Contributions to the Design of a Water Pumped Storage System in an Isolated Power System with High Penetration of Wind Energy

Antonio Setas Lopes, Rui Castro, Carlos Silva

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A. Setas Lopes[1], Rui Castro[2] and Carlos Silva[3]

[1] IST, University of Lisbon, as.l@netcabo.pt, [2] INESC-ID/IST, University of Lisbon, rcastro@tecnico.ulisboa.pt, [3] IN+/IST, University of Lisbon, carlos.santos.silva@tecnico.ulisboa.pt

Abstract. The increasing penetration of renewable energies in the electrical systems, particularly in small and isolated systems, like the case studied in this paper, Terceira Island in Azores, Portugal, creates challenges in the dispatch related to the variability and the difficulty to forecast the renewable resources. One way to deal with such issues is to use Water Pumping Storage Systems (WPSS) to regulate the system electricity production by storing energy surplus in low load periods and returning it back in high load periods, reducing at the same time the need to curtail wind. This paper describes and compares a deterministic and a metaheuristic methodology, using Particle Swarm Optimization (PSO), used to determine the best configuration of the WPSS in terms of number and unit power of pumps and turbines, and upper and lower reservoir capacity that lead to the best economic value, determined by the Net Present Value (NPV) of the investment.

Keywords: Renewables integration, Water pumped storage systems (WPSS), Particle Swarm Optimization (PSO), Computational algorithms, Cyber-Physical Systems.

1   Introduction

The integration of renewable energies in the electrical systems has brought issues related with the variability of the primary sources, such as network instability, with possible negative impacts, namely in small and isolated systems.

Wind curtailment strategies combined with high reserve margin values for the thermal base generating units are the usual measures to cope with this issue. This has the consequence of increasing system costs, and wasting renewable resources. One way to deal with the problem is to use WPSS, designed to absorb excess energy in low load periods and later return it in peak periods, providing a balance to the system. However, it is necessary to verify the feasibility of such systems, as compared to the above mentioned solutions.

The models used to simulate the energy balance of such systems generate the need to develop tools that are able to deal with large amounts of data. There are several tools available as described in [1], where an extended list of energy system analysis tools is covered, for a wide range of applications, in terms of time scale and

application area; as well as several optimization methods described in [2], where a review on several studies approaching the use of optimization methods supporting the integration of renewables is done, concluding that this type of tools is becoming increasingly important.

The study presented in this paper intends to verify if the use of such optimization methods, namely Particle Swarm Optimization (PSO), to the design of a WPSS, leads to the same results for the configuration of the WPSS, with better performance in terms of computational times, than the deterministic model.

PSO was used, because there are several examples in the available literature showing that it presents good approximations of the correct results, the convergence is fast and the involved computational time is reasonable.

The decision to develop a dedicated algorithm for Terceira case, instead of using available tools, was based on the fact that none of the tools seems to cover, in an integrated way, the optimization of a WPSS, considering both the energy balance and investment analysis models.

All the algorithms were implemented using MATLAB language. MATLAB was chosen because it is a well-known language with a wide network of developers, providing a large set of toolboxes that can be used in this type of problems.

2   Benefits and Contribution from Cyber-Physical Systems

In this study several computational algorithms implemented in MATLAB language, using both deterministic and metaheuristics models were used to solve the problem of determining the configuration of a WPSS, leading to the best Net Present Value (NPV).

Using an integrated approach that includes the electrical system energy balance, the system design, and the economical analysis, leads to a complex problem that involves large amounts of data; the use of computational calculus is therefore mandatory.

Besides that, the use of metaheuristics methods, namely PSO, shows that with the support of computational optimization algorithms is possible to reach optimal results in solving complex problems, using less CPU time than the deterministic methods.

The research presented in this paper intends to be a contribution to the optimization of the electrical energy production in an islanded power system. This can be regarded also as a contribution to the development of the Smart Grid concept, in which renewable energies are expected to be fully integrated under the Smart Environment paradigm.

