Energy Conversion and Management 160 (2018) 341–353

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Meta-heuristic optimization for a high-detail smart management of complex energy systems

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A R T I C L E I N F O

Keywords:
Distributed generation
CHP
Trigeneration
Smart management
Fuel cells

A B S T R A C T

Distributed generation and, in particular, cogeneration and trigeneration are generally considered viable solutions to reduce energy consumption and mitigate the environmental impact of developed economies. Nonetheless, such systems need to be carefully designed and managed to effectively meet all the economic and environmental expectations. The design of a distributed generation plant and the choice of its proper management policy are complex tasks that require effective support methodologies and tools.

In this paper, we develop a methodology to determine the optimal control strategy for a trigeneration plant. The model enforces mass end energy balances and accounts for the nonlinear and the basic dynamic behavior of each energy converter, for the time varying energy prices and environmental conditions, for maintenance and cold start costs, and for the possibility to store energy. We built on a methodology previously developed and we dramatically broaden its field of application to complex smart grids with a very high temporal detail, by cutting down its computational costs. To this aim, we implement an heuristic procedure that reduces the computational complexity of the non linear optimization problem. The total cash flow, the primary energy consumption, the plant efficiency, and the CO_2 emissions, besides the instantaneous set-point of the plant, are among the most relevant results of the model.

The model is first validated through 11 test-cases specifically designed to stress the possible weaknesses of the heuristic procedure. The validation evidences that the proposed procedure does not introduce further approximations to the mathematical model. The global optimum is retrieved for all the considered cases. Afterwards, we apply the proposed methodology to a realistic energy management scenario: the assessment of a fuel cell based trigeneration plant for a civil building for a whole year. The discussion highlights the effectiveness of the proposed method for different applications including the optimization of the control strategy for existing plants, the design of new distributed generation systems, the assessment of innovative energy conversion technologies, and the evaluation of national energy policies.

1. Introduction

The curtailment of the energy consumption and of Green House Gas emissions (GHG) is among the most relevant issues on industrialized countries agenda [1,2].

In the last century, the worldwide Primary Energy Consumption (PEC) has constantly grown, reaching 13,700 Mtoe/year in 2015, more than 2.5 times the PEC of 1971 [3,4]. In the same time span, the CO_2 emissions rose from 15,500 Mton/year in 1973 to 32,300 Mton in 2015. PEC and GHG emissions of non-OECD economies have sharply increased in the last decades, overwhelming the efforts of OECD countries towards a less energy intensive development [3].

Despite the investment on energy efficiency have risen from more than 150 billion $ per year in 2007 [5] to more than 1.7 trillion $ per year in 2016 [6], a wider effort is required to meet the goal of keeping the global warming below 2 °C. According to the international energy agency (IEA) projections, following the actual energy policies the world will consume about 18,000 Mtoe emitting more than 36,000 Mt of carbon dioxide by 2014 [4]. However, by the same year, PEC should be lower than 15,000 Mtoe to limit the average temperature increase below 2 °C. The GHG situation is even more critical, since CO_2 emissions should not exceed 18,500 Mt/year [4], about a half compared to what expected given the actual trends.

Several technological alternatives might contribute to reduce energy consumption and GHG emissions including, among many other: (i) incrementing the renewable energy penetration [7–9]; (ii) improving the buildings efficiency [10,11]; (iii) decarbonizing the transport sector [12]; (iv) promoting distributed generation (DG) and cogeneration

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https://doi.org/10.1016/j.enconman.2018.01.035
Received 14 November 2017; Received in revised form 14 January 2018; Accepted 16 January 2018
0196-8904/

Nomenclature

CHCP	Combined Heat Cooling and Power
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COP_{HP}	Coefficient Of Performance of the heat pump
$\overline{COP}$	average coefficient of performance
C_f	fuel cost
C_m	maintenance cost
C_s	cold start ost
DG	Distributed Generation
E_{ch}	total cooling energy required throughout the year
E_{el}	total electrical energy required throughout the year
E_f	fuel energy
E_{grid}	electricity exchanged with the grid
E_{th}	total thermal energy required throughout the year
FC	Fuel Cell
GHG	Green House Gas Emissions
HoP	Heat over power ratio
LHV	Lower Heating Value
NG	Natural gas
N_{st}	number of possible set-points for the thermal storage
N_{sys}	number of subsystems of the plant
PEC	Primary Energy Consumption
PEF_f	Primary Energy Factor of the fuel
PEF_{grid}	Primary Energy Factor of the grid
P_{el}	electrical power
R	revenue/cost yielding from the electricity exchanged with the grid
UF	Utilization factor
$UF_{boi} = 0$	boiler utilization factor
UF_{FC}	fuel cell utilization factor
$c_{el,buy}$	unit cost of electricity acquired from the grid
$c_{el,local}$	unit cost of locally produced electricity
$\overline{c_{el,sell}}$	average unit price of electricity sold to the grid
$c_{el,sell}$	unit price of electricity sold to the grid
c_{fuel}	unit cost of the fuel
c_{gas}	unit cost of natural gas
c_{on}	cold start cost for a single equipment
h	time interval
i	index of the subsystem
$n_{\psi(i)}$	number of the elements of ψ
n_{sp}	number of discrete set-points considered for each equipment
p	number of nodes of the graph
q	number of arcs of the graph
$s(h)$	plant state
t	time
$\mathscr{I}$	capital investment
Θ	number of equivalent hours per year
η_{boi}	boiler efficiency
η_{eg}	efficiency of the electric generator
ψ	constraints array related to cold start costs and minimum stay constraints
$\sigma_{c_{el,sell}}$	standard deviation of $c_{el,sell}$
τ_{off}	minimum stay constraint relative to the off state
τ_{on}	minimum stay constraint relative to the on state

