Energy Conversion and Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Parametric optimization of supercritical coal-fired power plants by MINLP and differential evolution

Ligang Wang [a,b], Yongping Yang [a,*], Changqing Dong [a], Tatiana Morosuk [b], George Tsatsaronis [b,*]

[a] School of Energy Power and Mechanical Engineering, North China Electric Power University, Beinong Road 2, Beijing 102206, China
[b] Institut für Energietechnik, Technische Universität Berlin, Marchstraße 18, Berlin 10587, Germany

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Parametric optimization
Multi-objective optimization
MINLP
Superstructure
Differential evolution
Coal-fired power plants

ABSTRACT

The design trade-offs between thermodynamics and economics of energy conversion systems can be more effective by combining a superstructure and mixed-integer non-linear programming (MINLP) techniques. The front of decision space showing the optimal sets of economic behavior and system efficiency with different corresponding optimal system structures and process variables can provide additional and useful information on cost-effective design of thermal systems. In this paper, this idea was successfully applied to supercritical coal-fired power plants to investigate the economically-optimal designs at each efficiency level. The superstructure involving up to ten feedwater preheaters, up to two reheatings and a secondary turbine with steam extractions (ET) was built. An improved differential evolution algorithm was used to simultaneously solve the parametric and structural optimization problem. The differences among the fronts of various types of plants, the front changes with plant efficiency and the effects of introducing an ET were discussed in detail. For a single reheating unit, a decrease of 2% in cost of electricity can be achieved. The optimal pressure ratios of reheatings are 0.15–0.25 (for single reheating), 0.2–0.3 and 0.15–0.3 (for double reheatings).

1. Introduction

The ever-increasing rate of fossil fuel depletion and the severity of environment damages underline the necessity of higher efficiencies of coal utilization [1–5] and of the development of new technologies for a sustainable energy future [6], in which pollutant issues are certainly involved with great concerns. However, current new technologies for reducing pollutants emissions from power generation and for energy conversion are regarded to be too risky or too expensive [7]. For example, industrial tests and techno-economic analysis of CO_2 capture in a coal-fired power station [8] show that the specific coal consumption for power supply reaches as high as 295 g/kW h with an increase of the electricity purchase price by 29%. Therefore, currently both the attention and the emphasis should be still directed toward a reliable alternative, i.e. further enhancing the thermodynamic performances of coal-fired power plants in cost-effective ways, which is almost an unrealistic task without the aid of certain optimization techniques.

With the exception of the commonly-used pure thermodynamic optimization and exergoeconomic optimization, mathematical optimization techniques of thermal systems, which are regarded to be more powerful, more robust and reasonably time-effective, have been the focus of significant attention recently due to the increasing computing power and the interesting developments of optimization algorithms [9–11] in the last few decades. Among these problems, the simultaneous optimization of both system structure and process parameters, which can be usually treated as mixed-integer nonlinear programming problems (MINLP), are most frequently discussed in a wide range of references, for example, [9,12,13].

There are mainly two alternatives for solving MINLP, derivative-based and stochastically heuristic approaches. A large number of advanced gradient-based solvers [11], such as LINGO, have been integrated into several modeling systems, e.g. general algebraic modeling system (GAMS), and widely applied to cost-effective designs or management of various thermal systems, e.g., combined-cycle-based co-generation plants [14,15], district heating networks [16], and energy planning problems [17]. However, the simplifications required to reduce the non-linearity and the possibility that the algorithm will find only local optimum, limit its applications to relatively simple problems. Additionally, considering the trade-offs between thermodynamic and economic objectives, the derivative-free stochastic searching algorithms, especially differential evolution (DE) [18–24], seems to be significantly better at exploring the decision space for the desired fronts and are more suitable in this case for solving large-scale non-convex problems

* Corresponding authors.
E-mail addresses: yyp@ncepu.edu.cn (Y. Yang), tsatsaronis@iet.tu-berlin.de (G. Tsatsaronis).

http://dx.doi.org/10.1016/j.enconman.2014.01.006
0196-8904/

Please cite this article in press as: Wang L et al. Parametric optimization of supercritical coal-fired power plants by MINLP and differential evolution. Energy Convers Manage (2014), http://dx.doi.org/10.1016/j.enconman.2014.01.006