Given the nature and dimension of the problem, it would not be practical to build a real model, even at laboratory scale, where several WPSS configurations could be tested in order to find the one that leads to the best results. Nevertheless, it is the authors purpose to compare the results obtained using the presented model with the results of the real system, after its construction and commercial operation starts. Another issue that we would like to point out is that economic aspects are much relevant and have to be assessed. As so, a theoretical economic model seemed to be the best way to accomplish this task.

With the increasing complexity of Energy Systems (ES), Cyber-Physical Systems (CPS) will play an important role in the management of ES. As so, the development of simulation tools that are able to recreate the conditions found in the operation of ES is also of importance, as mentioned in [3].

We believe that a possible contribution of our work is to provide a simple simulation tool of the energy balance between load, generation and storage. Although the generation and storage is dealt in the model in an aggregated form, it would be possible to further refine it including unit commitment modules for optimum scheduling of the thermal units. Furthermore, the data supplied by this model could then be used to feed the models that deal with the dynamic behavior of the ES components.

3   State of the Art

Several papers on the utilization of computational optimization methods to find the best configurations of WPSS are available, in [4] the sizing of a WPSS is done with the support of Genetic Algorithms (GA), on the investor's perspective, by looking at the tariffs and applicable energy effects in the investment, and on the system perspective, by looking at the reduction of the Levelized Cost of Electricity (LCOE) and the increase of renewable energy sources penetration. [5] explores the application of a PSO approach to the design optimization of a pump storage system, combined with a photovoltaic system. In [6] the authors compare different approaches using several optimization methods, GA, PSO and Simulated Annealing, concluding that the suitable approach may depend on the type of application and user requirements, nevertheless, promoting the applicability of renewable energy systems (RES).

4   Research Contribution and Innovation

4.1   Energy Balance and Economic Models

Characterization of Terceira Power Generation System. This system, as planned for 2020, comprises the power plants of: Central Térmica de Belo Jardim (CTBJ), a thermal power plant using as prime movers internal combustion engines, with total installed power of 47.6 MW divided by 4 units of 5.9 MW each and 2 units of 12 MW each; Parque Eólico da Serra do Cume (PESC), a wind farm with 10 units, each of 0.900 MW, plus 4 equal additional units to be installed; 3 small-hydro adding to 1,432 MW; A geothermal power plant of 3 MW; A waste to energy power plant of 1,7 MW. The voltage and frequency control are assigned to the CTBJ power plant, by choice of the system operator.

The base data set consists of the electricity demand; hydro and wind based electricity production records, as well as wind speed, in periods of 30 minutes, for the

year of 2012, geothermal and waste to energy were considered to run continuously at power plant rated power.

The used methodology aims at determining, for each analyzed period of 30 minutes, the excess of electric energy available after the demand is supplied by the existing power plants, using as much as possible the electricity produced by wind energy conversion systems. This surplus energy is stored, subject to operational restrictions and limits of the electricity production and water storage systems. The stored energy in a WPSS is dispatched for each period, in order to minimize the thermal based electricity.

Calculation of Excess Energy Available For Storage. The excess energy Eeei, for each period i is calculated by:

$$Eee_i = (Ectbj_i + Eh_i + Epesc_i + Egth_i + Ewte_i - Eload_i)\eta_{pump} . \quad (1)$$

where: $Eload_i$, is the total demand for period i; $Ectbj_i$, is the thermal power production for period i; Eh_i, is the hydro power production for period i,; $Epesc_i$, is the wind power production for period i; $Egth_i$, is the total geothermal power production for period i, assumed equal to continuous rating; $Ewte_i$, is the total waste to energy power production for period i, assumed equal to continuous rating; η_{pump}, is the pumping efficiency.

Constraints and Limits. Constraints: Load satisfaction; Spinning Reserve; Technical operational minimum and maximum load of the thermal units; Feasible states of operation of the thermal power plant; Upper and lower reservoirs maximum capacity; Minimum number of consecutive operation periods for thermal units.

Limits: Pump efficiency and its minimum load; Turbine efficiency and its minimum load.

