Applied Energy 146 (2015) 453–470

Contents lists available at ScienceDirect

Applied Energy

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

Optimization of a network of compressors in parallel: Operational and maintenance planning – The air separation plant case

Georgios M. Kopanos [a,b,*], Dionysios P. Xenos [a], Matteo Cicciotti [c,d], Efstratios N. Pistikopoulos [a], Nina F. Thornhill [a]

[a] Imperial College London, Department of Chemical Engineering, Centre for Process Systems Engineering, London SW7 2AZ, UK
[b] Cranfield University, School of Energy, Environment & Agrifood, Bedfordshire MK43 0AL, UK
[c] Imperial College London, Department of Mechanical Engineering, London SW7 2AZ, UK
[d] BASF SE, Advanced Process Control, Automation Technology, 67056 Ludwigshafen, Germany

HIGHLIGHTS

- We study the detailed planning in networks of air compressors in air separation sites.
- Operational and several types of maintenance tasks for compressors are modeled.
- The power consumption in the compressors is expressed by regression functions.
- Our optimization framework can be directly used in a rolling horizon scheme.
- Our approach has been successfully applied to an industrial air separation plant.

ARTICLE INFO

Article history:
Received 18 July 2014
Received in revised form 20 January 2015
Accepted 21 January 2015
Available online 13 March 2015

Keywords:
Scheduling
Mixed integer programming
Rolling horizon
Compressors
Maintenance
Air separation

ABSTRACT

A general mathematical framework for the optimization of compressors operations in air separation plants that considers operating constraints for compressors, several types of maintenance policies and managerial aspects is presented. The proposed approach can be used in a rolling horizon scheme. The operating status, the power consumption, the startup and the shutdown costs for compressors, the compressor-to-header assignments as well as the outlet mass flow rates for compressed air and distillation products are optimized under full demand satisfaction. The power consumption in the compressors is expressed by regression functions that have been derived using technical and historical data. Several case studies of an industrial air separation plant are solved. The results demonstrate that the simultaneous optimization of maintenance and operational tasks of the compressors favor the generation of better solutions in terms of total costs.

1. Introduction

In most process industries, compressed air, which is provided by compressors, is an indispensable utility for the main production processes. In industrial environments, several compressors are connected *in series* or *in parallel*, depending on the purpose of the system into which they are integrated. These networks of compressors can involve a number of compressor units that may differ in type of drive and technical specifications (e.g., maximum load capacity, efficiency and operational range).

Indeed, compressors are among the most energy-intensive parts of most industrial environments [1,2]. For this reason, they are good targets for energy and cost savings. As Xenos et al. [3] showed, the energy consumption of a network of compressors can be improved by sharing the load among them in order to take into advantage the different characteristics of the compressor units.

This work deals with the simultaneous optimization of the maintenance and the operational tasks of the compressors. The proposed methodology is applied to an industrial compressor station that is serving with compressed air a typical air separation plant and an energy-intensive large chemical plant. The prior literature on compressors optimization is limited. A brief literature review on the subject follows.

For the transfer of fluids, such as natural gas or ethylene, through long pipelines, several compressors or sub-networks of

---

* Corresponding author at: Cranfield University, School of Energy, Environment & Agrifood, Bedfordshire MK43 0AL, UK. Tel.: +44 123 475 8316; fax: +44 123 475 8230.

E-mail address: g.kopanos@cranfield.ac.uk (G.M. Kopanos).

http://dx.doi.org/10.1016/j.apenergy.2015.01.080
0306-2619/

Nomenclature

Indices/sets

$e \in E$	distillation products (e.g., N_2 and O_2)
$i \in I$	compressors
$j \in J$	headers
$n \in N$	process plants
$t \in T$	time periods
$u \in U$	distillation columns
$z \in Z$	storage tanks