Nomenclature

CC	capital cost
CELF	constant-escalation levelization factor
COE	cost of electricity
CP	condensate pump
CRF	capital recovery factor
DA	de-aerator
DE	differential evolution
EOD	economically-optimal design
ESAO	analysis and optimization of energy conversion systems
ET	a secondary turbine with steam extractions
FC	fuel cost
FP	feedwater pump
G	electric generator
H, Hi	feedwater preheaters
HARP	heaters above reheat point
HBRP	heaters below reheat point
LHV	lower heating value
MCP	mutation and crossover process in DE
MINLP	mixed-integer nonlinear programming
MODE	multi-objective differential evolution algorithm
MT	main turbine
OMC	operation and maintenace cost
OT	an ordinary turbine without steam extractions
PEC	purchased equipment cost
RP	random process in DE
SG	steam generator
TCI	total capital investment

Greek symbols

η_s	isentropic efficiency
ψ	system structure (layout)
$\triangle$	difference

Mathematical symbols

$\dot{Q}$	heat
$\dot{W}$	work
$\dot{m}$	mass flow rate
$\dot{W}_{net}$	net power output
$\mathbf{b}$	array of binary variables
$\mathbf{c}$	array of integer variables
ω	the average capacity factor
ρ	crossover factor
F_η	the efficiency related factor
F_M	the mass flow rate related factor
F_P	the pressure related factor
F_{SHRH}	the factor of reheating in cost function
F_T	the temperature related factor
i_{eff}	annual effective interest rate
r_n, r_{nf}	nominal escalation ratios for CC and FC
S_a, S_b, S_c, S_n	a solution in differential evolution
b	binary variable for the existence of component
c	integer variable for feedwater preheater number
h	enthalpy
N	the number of hours of plant operation each year
n	plant economic life
p	pressure
r	random number between 0 and 1
s	entropy
t	temperature

Subscripts

cw	cooling water
fw	feedwater
i	inlet
L	levelized value of cost
log	log temperature difference
o	outlet
p	pinch
r	reference
rh	reheated steam
s	steam
sh	superheated steam
ut, lt	the upper (lower) terminal difference

with flexible handling of continuous, binary and discrete integer variables.

To our best knowledge, this paper might be the first attempt to combine MINLP and multi-objective techniques for investigating the parametric and structural optimization of such a complex energy conversion system. In this paper, a superstructure considering up to ten feedwater preheaters, two reheatings and the existence of a secondary turbine with steam extractions was first built with the aid of a process simulation software, EBSILON Professional [25]. The ET is a key point of the designs of future 700 °C units [2] to avoid the overheat crisis of feedwater preheaters, which can be caused by high temperature steam extractions after reheatings. The cost functions expressing relations between the purchased equipment cost (PEC) and certain characteristic parameters were formulated with key coefficients adjusted from several open references. A software named ESAO, which integrates both an improved differential evolution and extended multi-objective algorithms, was then developed based on VB.NET and EbsOpen to manipulate the behavior of Ebsilon software and to find the decision-space fronts of the MINLP problem with both thermodynamic and economic objectives. The frontiers (not only the Pareto fronts) of the cases with both single and double reheatings were compared in relation with the effects of replacing the secondary turbine without steam extractions (OT) with an ET. The optimal positions and pressure ratios of single and double reheats were also given considering economic factors.

2. Modeling of the superstructure

2.1. Coal-fired power plants

For coal-fired power plants running in a stationary operation mode, the entire fuel is fed to the steam generator, where the feedwater from the preheating system and the cold reheat steams returned from the turbine are heated to the specified conditions. The main steam and the reheated steam then enter the turbines for generating shaft work. After the low-pressure (LP) turbine, the steam is condensed to saturated water in a condenser and is subsequently heated with pressure elevations by steam extractions from the main turbine or an additional turbine allowing steam extractions, as announced in [26]. Normally, three high-pressure feedwater preheaters, four low-pressure feedwater preheaters and one deaerator are configured as a conventional feedwater regenerative system as the schematic representation (Fig. 1) of current coal-fired power plants with a single reheat.