Load Satisfaction. As in any electrical power system, the load must be fulfilled independently of existing storage or not, and this is translated by:

$$Ectbj_i + Eh_i + Epesc_i + Egth_i + Ewte_i - Eee_{i-1}\eta_{turbine} = Eload_i . \quad (2)$$

Where, Eee_{i-1}, is the total excess energy stored up to the end of period i-1 and $\eta_{turbine}$, is the turbine efficiency.

Spinning Reserve. SR is provided by the thermal units plus the stored energy (turbine units), and is established by the power system operator as a function of the average wind speed at PESC.

Technical Operational Minimum and Maximum Load of Thermal Units. A minimum of two thermal units operating and at no less than 6 MW.

Feasible States of Operation of the Thermal Units. Determined by simple enumeration, considering that a minimum of two units has to be operating, running on

50% minimum load. Note that for the units with 5.9 MW rated power, the minimum power was set to 3 MW, in order to satisfy the operator's demand of 6 MW minimum.

Upper and Lower Reservoirs Maximum Capacity. The upper and lower reservoir maximum capacity was obtained by calculating the volume of water corresponding to the potential energy equal to the maximum excess energy available, for each 24 hour period, affected by the pump efficiency.

Minimum Number of Consecutive Operation Periods for Thermal Units. Established as a minimum of 2 hours of continuous operation for the same configuration of units, except where transition to a higher power state is needed in order to satisfy demand.

Pump and Turbine Operating Limits. For units 1-5 MW, based on existing references [7] efficiencies of 80%, for both the pump and turbine, were considered.

The considered minimum operating loads are 70% of nominal rated power for pumps and 15% for the Pelton turbines [8].

Economic Model. The economic assessment is based on an NPV model, for a 30 years period, of the cash flows resulting from the difference between the WPSS investment and operation costs and the savings obtained by not running the thermal units.

The WPSS investment costs are obtained by estimates of the civil works, including reservoir, electromechanical and engineering costs; based on the cost functions determined in [9] and cost breakdown explained in [10], as: Civil costs: 60% of total investment; Electromechanical costs: 33%; Engineering costs: 7%.

Electromechanical equipment costs were determined using the cost function for single Pelton units [9]:

$$Em_{cost1}=aP^{b-1}H^c, a=17.693, b=0.635275, c=-0.281735 . \qquad (3)$$

Adapted to multiple units using the cost formulas determined in [11], resulting in the following cost formulas:

Two units	$Em_{cost2}=a_2P^{b-1}H^c , a_2=27.070 .$	(3a)
Three units	$Em_{cost3}=a_3P^{b-1}H^c, a_3=35.209 .$	(3b)
Four units	$Em_{cost4}=a_4P^{b-1}H^c, a_4=42.109 .$	(3c)

Where: *Em_{cost}*, is the cost of the electromechanical equipment, in €/kW; P, is the rated power, in kW; H, is the net head in meters, in this case 300 meters.

The costs for the pump units, including the electrical drive, were estimated as equal to the turbine/generator groups.

Calculation Process: Excess energy, storage, wind curtailment and NPV, A flow chart describing the process is depicted in Figure 1

4.2   Optimization Approaches

For both approaches, the same models that simulate the energy balance and that make the investment economic analysis, are used.

Fast Deterministic method.   To reduce computational time, the applied method uses a stepped approach:

