesel generator.
4. Batteries.
5. Solid-state inverters and rectifiers.

In the SIPS simulation procedure, the time step is considered to be hourly.

4.2 Tabu search algorithm for optimal sizing of SIPS

The TS algorithm for the optimal sizing of SIPS is composed of the following steps:

1. Random generation of an initial feasible solution.
2. Calculation of cost of energy for this solution, using eq. (1).
3. Setting of the global best solution equal to the current solution.
4. Finding of a set of feasible trial solutions that are neighbours to the current solution and sorting of them in ascending order. In the proposed algorithm, a move is defined by changing each time the size of one SIPS component around its neighbourhood.
5. Checking if the selected move of the trial solution belongs to the tabu list. If it belongs, a selection of the next solution of the sorted set of trial solutions has to be done. If not, the solution is accepted and the update of the tabu list is performed by adding in it the chosen move, and by

removing from it the oldest move.

6. Examination if the aspiration criterion is satisfied. In the proposed algorithm a move aspiration is satisfied if the move yields a solution better than the best obtained so far.

7. Update of the global best solution if the best acceptable solution found from the trial set has a better value.

8. Stop the procedure if the termination criterion is satisfied. In this paper the search is terminated if a maximum predefined allowable number of iterations is reached.

5. System modeling

5.1 Wind turbines

Each WT has a characteristic power curve that describes its power output as a function of the wind speed at its hub height. The WT modeling is implemented using a power curve profile that is based on manufacturer's data. The selected WT has the following characteristics: hub height equal to 30 m, rated power P_R equal to 10 kW, cut-in speed V_{in} equal to 3 m/s, and cut-out speed V_{out} equal to 24 m/sec 0.

For the WT power curve fitting, a seventh order polynomial expression has been selected, as it provides accurate correlation with real data (Fig. 1), while it presents exclusively positive values for the generated power P_{WT} (kW) in the interval [V_{in} V_{out}]. The obtained equation is shown in eq. (5):

$$\begin{aligned} P_{WT}(V) = \; & 5.36\cdot 10^{-7}\cdot V^7 - 6.01\cdot 10^{-5}\cdot V^6 \\ & + 2.68\cdot 10^{-3}\cdot V^5 - 0.06\cdot V^4 + 0.71\cdot V^3 \\ & - 4.23\cdot V^2 + 12.12\cdot V - 13.18 \\ & for \quad V_{in} \le V \le V_{out} \end{aligned} \tag{5}$$

where V is the wind speed (m/s).

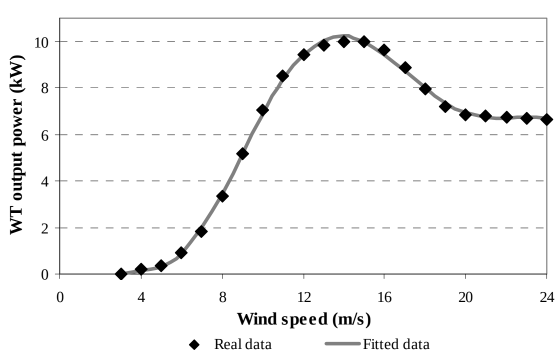

Fig. 1. WT power curve fitting.

5.2 Photovoltaics

For the calculation of PV output power P_{PV}, it is assumed that a PV panel produces electricity in direct proportion to the global solar radiation incident upon it, independent of its temperature and the voltage to which it is exposed. P_{PV} (kW) is computed by:

$$P_{PV} = f_{PV}\cdot Q_{PV}\cdot\left(I_T/I_s\right) \tag{6}$$

where f_{PV} is the PV derating factor considered here as 90%, Q_{PV} (kW$_p$) is the PV array capacity, I_T (kW/m^2) is the global solar radiation incident on the PV array, and I_s is 1 kW/m^2, which is the standard amount of radiation used to rate the capacity of PV modules.

For the estimation of I_T, a time series with hourly time steps of the global solar radiation on Earth's surface I is needed. According to solar geometry equations provided in 0, an estimation of extraterrestrial horizontal radiation G_0 can be done, which is identical for a specific location. The integration of G_0 over one hour gives the hourly average extraterrestrial horizontal radiation I_0.

