Genetic Algorithm Solution to Optimal Sizing Problem of Small Autonomous Hybrid Power Systems

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Abstract. The optimal sizing of a small autonomous hybrid power system can be a very challenging task, due to the large number of design settings and the uncertainty in key parameters. This problem belongs to the category of combinatorial optimization, and its solution based on the traditional method of exhaustive enumeration can be proved extremely time-consuming. This paper proposes a binary genetic algorithm in order to solve the optimal sizing problem. Genetic algorithms are popular optimization metaheuristic techniques based on the principles of genetics and natural selection and evolution, and can be applied to discrete or continuous solution space problems. The obtained results prove the performance of the proposed methodology in terms of solution quality and computational time.

Keywords: Combinatorial optimization, genetic algorithms, metaheuristics, renewable energy sources, small autonomous hybrid power systems.

1 Introduction

A small autonomous hybrid power system (SAHPS) is a system that generates electricity in order to serve a local low energy demand, and it usually operates in areas that are far from the main grid. Renewable energy sources (RES) can often be used as a primary source of energy in such a system, as they are usually located in geo graphically remote and demographically sparse areas. However, since renewable technologies such as wind turbines (WTs) and photovoltaics (PVs) 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 is either to use storage as a type of energy-balancing medium, or to install conventional generators in the system such as diesel generators.

The problem of optimal sizing of a SAHPS belongs in the category of combinatorial optimization problems, since the sizes of system's components, which constitute the input variables, can only take specific values. For the solution of this problem, several methods have been proposed. The most direct method is the complete enumeration method. This approach is used by HOMER software [1] and ensures that the

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best solution is obtained, but it can be proved extremely time consuming. In [2] linear programming techniques are used in order to optimize the design of a hybrid WT-PV system. Heuristic methods have been also applied, as stated in [3].

In recent years, a number of new methods have been developed, in order to solve many types of complex problems, particularly those of a combinatorial nature. These methods are called metaheuristics and include genetic algorithms (GAs), simulated annealing (SA), tabu search (TS) and particle swarm optimization (PSO). Metaheuristics combine characteristics of local search procedures and higher level search strategies in order to create a process capable of escaping from local optima and performing a robust search of the solution space. From the area of metaheuristics, TS [4], PSO [5] and GAs [6]-[8] have been proposed for the solution of optimal SAHPS sizing. Moreover, HOGA software [9] uses a GA in order to minimize the net present cost of a hybrid power system.

This paper proposes the application of a GA in the optimal sizing of a SAHPS. The paper is organized as follows: Section 2 formulates the SAHPS optimal sizing problem. Section 3 describes SAHPS components and modeling and Section 4 presents the main characteristics of the proposed GA methodology. Section 5 presents and discusses the obtained results and Section 6 concludes the paper.

2 Problem Formulation

The objective function to be minimized is the system's cost of energy (*COE*):

$$COE = \frac{C_{tot,ann}}{E_{tot,ann,served}} \tag{1}$$

where $C_{tot,ann}$ is the total annualized cost and $E_{tot,ann,served}$ is the total annual useful electric energy production. $C_{tot,ann}$ takes into account the annualised capital costs, the annualised replacement costs, the annual operation and maintenance (O&M) costs, the annual fuel costs (if applicable) of system's components.

The constraints that have been taken into consideration in this paper are:

1. Initial cost constraint: The available budget (total initial cost at the beginning of system's lifetime) is limited to $IC_{\max}$.

2. Unmet load constraint: The annual unmet load (which was not served due to insufficient generation), expressed as a percentage of the total annual electrical load, cannot exceed a fixed value $f_{UL\max}$.

3. Capacity shortage constraint: The annual capacity shortage fraction, which is the total annual capacity shortage divided by the total annual electric energy demand, cannot exceed a fixed value $f_{CS\max}$.

4. Fuel availability constraints: The maximum amount of each fuel that is consumed throughout a year cannot exceed a specific limit $FC_{gen\max,ann}$.

