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Optimal economic strategy for the multiperiod design and long-term operation of natural gas combined cycle power plants

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HIGHLIGHTS

► Economic optimal power plants are determined by means of a multiperiod NLP model.
► Trends in the system behavior are identified.
► The original problem is reduced to a system of equations plus additional constraints.
► Accurate estimations of the optimal decision variables are efficiently obtained.

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ABSTRACT

Optimal power plant designs are achieved by means of a proposed multiperiod non-linear programming formulation that utilizes the net present value as objective function, while construction, operation and dismantling of the generation facility are accounted for. In addition, optimal operative characteristics are also established for each operative time period, in a way that the system constraints are always satisfied.

Based on the life cycle oriented economic optimal characteristics, a reduced model is proposed as strategy for simplifying the resolution of the rigorous multiperiod model. Trends in the system behavior are identified, enabling the reduction of the multiperiod formulation into a system of non-linear equations plus additional constraints, which allows easily computing accurate estimations of the optimal values of the design variables as well as the time-dependent operative variables.

1. Introduction

1.1. Economic decision-making regarding energy systems

Economic optimization becomes critical when designing a new energy system, in order to determine the optimal values of the project financial indicators. Different aspects of this problematic have been addressed in the literature (sensitivity analysis for fuel price [1], relation with thermodynamics [1,2], different market scenarios [3]), while converging toward a comprehensive framework which may be able to cope with the economic evaluation and optimization as a whole.

A life cycle oriented approach, which makes decisions based on economic indicators that refer to the whole life cycle of the generation system (which usually consists of several phases such as synthesis and design, construction, operation, and eventually disposal [4]), is critical under today's business conditions due to increased competition and market uncertainties, among others. Moreover, from the economic point of view, decisions made during the early stages of synthesis and design largely determine the economic performance of the plant across its entire life cycle.

A detailed model of the generation system requires NLP formulations, which resolution within a multiperiod time framework turns out to be rather challenging due to their inherent initialization and convergence difficulties. From the state of the art, it is observed that multiperiod design and long-term operation of energy generation systems are achieved through MILP models. In this regards, Iyer and Grossmann [5] formulated a MILP model for the operational planning of utility systems, which aims at determining the optimal schedule that meets the demand at the lowest total cost, while the system gets designed to handle a range of demands because of the uncertain nature of such parameter. Oliveira and Matos [6] presented an extension of the multiperiod models described by Iyer and

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Nomenclature

Acronyms

NGCC	natural gas combined cycle
GT	gas turbine
ST	steam turbine
HRSG	heat recovery steam generator
NLP	non-linear programming
MILP	mixed integer linear programming

Mathematical symbols

f	objective function
$\underline{x}$	set of model variables
$\hat{\underline{x}}$	set of model variables − estimated values
$\underline{x}^*$	set of model variables − optimal values
$\underline{x}_k$	subset of decision variables
$\underline{x}_d$	subset of design variables
$\underline{x}_{op,oi}$	subset of operative variables at operative period *oi*
$\underline{h}$	set of equality constraints
$\underline{g}$	set of inequality constraints
$\underline{R}_{j,ti}$	ratios at period *ti*
$\hat{\underline{R}}_{j,ti}$	ratios at period *ti* − estimated values
$\underline{R}^*_{j,ti}$	ratios at period *ti* − optimal values
$\alpha_{j,ti}$	*j*-th adjustment parameter at period *ti*
$\psi_{j,ti}$	*j*-th functional relationship at period *ti*
γ_{lj}	*l*-th parameter for j-th ratio correlation
γ_{1j}	parameter for *j*-th ratio linear correlation
γ_{2j}	parameter for *j*-th ratio linear correlation

Time periods

ti	set of time periods
pi	set of pre-operative time periods
oi	set of operative time periods
li	set of post-operative time periods
N_{oi}	number of operative periods

