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A Multi-Objective Genetic Algorithm methodology for sizing and power electronics selection of standalone renewable energy systems

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ABSTRACT

This work proposes a design methodology to optimize multiple design metrics of a stand-alone PV/battery system at the same time. The relevance of each objective can be adjusted by the designer and this paper explores the correlations among them. An application example is proposed, where the objectives are the minimization of investment and operational cost, with a boundary set on the system reliability. The variables are six and represent the size of the generation, storage, and power conversion elements, as well as the converters selection. The example design is repeated with two battery types, Lead-Acid and Li-Ion. The use of a genetic algorithm reduces the computational power, allowing the quick execution of several optimizations with different settings.

INTRODUCTION

The switch to renewable energy is nowadays a reality with a bright future, but the increasing penetration of volatile energy sources risks compromising the reliability of national grids. Extensive research is being carried out to address this concern, exploring possibilities such as smart grids [1], energy storage technologies [2], energy management [3], and distributed energy systems [4]. Much of the research in the latter area revolves around using automated methods for either system-level [5,6,7,8] or component-level optimizations [9,10], which are usually treated separately, with simplifying assumptions. Such assumptions are also adopted by existing and widespread design software, like HOMER [11,12,13], which make inaccessible their component specifications [14,15].

This paper attempts to make a step in exploring how these two design aspects affect each other while applying the findings of [16]. The dependency studied here is mono-directional (converters selection is based on system architecture, and not vice-versa), but an iterative approach will be adopted in future work.

PROBLEM FORMULATION AND METHODOLOGY

Figure 1: Schematic of the energy system.

As shown in Fig. 1, the system architecture that this design method analyzes is composed by a photovoltaic element and a battery pack, each connected to a control system via an array of DC-DC converters. The size of PV and battery elements are the independent variables of the study. The sizing and selection of the converters arrays are carried out based on independent variables. In evolutionary terms, each design solution can be represented by a combination of 6 variables: 1) number of PV units (u_{PV}); 2) number of battery units (u_{bat}); 3) converter model for Array 1 ($type_{arr1}$); 4) converter model for Array 2 ($type_{arr2}$); 5) number of converters in Array 1 (u_{arr1}); 6) number of converters in Array 2 (u_{arr2}). The “quality” of the i -th combination is evaluated with the fitness function in eq. (1), which must be minimized:

$$F_i(u_{PV,i}, u_{bat,i}, type_{arr1,i}, type_{arr2,i}, u_{arr1,i}, u_{arr2,i}) = \frac{W_1 C_{a,inv,i} + W_2 C_{a,op,i}}{W_1 + W_2}, \quad (1)$$

where W_1 and W_2 are the weights given to each objective, $C_{a,inv,i}$ and $C_{a,op,i}$ are the investment and operational costs of the i -th combination, annualized [17] to the current year.

A solution to this problem is found using the Genetic Algorithm represented in Fig. 2: the GA is initialized by randomly creating n_{ind} different combinations of the two independent variables (u_{PV} and u_{bat}). Then,

the converters that are compatible with these are selected from a database of commercially available DC-DC converters. The compatibility is verified if the following conditions are satisfied:

$$V_{out,conv} = V_{bus} ; V_{in,conv,max} \leq V_{max,sys} , \quad (2); (3)$$

where $V_{out,conv}$ is the output voltage of the converter, V_{bus} is the bus voltage, $V_{in,conv,max}$ is the maximum input voltage the converter can handle, $V_{max,sys}$ is the maximum output voltage of the part considered. Among the converters selected this way, one is randomly assigned to each “individual” ($type_{arr1,i}$ and $type_{arr2,i}$). Finally, u_{arr1} and u_{arr2} are estimated as a ratio between the maximum output power of an element ($W_{out,max,PV}$) and the power rate of a converter unit ($W_{n,conv}$):

$$u_{arr1} = \left\lceil \frac{W_{out,max,PV}}{W_{n,conv}} \right\rceil. \quad (4)$$

Once the 6 “genes” are available for all the individuals of the first generation, a typical year is simulated as described in the next section, and their fitness F_i is calculated using (3). The n_{par} individuals with the lowest F_i survive to the next generation and are bred to produce “offspring” with mixed characteristics, which will become part of the next generation, together with n_{mut} random “mutations”, generated to avoid local minimum traps. This iteration cycle continues until the relative improvement (the percentual difference between the fittest individuals of consecutive generations) becomes smaller than the threshold TH for n consecutive times (TH and n are set by the designer). This method provides rapid convergence even in non-linear scenarios.

