Comparison of Batteries and Pumping Hydro with PaTs as energy storage technologies for a micro-hybrid generation system: Multi-objective optimization through a MILP algorithm

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Abstract. Small-scale hybrid energy systems are often composed by different power production technologies and adopted in mini-grids. In this work, a Mixed Integer Linear Programming optimization algorithm has been developed to compute the optimal scheduling of a micro-grid constituted by Internal Combustion Generators (ICGs) and a Storage System that can be either a conventional battery storage system or a Pumping Hydro energy Storage (PHES) based on Pump-as-Turbines. The algorithm computes the optimal energy generation scheduling of the micro-grid, minimizing a multi-objective fitness function constituted by the total costs of the energy system and the total CO₂ and NO_x emissions. In particular, the emissions are modelled with varying trends depending on the ICG load and not with constant values, which represents a simplification that is often adopted but that can induce misleading results. Furthermore, the algorithm takes into account all the physical constraints related to the generators and the storage system, such as maximum and minimum power generation, ramp-up and ramp-down limits and minimum up and down-time. The two energy storage technologies are compared and results show that a management strategy based on this algorithm can reduce significantly the total emissions of the system.

1 Introduction

In a scenario where the effects of climate change are no longer negligible, human activities are responsible of global warming with consequences that will become soon irreversible. The energy sector, in particular the greenhouse gases emissions correlated with its activities, is one of the major contributors. A field of intervention to reduce greenhouse gases emissions is related to energy systems and hybrid renewable energy systems efficiency, which has to be necessarily improved. To this purpose, it is fundamental to investigate and develop optimization methods during the operating phase of complex energy systems and energy hubs [1]. When dealing with the management of such complex energy systems, the optimal unit commitment of generators is a fundamental aspect to consider [2]. Optimization techniques have thus to be adopted and they can be based on mathematical approaches like linear programming (LP) and mixed integer linear programming (MILP), or on heuristic methods like particle swarm optimization (PSO)

algorithm and genetic algorithms (GA). For instance, a MILP method has been applied to investigate the optimal operation of 14 hydro-thermal-nuclear plants in to reduce the peak power of the East China Power Grid [3]. Regarding heuristic methods, the authors of [4] implement a GA to solve generators unit commitment problems to minimize fuel and start-up costs of energy systems. In [5], PSO methods have been used to compute the optimal scheduling of hydro and thermal power plants minimizing an objective function that considers power plants operational costs. In this work, a MILP algorithm has been developed to compute the optimal unit commitment that minimizes the total costs and greenhouse gases emissions of a hybrid energy system composed by four Internal Combustion Generators (ICGs) and a storage system that can be constituted either by conventional batteries or a Pumping Hydro Energy Storage System (PHES). The MILP method has been chosen over other methodologies due the features that characterize optimal scheduling problems. They imply a complex search space characterized by the presence of local minima that

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complicate the use of heuristic algorithms. The novelty of this investigation work regards the use of greenhouse gases emissions trends of the ICG, which are usually considered as constant in literature also when ICGs are operating at partial load. Moreover, the algorithm has been tested on a case study where the machine used to simulate the PHES system is a Pump used as Turbine (PaT) [10]. It constitutes a promising technology that has still to be fully investigated and that can turn to be a feasible alternative to conventional batteries in many cases.

2 Case study

The algorithm has been tested on a theoretical case study that simulates an energy system constituted by four ICGs and a storage system, which have to satisfy the typical load demand of a micro-grid as reported in Fig. 1. The ICGs and the storage system characteristics are described in Sections 2.1 and 2.2. Since MILP algorithms compute the solution for a discretized time interval, simulations have been run considering a 24-hours span of time discretized every 15 minutes for a total of 96 time discretization steps. This choice has been indicated also in other research papers as a good trade-off between results accuracy and computational resources [6].