Atmospheric scattering and absorption reduce the amount of solar radiation striking Earth's surface to some fraction of the extraterrestrial radiation. This fraction is called clearness index k_T and is calculated from:

$$k_T = I/I_0 \tag{7}$$

Global solar radiation is divided into beam radiation I_b and diffuse radiation I_d. Their values can be estimated by the Erbs correlation 0, which gives the I_d as a function of k_T:

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & for \quad k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & for \quad 0.22 < k_T \le 0.80 \\ 0.165 & for \quad k_T > 0.80 \end{cases} \tag{8}$$

The obtained information along with location data are then used for the I_T estimation through HDKR model 0. In the whole calculation process of P_{PV}, no tracking system has been considered, while the slope of PV panels has been taken equal to the latitude of SIPS location.

5.3 Diesel generator

The diesel generator is the most common source of electric power in remote locations. It has the ability to produce power on demand and to response rapidly to a fluctuating electric load. When used in combination with renewable power sources, diesel generators can provide backup power during times of insufficient renewable output.

For constant-speed diesel generators, the rate of fuel consumption is well approximated by the following first-order equation 0:

$$F = 0.08415\cdot P_{rated} + 0.246\cdot P \tag{9}$$

where P_{rated} is generator's rated power and P is generator's output power. The fuel cost is then equal to the product of the diesel price (considered here as 0.6 €/lt) with the corresponding fuel consumption, as calculated by eq. (9).

To avoid engine damage, constant-speed diesel generators typically do not operate below a minimum load ratio of their rated capacity. In this paper, this ratio is set equal to 30%.

5.4 Batteries

Batteries have been considered to be lead acid, and have been modeled as follows:

- 85% overall efficiency
- 4V nominal voltage
- 1875 Ah (7.5 kWh) nominal capacity (per unit)
- 10,000 kWh lifetime
- Minimum state of charge equal to 30% of their nominal capacity
- Charge current cannot be greater than the one fifth of battery's nominal capacity (in Ah)
- Self-discharge losses are not considered

5.5 Solid-state inverter and rectifier

Renewable power systems commonly comprise a mixture of AC and DC loads and components, and hence require AC/DC conversion, which can be performed by solid-state inverters and rectifiers. An inverter converts DC current to AC, while a rectifier converts AC current to DC. The power flow through solid-state inverters and rectifiers can be modeled by the following equation 0:

$$P_O = \alpha \cdot (P_I - \beta) \tag{10}$$

where P_O is the output power, P_I is the input power, and α and β are constants. The value of β, often called the ''standing losses,'' is small compared to the capacity of the inverter and it is ignored in this paper. The efficiency for the inverter and the rectifier is assumed equal to 90%.

5.6 Dispatch strategy

Renewable power sources (WTs and PVs) have a priority in supplying the electric load. For each simulation hour, their capability to achieve this objective is checked. If they are not capable to fully serve the load, the remaining electric load has to be supplied by the diesel generator and/or the batteries. From all possible combinations, it is selected the one that supplies the load at the least cost (i.e., the sum of fixed and marginal costs).

Moreover, an additional aspect of system operation arises, which is whether (and how) the diesel generator should charge the battery bank. Two common control strategies that can be used are load following strategy and cycle charging strategy. It has been found 0 that over a wide range of conditions, the better of these two strategies is virtually as cost-effective as an ideal predictive strategy, which assumes the existence of perfect knowledge in future load and wind conditions.

In the load following strategy, batteries are not charged at all with diesel generated energy. The diesel operating point is set to match the instantaneous required load. An exception may occur if the required load is less than the minimum power of diesel generator; then the excess generated power is stored in the batteries. Load following tends to be optimal in systems with a lot of renewable power, when the renewable power output sometimes exceeds the load.

In the cycle charging strategy, whenever the diesel generator needs to operate to serve the primary load, it operates at full output power. A setpoint state of charge, SOC_a, has also to be set in this strategy. The charging of the battery by the diesel generator will not stop until it reaches the specified SOC_a. In this paper, a SOC_a equal to the 78% of total battery capacity has been considered. Cycle charging tends to be optimal in systems with little or no renewable power.

Table 1. SIPS component characteristics.