Figure 2: Flowchart of Multi-Objective Genetic Algorithm.

EXAMPLE OF APPLICATION

A case study is simulated to demonstrate the applicability of the proposed methodology. In this scenario, the load is represented by a stand-alone LTE base station (BS) in the council of Norcia, an isolated town in central Italy, where mobile internet connection is often very slow, if not absent. The power consumption of such base station (P_{BS}) is modeled as an adaptation of the formula proposed in [18]:

$$P_{BS} = \begin{cases} N_{TRX}(P_0 + \Delta P_{out}), & 5 < \%_{users} < 100 \\ N_{TRX}P_{idle}, & \%_{users} \leq 5 \end{cases} \quad (1)$$

The number of users is represented as a sinusoidal function of day and time, as suggested in [19]. When the percentage of users is under 5%, the idle mode is triggered to reduce the power consumption. A boundary condition discards the solutions providing less than a certain service availability (quote of users successfully served). The power generator is assumed to be working at its MPP for 95% of the active time. This allows to simplify the 5 parameters model [20] and calculate the MPP voltage and current at any irradiation and temperature conditions with (10) and (11) of [21]. Cell temperature is calculated as suggested in [22], with the irradiation (G) and ambient temperature (T_a) data provided by [23], and the technical data of the panel by its datasheet [24]. The energy stored in the battery pack at any time, $E_{batt}(t)$, is tracked using (2) [25]:

$$E_{batt}(t + 1) = E_{batt}(t) + \eta_{batt}[P_{PV}(t) - P_{BS}(t)]\Delta t. \quad (2)$$

Two battery types are compared: a lead-acid [26] and a lithium-ion battery pack [27]. The lifetime of the cells is estimated as a function of DoD and T by applying, respectively, the models in [28] and [29].

Figure 3: GA representation with Lead-Acid: $W_1 = W_2 = 1$, $TH = 0.00001$, $n = 4$, $n_{ind} = 25$, $n_{par} = 6$, $n_{mut} = 4$.

RESULTS

Six optimizations were carried out using different weights W_i and two battery types to highlight their effect on the system design. The results are displayed in Table 1: focusing on the reduction of investment cost ($W_1 = 1000$) produces an under-sized system, with a service availability near the lower boundary of 98%. This has a negative impact on the overall cost because the operational cost soars; on the other hand, focusing on the operational cost produces the best availability results, showing how these two parameters are related. Fig. 3 shows the convergence of generations toward the minimum of the fitness function. The impact of converters selection can be noticed as some points fall on the same horizontal coordinates but have a different fitness value.

		<i>PV panels</i>	<i>Battery Capacity [kWh]</i>	<i>Ann. Inv. Cost [€/y]</i>	<i>Ann. Op. Cost [€/y]</i>	<i>Service Availability [%]</i>	<i>u_{arr1} - type_{arr1}</i>	<i>u_{arr2} - type_{arr2}</i>
$W_1 = 1000$ $W_2 = 1$	Lead	3	0.432	516.41	800.28	98.26	3 - 12	2 - 10
	Li-Ion	2	0.423	544.00	1,139.96	98.07	2 - 10	2 - 10
$W_1 = 1$ $W_2 = 1000$	Lead	6	1,320	1,244.67	266.98	99.94	6 - 12	5 - 10
	Li-Ion	2	1.039	824.71	124.26	99.49	2 - 12	4 - 10
$W_1 = 1$ $W_2 = 1$	Lead	3	0.768	693.00	400.88	99.01	3 - 12	3 - 10
	Li-Ion	1	1.039	746.79	127.79	99.22	1 - 12	4 - 10

Table 1: Results of optimization for Lead and Li-Ion batteries, with various weights.

CONCLUSIONS

In the present work, a methodology was proposed to design a stand-alone energy system with optimized investment and operational cost. The resulting design is a combination of six variables, plus the battery type, that is manipulated manually. The methodology was applied to a case study to show that it is easily adapted and produces realistic results. Furthermore, weights on the objective function have shown to work as expected, improving one or another criterion consistently with the designer's preferences. Unlike other computer tools, the proposed methodology allows a high level of customization, so that it can be adapted to several scenarios, new technologies, and design preferences.

In the final submission, more information, both quantitative and qualitative, will be provided on the current research context, the methodology, the mathematical models, the economic parameters, and the results. The library of converters will be extended and the relation between system design and converters selection will be explored in more detail. Furthermore, the results provided by the Genetic Algorithm will be enhanced with the addition of a “surroundings exploration” technique.

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