Fig. 1. Load profile

2.1 ICGs model

ICGs have modelled considering the features of the diesel-biodiesel fuelled engine described in [7] indicated in this work as ICG₂ and characterized by a pure fossil diesel fuel feed. Due to the lack of experimental data describing emission curves of ICGs and in order to test the algorithm with different technologies, the other ICGs have been assumed similar to ICG₁ with regard to their emission curves and sizes, but with a growing bio-diesel fraction into the fuel mixture. The parameters used to model the ICGs are thus related with: i) the electrical power that each ICG delivers during each time step, expressed by Equation 1; ii) power limitation outputs and operational limits; iii) pollutant emissions expressed by Equations 2 and 3. Table 1 summarizes these parameters. As it can be noticed, Equation 2 and 3 express the ICGs CO₂ and NO_x emissions through a semi quadratic function as a function of the coefficient D_f that is the bio-diesel fraction into the fuel mixture and E_l that

is the electrical load. In this case, a linear piece-wise approximation of non-linear functions has been considered as an effective method to overcome the MILP limitation as indicated in [8].

$$P_m = \frac{P_{el}}{\eta_{el}} \quad (1)$$

$$CO_2 = 0.7 + 2.7 \cdot E_l + 0.08 \cdot D_f + 0.005 \cdot E_l \cdot D_f + 2.2 \cdot 10^{-5} \cdot D_f^2 \quad (2)$$

$$NO_x = -0.25 + 181 \cdot E_l - 2.7 \cdot D_f - 2.9 \cdot E_l \cdot D_f + 0.0561 \cdot D_f^2 \quad (3)$$

Table 1. Parameters characterizing ICGs

ICGs models parameters	
P_{max} [kW] : Rated Power	F_c [€/kWh] : Fuel cost
P_{min} [kW] : Minimum output power	O_c [€/h] : Operating cost
P_{Rup} [kW/h] : Ramp-up power limit	Sup_c [€/start-up] : Start-up cost
P_{Down} [kW/h] : Ramp-down power limit	w_{CO_2} [€/ppm] : CO ₂ emissions cost
U_t [h] : minimum up-time	w_{NO_x} [€/ppm] : NO _x emissions cost
D_t [h] : minimum down-time	η_{el} : electrical efficiency

The piece-wise linearized functions that describe the CO₂ and NO_x emissions of ICGs are depicted in Fig. 2 and Fig. 3, while the ICGs efficiencies have been assumed as constant.

Fig. 2. ICGs CO₂ emission curves

Moreover, other parameters have been included in the ICGs model in order to realize a more complete algorithm able to simulate the effective energy-system behaviour. For instance, the ramp-up and -down power limits and the maximum and minimum up- and down-time are typical of large size ICGs and large size electrical power plants. In this case, they have been introduced to increase the algorithm complexity and to simulate some limitations that may occur during non-ordinary operations. In Table 3, Table 4 and Table 5 the ICGs characteristics and costs used in the simulation are listed. Also a cost for the emissions is supposed to take into account an incentive mechanism of renewable sources

Fig. 3. ICGs NO_x emission curves

Table 2. ICGs type and biodiesel fraction in the fuel mixture

Gen	Biodiesel fraction	LHV [MJ/kg]	P[kg/m ³]
ICG ₁	25%	41.3	832.5
ICG ₂	0%	42.6	827.7
ICG ₃	50%	40.1	847.2
ICG ₄	75%	38.8	859

Table 3. ICGs power limits and efficiency

Gen	P _{max} [kW]	P _{min} [kW]	η _{el}
ICG ₁	4	1.5	0.19
ICG ₂	3.7	1.2	0.19
ICG ₃	2.9	0.7	0.20
ICG ₄	2.5	0.5	0.21

Table 4. ICGs operational limits

Gen	P _{rup} [kW/h]	P _{down} [kW/h]	U _t [h]	D _t [h]
ICG ₁	1.2	2.4	1	0.75
ICG ₂	2	1.6	0.75	0.25
ICG ₃	2.9	2.9	0.5	1
ICG ₄	2.5	2.5	0.25	0.25

Table 5. ICGs costs

Gen	F _c [€/kWh]	O _c [€/h]	Sup _c [€/Sup]	wCO ₂ [€/ppm]	wNO _x [€/ppm]
ICG ₁	0.20	0.12	0.88	0.02	0.04
ICG ₂	0.16	0.08	0.76	0.02	0.04
ICG ₃	0.24	0.16	0.84	0.02	0.04
ICG ₄	0.28	0.20	0.80	0.02	0.04

2.2 PHES and battery models

The storage system is responsible to store the excess of the energy produced and to equilibrate the electrical energy supply. In this model, the energy storage is provided by two technologies that can be set alternatively. A PHES, which is usually more suitable for large size energy systems, and battery units that are usually utilized in small-scale energy systems. However, also in small-scale systems, a PHES equipped with reversible PaTs technology can constitute an alternative to conventional batteries. Table 6 and

Table 7 list the parameters used to model the PHES unit and the batteries.