Economic variables

NPV	net present value
$C_{\mathrm{Inv,A}}$	investment cost on transfer area
$C_{\mathrm{Inv,PT}}$	investment cost on process turbines
IFC	investment on fix capital
IFC_{pi}	investment on fix capital at pre-operative period *pi*
$C_{\mathrm{Op},ti}$	total operative costs at period *ti*
$C_{\mathrm{RM},oi}$	raw materials and utilities costs at operative period *oi*
$C_{\mathrm{Mant},\ oi}$	maintenance costs at operative period *oi*
$C_{\mathrm{OS},oi}$	operative supplies costs at operative period *oi*
$C_{\mathrm{MP},ti}$	manpower costs at period *ti*
$C_{\mathrm{Tax},ti}$	taxes at period *ti*
$C_{\mathrm{GE},oi}$	general expenses at operative period *oi*
Dep_{oi}	depreciations at operative period *oi*
SVFC_{li}	salvage value of fix capital at post-operative period *li*
Sales_{oi}	energy sales at operative period *oi*
NIT_{oi}	net income taxes at operative period *oi*
COE_{oi}	cost of electricity at operative period *oi*

Model variables

$\eta_{T,oi}$	thermal efficiency at operative period *oi*
$\dot{W}_{0,\max}$	upper bound on the power demand
$\dot{W}_{\mathrm{Net},oi}$	net generated power at operative period *oi*
A_{Net}	net heat transfer area
$\dot{W}_{\mathrm{PT,D}}$	process turbines design (or nominal) generation capacity
$\dot{Q}_{\mathrm{F},oi}$	net heat consumption (as fuel) at operative period *oi*
$\dot{m}_{\mathrm{W},oi}$	process water consumption at operative period *oi*
$\dot{m}_{\mathrm{CW},oi}$	cooling water consumption at operative period *oi*

Grossmann [5] in order to include the concept of global emissions of the gaseous pollutants, turning the problem of synthesis and operational planning of the utility system into a multi-objective optimization from a superstructure of alternatives, where economic and environmental concerns are considered.

Later, Aguilar et al. [7,8] addressed the design optimization of flexible utility plants, while simultaneously considering different scenarios and equipment part-load operation in order to deal with energy prices that are driven by the equilibrium among supply and demand.

In all cases, it is observed that the economic optimization of complex energy systems usually turns out to be quite challenging, due to the large number of decision variables and constraints involved and the inherently non-linear nature of the problem (if the model considers a rigorous and detailed description of the plant characteristics).

While trying to cope with this complex task, Godoy et al. [9] introduced a design strategy which allows accurately estimating the economic optimal characteristics of combined cycle power plants, including the associated optimal values of its operative variables, for a wide range of power demands. The authors also took advantage of the characteristics of the families of optimal thermodynamic solutions for power plants [10], and an adequate manipulation of functional relationships among the optimal values of the decision variables. Such strategy is briefly summarized as follows:

- Economic optima are determined for two different power generating facilities, by means of a non-linear programming model where the total annual cost is selected as objective function. This approach allows observing the behavior of the design and operative variables when facing different market conditions as given by the costs ratio (i.e. the relative weight of the costs of investment on transfer area versus the operative costs due to fuel consumption).
- Thermodynamic optima of the combined cycles are determined as their thermal efficiency is maximized, by means of a non-linear programming model, for different values of the specific transfer area (i.e. the ratio between net heat transfer area and generated power).
- Based on the economic optimal solutions, a linear economic optimal relationship between the specific transfer area and the costs ratio is determined. Also, linear functional relationships between the optimal decision variables (including transfer areas of the HRSG sections, power production of each turbine, fuel consumption, steam mass flow rates, operative pressures and temperatures, etc.) and the specific transfer area are identified.
- A novel reduced model shaped as a system of non-linear equations plus additional constraints is structured when considering the previous items. This strategy allows obtaining accurate estimations of the economic optimal values of the power generating facility design and operative variables, while it enables the reduction of the space of feasible solutions and spares the need of solving the corresponding mathematical optimization problem (which is a difficult task due mainly to initialization and convergence issues).