#1 considers combinations of one turbine and one pump, starting with 100 kW for each and increasing in steps of 100 kW, up to the maximum of 5000 kW; the combination leading to the best NPV is then identified. #2 a new range of values is defined, by adding and subtracting 1000 kW to the previous values of the best combination obtained; these values are then divided in 1 to 4 units each, for pump and turbine, and run again for NPV calculation with steps of 10 kW; #3 is similar to #2, but with steps of 1 kW and a tighter variation band for the range of power values, the combination with best NPV results is then chosen as the best one. With this approach is possible to reach to the pump and turbine combination values for the WPSS configuration, without the need of looking through all possible combinations, which would take too long time to be considered, for instance, considering that each iteration takes about 0.1 second, all the combinations of 4 pumps plus all the combination of 4 turbines, would take approximately 6.7e+20 days. In the stepped approach it took only 31697 seconds.
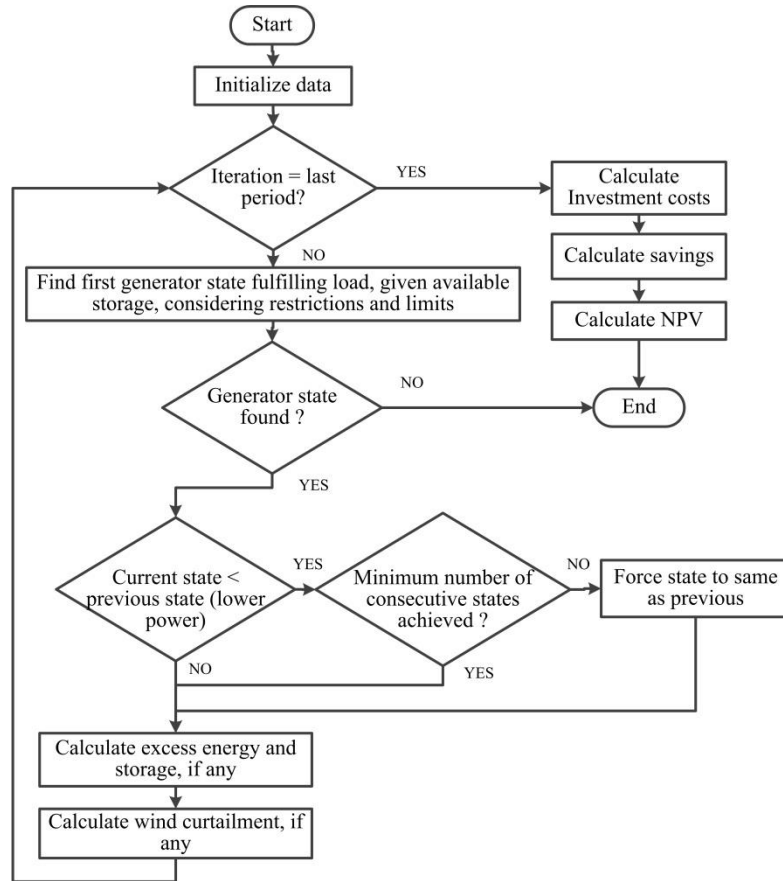
Fig. 1. Excess energy, storage, wind curtailment and NPV calculation

Particle Swarm Optimization method. The PSO method is a meta-heuristic optimization model initially developed by James Kennedy and Russell Eberhart [12].

The method used here results from several evolutions of the first method [13]–[15] and is based in the work of [16]. The method starts by randomly initializing a group of possible configuration of pump and turbines, the so called particle positions, however testing for limits in the number and unit power of each unit. For each particle position the corresponding best NPV is calculated and stored (called Local Best), the best NPV of all particles is also stored (called Global Best). Then the next particle position is calculated based on its previous position and its velocity. The velocity is calculated from the difference between its current position and the Local Best and Global Best. The procedure is: Initialize particle positions P_{ij} (pn_{ij}, pp_{ij}, tn_{ij}, tp_{ij}) and velocity v_{ij}; For each particle i position and current iteration j, calculate its NPV value and determine its Local Best (LB_i); For all particles determine the best NPV, which becomes the Global Best (GB); Update next iteration (j+1) particle position, by adding its updated velocity to its current position, according to following equations:

$$P_{ij+1}\left(pn_{ij+1}, pp_{ij+1}, tn_{ij+1}, tp_{ij+1}\right) = P_{ij}\left(pn_{ij}, pp_{ij}, tn_{ij}, tp_{ij}\right) + v_{ij+1} \tag{4}$$

$$v_{ij+1} = K(v_{ij+1} + \varphi_1 \text{rand}\left(Pbest_i - P_{ij}\left(pn_{ij}, pp_{ij}, tn_{ij}, tp_{ij}\right)\right)$$
$$+ \varphi_2 \text{rand}\left(Gbest - P_{ij}\left(pn_{ij}, pp_{ij}, tn_{ij}, tp_{ij}\right)\right)) \tag{5}$$

$$K = \frac{2}{\left|2 - \phi - \sqrt{\phi^2 - 4\phi}\right|} \tag{6}$$

With φ= φ1+ φ2. The values of φ1 and φ2 are chosen with basis on experience from several runs of the algorithm, as the ones that lead to convergence and best results. Several literature [13], [16], [17] advise the use of φ1=2.8; φ2=1.3; in any case, φ>4.