Table 6: Modelling parameters of the PHES unit

PHES model parameters in turbine and pump mode	
P_{max}^{phes} [kW] : Maximum Power output	η_{el}^{phes} : electrical efficiency
P_{min}^{phes} [kW] : Minimum output power	O_c^{phes} [€/h] : Operating cost
P_{rup}^{phes} [kW/h] : Ramp-up power limit	Sup_c^{phes} [€/start-up] : Start-up cost
P_{down}^{phes} [kW/h] : Ramp-down power limit	V_{max} [m ³] : maximum water volume of the upper reservoir
U_t^{phes} [h] : minimum up-time	V_{min} [m ³] : minimum water volume of the upper reservoir
D_t^{phes} [h] : minimum down-time in	H [m] : water head that the machine can exploit

Table 7. Battery characteristics

Battery model parameters	
C_{max} [kWh] : Maximum capacity	O_{bc} [€/h] : Operating cost
DOD [%] : Depth of discharge	η_b [-] : Battery efficiency

In Table 8, the values used in this case study are reported. To model the PHES system a centrifugal pump Calpeda N32-125 A/A has been selected. Its performance in both pump and turbine mode are fully described in [9] and [10]. The operational limits of the PaT have been selected in order to operate it always at its Best Efficiency Point (BEP) both in pump and turbine mode.

Table 8. Parameters values used to model the PHES and the battery unit

PHES			
Parameter	Value	Parameter	Value
$P_{max,t}^{phes} [kW]$	1.3	$U_t^{phes} [h]$	0.25
$P_{max,p}^{phes} [kW]$	1.2	$D_t^{phes} [h]$	0.25
$P_{min,t}^{phes} [kW]$	0.6	$O_c^{phes} \left[\frac{c\epsilon}{h} \right]$	2
$P_{min,p}^{phes} [kW]$	0.5	$Sup_c^{phes} \left[\frac{c\epsilon}{Sup} \right]$	1
$\eta_{el}^{phes,t} [\%]$	68	$V_{max} [m^3]$	62
$\eta_{el}^{phes,p} [\%]$	71	$V_{min} [m^3]$	20
$P_{rup}^{phes} \left[\frac{kW}{h} \right]$	1.3	$H_t [m]$	22.8
$P_{down}^{phes} \left[\frac{kW}{h} \right]$	1.3	$H_p [m]$	20
Batteries			
Parameter	Value	Parameter	Value
$C_{max} [kWh]$	8.7	$Ob_c [c\epsilon/h]$	5
$DOD [\%]$	20	$\eta_b [-]$	0.97

3 MILP optimization algorithm

An optimization algorithm is constituted by three elements: i) the objective function ii) a set of optimization variables and iii) a set of constraints. The objective function is composed by optimization variables and its final value depends thus on the values assigned by the optimization algorithm to the optimization variables. The latter are subjected to constraints.

3.1 Objective function

The objective function of the problem is constituted by the sum the total costs of the system and the total greenhouse gases emissions expressed in terms of CO₂ and NO_x. It is thus a two-terms multi-objective function.

In order to be able to compare the two terms at a software level during the optimal solution computation, a weight factor must be assigned to the term related with the total greenhouse gases emissions to convert it into a cost. The weight factor has to be chosen such as the effects of the emissions terms are not considered either negligible or too relevant when compared to the other costs [11].

$$\min \left\{ \sum_{i=1}^N \left[\sum_j \left(F_c^j \cdot E_{ICG_j} + O_c^j \cdot Ut_{ICG_j} + Sup_c^j \cdot Nsup_{ICG_j} + Ob_c \cdot Ut_b + O_c^{phes} \cdot Ut_{phes} + Sup_c^{phes} \cdot Nsup_{phes} \right) + \sum_j (CO_2^j \cdot w_{CO_2} + NO_x^j \cdot w_{NO_x}) \right] \right\} \quad (4)$$

Where J represents the ICG number; $E_{ICG_j} [kWh]$ the energy delivered by the ICGj during the i -time step; $Nsup_{ICG_j}$ the number of start-ups of the ICGj; $Nsup_{phes}$ the number of start-ups of the PHES.