5. Minimum renewable fraction constraint: The portion of system's total energy production originating from RES technologies must be greater than or equal a specified minimum limit $f_{RES\min}$.

6. System component size range: The sizes of each system's component must lie between zero and $size_{comp\max}$.

3 System Modeling

The considered SAHPS has to serve electrical load, and it can contain the following component types: WTs, PVs, diesel generator, biodiesel generator, fuel cells, batteries and converters. Renewable power sources (WTs and PVs) have a priority in supplying the electric load. If they are not capable to fully serve the load, the remaining electric load has to be supplied by generators and/or the batteries. An additional aspect of system operation is whether (and how) the generators should charge the battery bank. Two common control strategies that can be used are load following (LF) strategy and cycle charging (CC) strategy [10].

In the LF strategy, the operating point of each generator is set to match the instantaneous required load. In the CC strategy, whenever a 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 generators will not stop until it reaches the specified SOC_a. In this paper, three values of SOC_a are considered: 80%, 90% and 100%.

4 Genetic Algorithm Implementation for SAHPS Optimal Sizing

Genetic algorithms mimic natural evolutionary principles to constitute search and optimization procedures, and can be classified in two categories:

1. Binary GAs: They borrow their working principle directly from natural genetics, as the variables are represented by bits of zeros and ones. Binary GAs are preferred when the problem consists of discrete variables.
2. Continuous GAs: Although they present the same working principle with binary GAs, the variables here are represented by floating-point numbers over whatever range is deemed appropriate. Continuous GAs are ideally suited to handle problems with a continuous search space.

The considered sizes of each component can take only discrete values, so the binary GA is selected. Two alternative GA coding schemes are examined: conventional binary coding and Gray coding. In the proposed GA, each chromosome consists of 8 genes, of which the first 7 genes represent the SAHPS component sizes (WT, PV, diesel generator, biodiesel generator, fuel cell, batteries and converters), while the eighth gene refers to adopted dispatch strategy. For the constraint handling, the penalty function approach is adopted, in which an exterior penalty term that penalizes infeasible solutions is used. Since different constraints may take different orders of magnitude, prior to the calculation of the overall penalty function all constraints are normalized.

The proposed GA offers the following significant advantages compared to other GA solutions of SAHPS sizing problem:

1. Additional aspects of GA performance are examined, e.g., coding schemes.
2. In comparison with GA methodologies of [6] and [7], the proposed GA is used for complex SAHPS that include a large number of conventional as well as renewable technologies.

3. The proposed GA considers the choice of the proper dispatch strategy as a decision variable.

4. Compared to [8], the proposed GA presents the advantage of simplicity, as the choice of optimal sizing and dispatch strategy is implemented in the same GA run.

5 Results and Discussion

5.1 Case Study System

In the considered SAHPS, the project lifetime is assumed to be 25 years and the discount rate has been taken equal to 8%. The maximum annual value of electric load has been set to 50 kW, the time step of the simulation has considered equal to 10 min (1/6 h), while the wind, solar and temperature 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 assumed equal to the capital cost. Moreover, with the exception of diesel and biodiesel generators, all components have constant increment of their size, as Table 1 shows. The considered sizes for the generators are 0, 3, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, and 50 kW. The dispatch strategy (LF or CC) represents also an optimization variable, as each component configuration has to be checked for both strategies. Table 2 presents the constraint values for the case study system.

Table 1. SAHPS component characteristics

Component	$size_{comp\max}$	Increment	Capital cost	O&M cost	Fuel cost	Lifetime
WTs (10kW rated)	10 WT	1 WT	15,000 €/WT	300 €/y	-	20 y
PVs	60 kW$_p$	1 kW$_p$	5,000 €/kW$_p$	0	-	25 y
Diesel generator	50 kW	Variable	200 €/kW	0.01 €/h per kW	1.0 €/L (diesel)	20,000 oper. hours
Biodiesel generator	50 kW	Variable	200 €/kW	0.01 €/h per kW	1.4 €/L (biodiesel)	20,000 oper. hours
Fuel Cells	40 kW	4 kW	2,000 €/kW	0.02 €/h per kW	0.8 €/L (methanol)	40,000 oper. hours
Batteries (625Ah, 12V)	150 bat.	10 bat.	700 €/bat.	0	-	9,000 kWh
Converter	60 kW	2 kW	1,000 €/kW	0	-	10 y