Pbesti, is the position of the particle that corresponds to the best result of all particles i, up to the current iteration, therefore corresponding to the value LBi,

Gbest, is the position of the particle that corresponds to the best result of all the particles, up to the current iteration, therefore corresponding to the value GB.
The stopping criteria is determined by a minimum number of consecutive iterations, where the position of a significant number of particle remains unchanged. In any case, the PSO stops at the maximum number of iterations.

5   Results and Discussion

With the Fast Deterministic method, values reached for the optimal configuration are: 2 pumps of 853 kW each and 1 turbine of 3843 kW; NPV:2,574,857 €; Computation time: 31,697 seconds.

With the PSO method, applied for several different combinations of parameters, each combination run 50 times, the results leading to the best NPV in each combination, are displayed in Table 1.

Table 1. PSO results

NPV (M€)	pn	pp (kW)	tn	tp (kW)	φ1	φ2	ptn	nmx	Stopping criteria	TCT (s)	ANI	f (%)
2574900	2	853	1	3843	2.3	1.8	20	3000	15 of 50	95,577	2564	22
2574900	2	853	1	3843	2.3	1.8	10	1000	8 of 20	16,105	818	8
2574900	2	853	1	3843	2.3	1.8	10	2000	8 of 50	24,183	1291	16
2574900	2	853	1	3843	2.3	1.8	15	2000	11 of 50	57,238	1512	8
2574900	2	853	1	3843	2.1	2.0	10	2000	8 of 50	23,607	1280	8
2574900	2	853	1	3843	2.1	2.0	15	2000	11 of 50	38,152	1363	11
2574900	2	853	1	3843	2.05	2.05	10	2000	8 of 50	12,519	250	10
2574900	2	853	1	3843	2.05	2.05	15	2000	11 of 50	25,069	501	6
2574900	2	853	1	3843	2.05	2.05	20	3000	15 of 50	31,973	640	10

The variables shown in Table 1 are NPV: Net Present Value; pn: number of pumps; pp: unit power of pumps; tn: number of turbines; tp: unit power of turbines; ptn: number of particles; nmx: maximum number of iterations for each PSO run; TCT: total calculation time for the 50 runs of the PSO; ANI: average number of iterations; f: frequency of occurrence of the best solution in 50 runs of the PSO; Stopping criteria is number of particles with unaltered position in the last number of iterations.

With the PSO method, the obtained results for the combination that leads to the best NPV, are the same as the ones obtained with the fast deterministic method, Furthermore, the best PSO result in terms of CPU time has a total CPU time of 12,519 seconds, which is less than half of the FD result. This shows a clear advantage for the PSO method.

Important to note that, although the frequencies of occurrence of the optimal solution are generally low, the sub-optimal solutions, not shown here, have NPV values close to the optimal NPV.

6   Conclusions

This study shows that metaheuristics methods can be used with good results to solve complex and large data problems in the field of renewable energy integration, namely in the study of economically feasibility of WPSS to support the integration of renewable energy sources.

The main advantage of using PSO is the reduction in computational time as compared to the fast deterministic approach. With PSO, it is possible to reach very good approximate results for the optimal WPSS configuration, in less than half of the computational time required for the fast deterministic approach. In fact, the results are the same, due to the precision used (1 kW for the pumps and turbines capacity)

Relaxing the number of iterations of the PSO method, as well as the number of particles, leads to higher dispersion of results, however resulting in faster total calculation times, as compared with the FD method.

Future work could be done in comparing other metaheuristic methods, like genetic algorithms, and compare its results with the findings of this work.

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