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# Metaheuristic methods applied to the pumps and turbines configuration design of water pumped storage systems

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ABSTRACT

The increasing penetration of fluctuating Renewable Energy Sources (RES), particularly in small isolated power systems, is raising some problems in the operational management of the system. The simpler way to solve the problem is to perform RES curtailment, but this is not the right decision from an environmental point-of-view. In this context, the storage alternative is becoming more and more a cost-effective option. This paper presents an integrated techno-economic model, whose purpose is to come up with the optimal configuration of a Water Pumped Storage System (WPSS). The expected output is the WPSS design configuration, i.e. the pump number and size and turbine number and size, which leads to the maximum Net Present Value (NPV) of the investment project. To reach the proposed objective, the model uses meta-heuristic optimization techniques, namely Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), with a Unit Commitment and Economic Dispatch module (UC + ED) of the thermal-based electrical generation units, in order to calculate the system operational costs. The Terceira Island, Azores archipelago, Portugal, is the case study presented as an application of the developed model. PSO and GA converge to the same results, pointing to an optimal WPSS configuration of 2 pumps of 490 kW and 1 turbine of 500 kW, with a 263 k€ positive NPV, therefore showing the economic and technical feasibility of a WPSS, in this application.

## 1. Introduction

The growing penetration of renewable energy sources with high variability, like wind and photovoltaic (PV), may result in increased operational management difficulties for the system operator. This is particularly true for small and isolated systems, like the ones in islands, or even at household level, especially for PV systems [1].

One of the possibilities to cope with such issues is the use of storage systems. The current work describes a model used to find the optimal configuration of a storage solution, based on a water pumped storage system (WPSS). The main objective is to find the configuration in terms of pump number and size and turbine number and size, which leads to the maximum net present value (NPV) of the corresponding investment project. NPV was chosen because it is a commonly used economic index, which accurately measures the economic added value of the project. Nevertheless, other indicators could be used as well, like for instance, the discounted payback period, but we believe it would not change the main conclusions of our work.

In order to do so, the model uses meta-heuristic optimization algorithms applied to a techno-economic model [2] with a unit commitment and economic dispatch module (UC + ED) of the thermal-based electrical generation units, used to calculate the system operational costs.

The use of optimization computational methods to support the studies on the integration of renewable energy sources in electrical systems has been increasing over the past decade, as shown in the review papers [3–5]. In particular, methods like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), are widely used and have been reported to achieve good results, especially because they can be used to model complex problems, under multi-objective optimization contexts.

For instance, in [6], GA are used to optimize the design of a small hybrid power system, consisting of solar PV modules, backup micro-turbine and battery storage, in order to reduce the cost of the produced electricity (COE). GA method is used to calculate the PV model parameters, as well as to size the other system components that will lead to the optimum COE. The study also compares the results of the hybrid system with another system where the micro-turbine is replaced by a diesel generator, concluding that using the micro-turbine leads to a more economical solution.

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In [7], a computational framework is presented to quantify and include the uncertainties of a distributed power system. These uncertainties are further incorporated in a stochastic security-constraint unit commitment model (SCUC). GA are applied to solve the problem and a comparison between the results obtained with the developed GA method against several benchmarks concludes that the results obtained are among the best of the reference literature.

Another study, [8], makes use of GA to minimize the levelized cost of energy (LCOE) of small renewable based integrated systems, considering several scenarios. These scenarios are defined upon the expected energy that is not supplied (EENS), i.e. a measure of the load that is not satisfied, and the optimization power factor (OPF), defined as the ratio between the deficit energy to total energy demand. A GA is built using as variables the characteristics of the generation systems, and determines, for the several scenarios, what are the optimum productions of each energy source.

PSO algorithms are also used to find the optimal design of hybrid renewable energy systems in multi-objective optimization problems, as it is the case in [9]. In this work, PSO has been applied to help the tool to design a system composed of wind turbines, PV panels, diesel generator, batteries, fuel cell, electrolyzer, and hydrogen tank. The approach combines the simulation of the energy system, which calculates the energy flow between all components (load, generation sources and storage), the CO2 emissions minimization and the loss of load probability (LLP). The PSO is used as a multi-objective optimization algorithm to find the system variables that will lead to the lowest total cost of the energy, considering as constraints the CO2 emissions level and LLP. The total cost is comprised of the investment and operation and maintenance costs. The results obtained with the proposed approach are compared to another method, the Strength Pareto Evolutionary Algorithm. It is concluded that the results obtained using the PSO lead to lower total costs. Further, the optimization model contributes to simplifying the approach to the problem.