(CHP) or trigeneration (CHCP) [9,7,13–17]; (v) employing mechanical, electrical or thermal energy storage [18–24]; (vi) promoting hydrogen energy technologies and fuel cells (FC) [10,25–28]. All these measures require large investments, significant design efforts, or might need further technological developments before industrialization and commercial diffusion (e.g. high temperature FCs). A significant increment of the renewable penetration also arises concerns on the stability of the electricity distribution networks [29–32].

The optimization of existing and new power plants is also a viable option to reduce energy costs, PEC, and the GHG emissions [33–38]. In fact, the control strategy significantly impacts the real performance of any energy system [33,34,39–42], as the efficiency and emissions of all the machineries are functions of their set-point [17,41,43]. On the one hand, this means that even the most efficient energy system should be carefully managed to effectively meet all the design expectations [44]. On the other hand, updating the control strategy of existing plants could generate significant benefits with negligible capital investments [33–35,45,44]. Similarly, optimized management policies could boost the performance of advanced technologies facilitating their exploitation [10].

The design of a new power plant, rather than relying on rated efficiency, should leverage on the evaluation of the effective performance that is influenced by the time varying energy demand and costs, by the environmental conditions, and by the machinery derating and constraints [10,17,34,43,45,46]. Similarly, policy makers could simulate realistic energy management scenarios to determine the impact of each technology on national energy systems, or to assess the effectiveness of the energy policies in promoting energy efficiency and GHG reduction [39]. As a consequence, models and methodologies that a priori determine the optimal management policy of an energy conversion plant are fundamental tools towards energy efficiency and against global warming and fossil fuel depletion.

The control strategy optimization of a generic power plant is a complex non linear problem that requires a significant modeling and computational effort [34,44]. Nevertheless, linear approximations are often utilized to describe inherently non linear energy conversion processes [47–50]. Instead the Authors of [51–53] use non-linear programming, while others [46,54] leverage on mixed integer linear programming. Stochastic optimization algorithms are also adopted for energy system dispatch [55–57] or sizing and placement [58] optimization and Lagrange multipliers are adopted in [43]. Dynamic programming is also an effective methodology for energy system optimization [10,21,22,26,35,45,59] that allows to account for the inherent non-linearity of energy conversion processes [35], for the basic dynamic behavior of the machineries [35], and for the possibility to store mechanical and thermal energy [22].

In this paper, we build on the methodology introduced in [22,35] to broaden its field of application by reducing the computational complexity. The effectiveness of such a method was demonstrated in different cases ranging from the optimization of CHCP systems [35], and heat ventilation and air conditioning plants [60], to the optimal sizing of energy storage systems [22], and the assessment of the performance of innovative conversion technologies [10]. Specifically, we introduce an heuristic model that drastically scales down the dimension (i.e. the number of nodes and arcs) of the graph that represents the optimization problem. Such an heuristic reduces the number of nodes by 6 order of magnitude for a realistic test case with respect to the baseline methodology.

The paper is organized as follows. In Section 2 we thoroughly describe and validate the optimization methodology. In particular, in Section 2.1 we focus on the heuristic, and in Section 2.2 we validate it through 11 specifically designed test-cases. In Section 3 we apply the proposed method to a realistic energy management scenario: the optimization of a CHP plant based on PEM fuel cells that serves a small Hotel in an heating based climate. The power plant is optimized for 8760 h following both cost and PEC minimization. Sections 3.1 and 3.2 describe the CHP plant and the encompassing energy system, while Section 3.3 discusses the energy demand. The results of the optimization are presented in Section 3.4 highlighting several potential applications of the proposed methodology. Conclusions are drawn in Section