3.2 Optimization variables

The optimization variables determine the final value of the objective function and their value is computed by the algorithm to minimize the latter. In this case study, the optimization variables are the energy that each ICG and the storage system delivers or store per time step, the ICGs and storage system operating time and the ICGs and PHES start-ups number. Since the time period has been discretised in 96 time steps and the energy system is composed by 4 ICGs and a storage unit, the total number of optimization variables will thus depend on all those three elements.

3.3 Constraints

Constraints objective is to limit the values assigned by the algorithm to the optimization variables in order to simulate the real system operations. The constraints defined for this optimization problem are related with: the power that during each time step can be delivered to the load expressed; the maximum and minimum power delivered to the load by the ICGs in each time step; the ramp-up and the ramp-down power limits of the ICGs; the minimum ICGs up- and down-time, that is the minimum time interval where ICGs have to operate or have to remain turned off when they are turned on or shut down respectively; the state of charge (SOC) of the battery unit and the maximum and minimum energy that can be stored or delivered during each time step; the greenhouse gases emissions that are a function of the delivered power of each ICG; the maximum and minimum power delivered to the load or stored by the PHES in each time step; the ramp-up and the ramp-down power limits of the PHES; the minimum PHES up- and down-time.

4 Results and comments

Fig. 4 shows the optimization results in case conventional batteries are chosen as storage system. ICG₁ and ICG₂ provide the major contribution to the generator target with a minor contribution of ICG₃ and almost a null contribution of ICG₄. The algorithm relies

majorly on ICG_1 and ICG_2 because they are characterized by the highest rated power and they are thus the most suitable assets to satisfy the load requirements. Moreover, ICG s NO_x emissions curves are characterized by a decreasing trend when they operate at full power. Fig. 5 depicts the SOC of batteries and highlights two main functions. The battery unit works as a generator during high peak demand periods and it equilibrates ICG s generation in order to make them operate at higher load characterized by better performances. Moreover, batteries are recharged at the end of the day to return to the initial condition. The bar charts of Fig. 6 depicts the percentage distribution of the total ICG s costs.

Fig. 4. ICGs and battery generation trends

Fig. 5. Batteries State of Charge (SOC)

Fig. 6. Percentage stacked ICGs costs with batteries

Obviously, the highest cost share is related to fuel costs; however, it is also worth noticing the share of polluting gases costs, which can significantly affect simulation results. Fig. 7 shows the generation and storage trends of ICG s and PHES. Also in this case, the most exploited ICG s are ICG_1 and ICG_2 . However, with respect to the previous case, ICG_3 increases its operations. The PHES system is mainly exploited in turbine mode when there is a peak of power demand with only a small

contribution of the pump mode. Anyway, the charge-discharge trend is similar to the case when batteries are adopted as storage system as shown in Fig. 8, which depicts the trend of volume of stored water in the upper reservoir. With respect to the battery unit, it is assumed that the upper reservoir is recharged by natural water inflows during the day. Furthermore, the limitations imposed to the PHES system to operate the PaT at its BEP and the fact that the system is only composed by controllable generators, do not allow to fully exploit the pump functionality of the PHES system. Fig. 9 shows the total ICG s costs percentage distribution. Also in this case, the highest cost share is related to fuel costs and it is remarkable the greenhouse gases costs shares and thus their effects on simulation results. It is also interesting to notice how the use of a PaT instead of conventional batteries does not change significantly the simulation results in terms of both total costs and optimal scheduling. Furthermore, centrifugal pumps are machines widely spread on markets; they are characterized by a high reliability, lower investment, replacement and O&M costs than conventionally batteries and by a lower carbon footprint. Moreover, the recent progress achieved by researchers that demonstrate their potential when working in reverse mode, make PaTs a promising and feasible alternative to be adopted in mini- and micro-grid development when natural upper reservoir are already present.

Fig. 7. ICGs and PHES generation trends

Fig. 8. Upper reservoir variation trend

Indeed, results change if investment C_{in} and replacement costs C_r of batteries [12] and PaTs [13] are introduced in the analysis. Table 9 shows these costs considering a system lifetime of 20 years and a battery replacement every four years. In this case, PaTs result to be not only a cleaner but also a cheaper technology.