In [10], a PSO algorithm is used to optimize the generated power from a hybrid power system in order to satisfy the load of a typical household. The objective is to minimize the LCOE of the power system. The hybrid power system is composed of a wind turbine, a PV module and a battery for storage purposes. It concludes that the PSO is a suitable tool for the optimization of such a kind of system costs.

A review of several optimization tools related to the integration of wind farms studies is done in [11]. In this paper, the performance of biology-based algorithms (e.g. GA), swarm-based (e.g. PSO), based on physical models (e.g. simulated annealing (SA)), and on heuristic rules/methods like tabu search. The paper concludes that, for the described application, consisting of finding the wind farm configuration that leads to the best integration of the renewable source into the electrical grid, the PSO shows a faster convergence and simpler implementation then the rest of the methods.

The present work's objective is to present a technical and economic model that is able to determine the optimal configuration of a WPSS, allowing for the maximum integration of electricity based on wind energy resources, in small and isolated power systems. The model is applied to the power system of the Terceira Island in the Azores, Portugal. Currently, due to the mismatch between the load diagram and the wind-based energy production, the technical restrictions of the thermal-based fuel-oil generator units and the spinning reserve needs determined by the system operator, the wind energy is being curtailed, therefore wasting the otherwise available renewable energy source. Using the WPSS it will be possible to store the excess wind-based energy in low demand periods and use it later during peak periods.

In the developed model, the benefits of using the WPSS are measured taking into consideration the cost reduction achieved by less operation of the thermal units. This benefit is calculated in terms of the Net Present Value (NPV) of the free cash flows resulting from the difference between the investment and operation and maintenance costs of the WPSS and the thermal units' fuel savings.

The work is innovative in the sense that it combines an integrated technical and economical approach, enhanced with thermal power stations Unit Commitment and Economic Dispatch (UC + ED) algorithms, with an optimization model. In order to verify the results and compare the performances, two different optimization models are used, PSO and GA.

These two optimization models were used, as they are well known, and usually present good convergence performance. As so, the major contribution of this study is to present an integrated optimized model, using meta-heuristics optimization methods, to determine the optimal configuration of a WPSS, the one that leads to the maximum NPV of the project.

The paper is divided into seven sections. The current section described the problem and the objectives and includes a literature review of similar works. Section 2 describes the techno-economic model. Section 3 describes the algorithm used to solve the UC + ED problem. Section 4 describes the objective function and the optimization models used, PSO and GA, and how these algorithms are structured. In section 5, the combined approach of the technical and economic model with each of the optimization methods is explained, as well as the calculation procedure sequence. The results and the respective discussion are presented in Section 6. Section 7 presents the conclusions and further work to be developed.

## 2. Techno-economic model

The techno-economic model used to estimate the operation costs of the system is based on an energy balance to the generation system combined with an economic model.

The energy balance model calculates the savings of the energy produced by thermal based fuel-oil generator units and its respective costs, taking into consideration the maximization of the wind-based power generation. The model can consider the use of WPSS or not. The inputs of the model are: the thermal power system, the renewable power system, and the WPSS characteristics, including the reservoir capacity; energy and investments costs. The electrical grid was not considered in our study. We recall that Terceira is a small isolated power system, in which the system operator (which is simultaneously the TSO and DSO) reports no congestion issues. We believe the consideration of the grid would have a negligible impact on the main outcomes of our work. The energy balance model outputs are then used to estimate savings and to calculate the Net Present Value (NPV) of the WPSS investment.

The model is described below, after the characterization of the Terceira Power Generation System.

### *2.1. Characterization of Terceira power generation system*

Terceira Island power generation system, as considered in this work, comprises one thermal power plant – Belo Jardim thermal power plant (CTBJ) – composed of six internal combustion engines, burning fuel-oil, driving electrical generators, with a total installed power of 47.6 MW, divided by 4 units of 5.9 MW and 2 units of 12 MW; a wind farm – Serra do Cume wind park (PESC) – with a total installed capacity of 12.6 MW divided by 14 units of 0.9 MW each; three small-hydro power plants, adding 1432 kW rated capacity, producing 3 GWh per year, with different head levels and independent of the WPSS under assessment; a geothermal power plant, rated at continuous operation of 3000 kW and a waste to energy power plant, rated at a continuous operation of 1700 kW.

This power generation system feeds load, with a peak of around 35MW. Geothermal and waste to energy power plants are run in a constant rated power operating mode. The voltage and frequency control is assigned to the thermal power plant, by decision of the system operator. The available data consists of the electricity demand; hydro and wind-based electricity production records, including wind speed