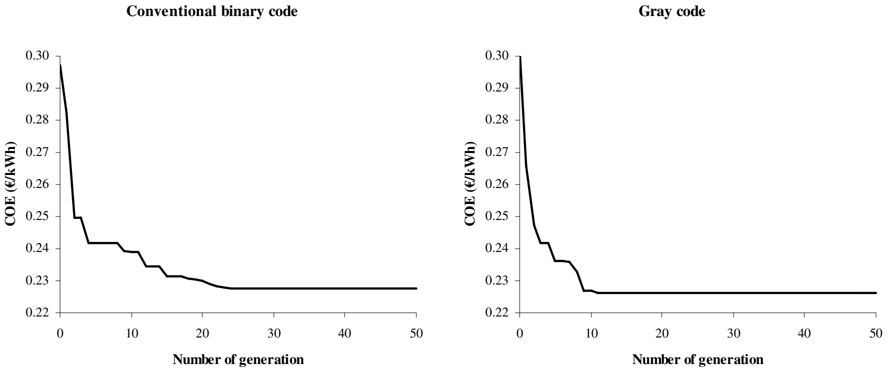
Table 2. Constraint values for the case study system

Constraint	Parameter	Value
Initial cost	$IC_{\max}$	300,000 €
Unmet load	$f_{UL\max}$	0.5%
Capacity shortage	$f_{CS\max}$	1.0%
Fuel availability (diesel)	$FC_{gen\max,ann}$	No constraint
Fuel availability (biodiesel)	$FC_{gen\max,ann}$	10,000 L/y
Fuel availability (methanol)	$FC_{gen\max,ann}$	10,000 L/y
Renewable fraction	$f_{RES\min}$	50%

For the SAHPS sizing problem of Table 1, the complete enumeration method requires:

$$\underbrace{11}_{\text{WTs}}\cdot\underbrace{61}_{\text{PVs}}\cdot\underbrace{12}_{\text{Dsl}}\cdot\underbrace{12}_{\text{Bio}}\cdot\underbrace{11}_{\text{FCs}}\cdot\underbrace{16}_{\text{Bat.}}\cdot\underbrace{31}_{\text{Conv.}}\cdot\underbrace{4}_{\text{Disp.}}\approx 2.1\cdot 10^{9} \qquad (2)$$

evaluations in order to find the optimal COE. The computational time for each COE evaluation is 3.5 seconds. Consequently, the evaluations of the complete enumeration method require approximately 234 years.



(a) (b)

Fig. 1. Effect of coding type in GA convergence (N_{pop}=50, gn=50, tournament selection, uniform crossover, 0.01 mutation rate): (a) binary code, (b) Gray code

5.2 Results

The optimum configuration parameters of the proposed GA are: population size N_{pop}=50, number of generations gn=15, Gray coding, tournament selection, uniform crossover, and 0.01 mutation rate. Fig. 1 shows the superiority of Gray coding compared to conventional binary coding, in terms of solution quality and convergence speed. The optimal configuration contains 9 WTs, diesel generator of 25 kW, biodiesel generator of 5 kW, 100 batteries, converter of 38 kW, and LF dispatch strategy, and the COE is 0.22635 €/kWh. The total number of performed objective function (COE) evaluations was 800.

6 Conclusions

This paper proposes the application of a binary genetic algorithm in the problem of optimal sizing of a small autonomous hybrid power system. The main advantage of the proposed methodology is that the calculation time was very short compared to the prohibitive time required using the complete enumeration method. The obtained system with the minimum cost of energy contains large capacities of wind turbines, batteries and diesel generator, negligible sizes of photovoltaics, fuel cells and biodiesel generator, while it uses load following as dispatch strategy.

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