Fig. 9: Percentage stacked ICGs costs with PHES

Table 9: Investment and replacement costs of batteries and PaTs

Battery	C_{in} [€/kWh]	1223
	C_r [€/kWh]	612
	Tot. [€]	13088
Pat	C_{in} [€]	10499
	C_r [€]	0
	Tot. [€]	10499

5 Conclusions

An optimization algorithm based on a MILP method has been developed to compute the optimal scheduling of a energy system that minimizes a multi-objective fitness function constituted by the total costs of the system and the greenhouse gases emissions defined as CO₂ and NO_x. The energy system is constituted by four ICGs with two storage options: conventional battery storage, or PHES equipped with PaT technology. Results show that PaTs are a promising solution that can constitute an alternative to conventional battery storage in small-scale power systems. Moreover, results depict the importance to model properly greenhouse gases emissions curves, which can affect significantly the simulation results. In this case, storage systems play a key role to equilibrate ICGs energy production in order to make them operate in load ranges that minimize greenhouse gases emissions. Future development of this paper will consider the effects of variable ICGs efficiency curves at partial load to further demonstrate the importance of storage systems to equilibrate the energy production of the whole energy system to keep a high global system efficiency.

References

1. R. Siddaiah and R. P. Saini, "A review on planning, configurations, modeling and optimization techniques of hybrid renewable energy systems for off grid applications," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 376–396, 2016.
2. S. Y. Abujarad, M. W. Mustafa, and J. J.

- Jamian, "Recent approaches of unit commitment in the presence of intermittent renewable energy resources: A review," *Renew. Sustain. Energy Rev.*, vol. 70, no. October 2015, pp. 215–223, 2017.
3. Z. kai Feng, W. jing Niu, C. tian Cheng, and J. zhong Zhou, "Peak shaving operation of hydro-thermal-nuclear plants serving multiple power grids by linear programming," *Energy*, vol. 135, pp. 210–219, Sep. 2017.
4. G. V. S. Reddy, V. Ganesh, and C. S. Rao, "Implementation of Genetic Algorithm Based Additive and Divisive Clustering Techniques for Unit Commitment," in *Energy Procedia*, 2017, vol. 117, pp. 493–500.
5. B. Yu, X. Yuan, and J. Wang, "Short-term hydro-thermal scheduling using particle swarm optimization method," *Energy Convers. Manag.*, vol. 48, no. 7, pp. 1902–1908, Jul. 2007.
6. R. Lamedica, E. Santini, A. Ruvio, L. Palagi, and I. Rossetta, "A MILP methodology to optimize sizing of PV - Wind renewable energy systems," *Energy*, vol. 165, pp. 385–398, Dec. 2018.
7. C. Caligiuri, M. Renzi, M. Bietresato, and M. Baratieri, "Experimental investigation on the effects of bioethanol addition in diesel-biodiesel blends on emissions and performances of a micro-cogeneration system," *Energy Convers. Manag.*, vol. 185, no. January, pp. 55–65, 2019.
8. J. K. Brunner, "Piecewise linear optimization," *Computing*, vol. 25, no. 1, pp. 59–76, Mar. 1980.
9. J. C. Alberizzi, M. Renzi, A. Nigro, and M. Rossi, "Study of a Pump-as-Turbine (PaT) speed control for a Water Distribution Network (WDN) in South-Tyrol subjected to high variable water flow rates," in *Energy Procedia*, 2018, vol. 148, pp. 226–233.
10. J. C. Alberizzi, M. Renzi, M. Righetti, G. R. Pisaturo, and M. Rossi, "Speed and Pressure Controls of Pumps-as-Turbines Installed in Branch of Water-Distribution Network Subjected to Highly Variable Flow Rates," *Energies*, vol. 12, no. 24, p. 4738, Dec. 2019.
11. M. Renzi, J. C. Alberizzi, and C. Caligiuri, "A Mixed Integer Linear Programming Algorithm for the Optimal Management of Energy Systems Fuelled with Bio-Fuels," in *4th SEE SDEWES Conference Sarajevo*, 2020.
12. A. Kaabeche and R. Ibtouen, "Techno-economic optimization of hybrid photovoltaic/wind/diesel/battery generation in a stand-alone power system," *Sol. Energy*, vol. 103, pp. 171–182, May 2014.
13. M. Rossi, A. Nigro, G. R. Pisaturo, and M. Renzi, "Technical and economic analysis of Pumps-as-Turbines (PaTs) used in an Italian Water Distribution Network (WDN) for electrical energy production," in *Energy Procedia*, 2019, vol. 158, pp. 117–122.