Component	x_i^{min}	x_i^{max}	Increment	Capital cost	O&M cost	Fuel cost	Lifetime
WTs (*i*=1, *j*=1)	0 WTs	20 WTs	1 WT	7,500 €/WT	500 €/y	-	20 y
PV (*i*=2, *j*=2)	0 kW_p	40 kW_p	1 kW_p	5,000 €/kW_p	0	-	20 y
Diesel generator (*i*=3, *j*=3)	0 kW	100 kW	1 kW	150 €/kW	0.1 €/h operating	0.6 €/l	20,000 oper. hours
Batteries (*i*=4)	0 batteries	200 batteries	1 battery	850 €/battery	0	-	10,000 kWh
Inverter and rectifier (*i*=5)	0 kW	100 kW	1 kW	700 €/kW	0	-	20 y

6. Results and discussion

6.1 Case study system

In the considered SIPS, the project lifetime is assumed to be 20 years and the discount rate has been taken equal to 5%. The maximum annual value of electric load has been set to 100 kW, while the wind and solar data needed for the estimation of WT and PV performance refer to the Chania region, Crete, Greece. The characteristics of system components are presented in Table 1. For each component, the replacement cost is considered equal to the capital cost. The maximum number of WTs, PVs and batteries is explained due to space and cost limitations, while the maximum power of diesel generator and converter is determined from the annual peak load value. The dispatch strategy (load following or cycle charging) represents also an optimization variable, as each component configuration has to be checked for both strategies.

6.2 Results

After trial and error, the selected TS parameters for the SIPS optimal sizing problem were a) tabu list size equal to 6, and b) number of iterations equal to 100. The initial solution contains one diesel generator with rated power equal to peak load (which guarantees the feasibility), random quantities of the remaining system components and random chosen dispatch strategy. The neighbourhood of each component, needed for the definition of a move, can contain at most twelve members, and it is determined: a) by selecting the three nearest larger and the three nearest smaller quantities of each component current size, b) by evaluating each obtained configuration for both dispatch strategies, and c) by checking the feasibility of the solutions (eq. (3) and eq. (4)). This means that at each iteration a maximum number of 60 objective function evaluations is performed (i.e., 12 neighbourhoods per component × 5 components).

For the implementation of the TS algorithm, a computer code in MATLAB was developed. The tests were performed at a laptop computer with Intel Pentium M 1.73 GHz processor, 512 MB RAM memory in Microsoft Windows XP environment. The execution time of the TS algorithm was 42 minutes.

The evolution of the TS procedure is shown in Fig. 2. The minimum value for system's COE is 0.239 €/kWh and it is obtained in the 73rd iteration of the algorithm. The optimum configuration contains 20 WTs, 0 kW_p PVs, diesel generator of 72 kW, 197 batteries and a solid-state inverter and rectifier of 70 kW, while the adopted dispatch strategy is cycle charging. The total number of objective function evaluations during the whole TS procedure was 5256, which is very small compared to 3.53×10^9 possible configurations of the specific SIPS, when applying complete enumeration of possible configurations.

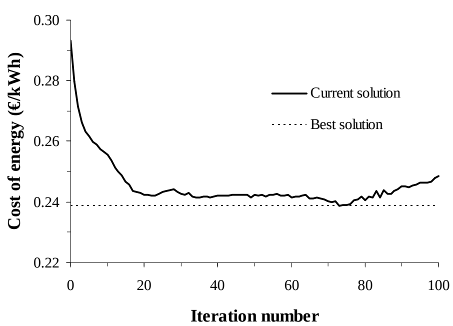

Fig. 2. Evolution of the TS procedure.

7. Conclusions

In this paper, the application of the tabu search metaheuristic method for the optimal sizing of small isolated hybrid power systems has been proposed. The advantages of this method are a) simplicity, as the problem can be modeled as a local search optimization method equipped with additional characteristics that help to avoid solutions cycling, b) dependence by less parameters compared to other metaheuristic methods, and c) fast convergence. The obtained system with the minimum cost of energy contains large capacities of wind turbines, batteries and diesel generator, no photovoltaics, while it uses the cycle charging dispatch strategy.

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* Corresponding author: ikatsigiannis@yahoo.gr