Subsets

I^{dm}	set of compressors that are subject to fixed maintenance
I^{fm}	set of compressors that are subject to flexible maintenance
$\tilde{I}_t^{dm}$	set of compressors that are under maintenance at the beginning of the current scheduling horizon (maintenance task started in the previous scheduling horizon)
I_j	set of compressors that could serve header j
J_i	set of headers that are connected to compressor i
J_n	set of headers that are connected to process plant n
J_u	set of headers that are connected to distillation column u
U_z	set of distillation columns that are connected to storage tank z
Z_e	set of storage tanks that can store product e

Superscripts

es	earliest
ls	latest
max	maximum
min	minimum

Parameters

α_j	coefficient for the load curve of header j
β_j	coefficient for the load curve of header j
$\gamma_{(e,u)}$	outlet mass flow rate of product e from distillation column u
$\delta_{(1\ldots3,i)}$	objective function coefficient factors for compressor i
ε_i	penalty cost for re-assigning header compressor i during its operation
$\zeta_{(e,t)}$	total demand for product e at the end of time period t
η_t	maximum number of simultaneous maintenance tasks in time period t
$\theta_{(n,t)}$	compressed air mass flow rate utility demand for process plant n during time period t
κ_t	conversion factor of mass flow to aggregated mass amount in time period t
λ_j	problem-specific large number that could represent the capacity of header j
μ_t	electricity price in time period t
ν_i	duration of flexible maintenance task in compressor $i \in I^{fm}$
$\xi_{(e,z)}$	storage capacity for product e in storage tank $z \in Z_e$
o_i	maximum on-line time after the startup of compressor i (maximum run time)
π_i	pressure ratio of compressor i
ρ_i	outlet compressed air mass flow rate from compressor i
σ_e	volumetric percentage of primary component of air e in the composition of air
τ_i	starting time for maintenance task in compressor i
$\upsilon_{(e,t)}$	cost for acquiring product e from external sources at the end of period t
ϕ_i	shutdown cost for compressor i
χ_i	startup cost for compressor i
ψ_i	minimum off-line time after the shutdown of compressor i (minimum shutdown time)
ω_i	minimum on-line time after the startup of compressor i (minimum run time)
$\tilde{\beta}_{(e,z)}$	initial inventory of product e in storage tank $z \in Z_e$
$\tilde{\eta}_{(i,t)}$	= 1, if compressor i is under pre-scheduled maintenance in time period t
$\tilde{\nu}_i$	total number of time periods that compressor i has been under maintenance (since the start of the maintenance task) at the end of the previous scheduling horizon
$\tilde{\varphi}_{(i,j)}$	active connection between compressor i and header j just before the beginning of the current scheduling horizon
$\tilde{\chi}_i$	operating status of compressor i just before the beginning of the current scheduling horizon
$\tilde{\psi}_i$	total number of time periods at the end of the past scheduling horizon that compressor i has been continuously off-line since its last shutdown
$\tilde{\omega}_i$	total number of time periods at the end of the past scheduling horizon that compressor i has been continuously on-line since its last startup

Continuous variables (non-negative)

$A_{(e,z,t)}$	amount of product e extracted from storage tank $z \in Z_e$ at the end of time period t
$B_{(e,z,t)}$	inventory level of product e in storage tank $z \in Z_e$ at the end of time period t
$C_{(e,u,t)}$	mass flow rate of product e from distillation column u in time period t
$L_{(e,u,z,t)}$	mass amount of product e from distillation column u that is sent to storage tank $z \in Z_e$ in time period t
$M_{(i,j,t)}$	compressed air mass flow rate from compressor i supplied to header $j \in J_i$ in time period t
$\bar{M}_{(i,j,t)}$	total compressed air mass flow rate supplied to header $j \in J_i$ that is served by compressor i in time period t (auxiliary variable)
$O_{(e,t)}$	amount of product e acquired from external sources at the end of time period t
$P_{(i,j,t)}$	outlet pressure of compressor i that serves header $j \in J_i$ in time period t

Binary variables

$D_{(i,t)}$	= 1, if compressor i changes header from time period $t-1$ to t
$F_{(i,t)}$	= 1, if compressor i shuts down at the beginning of time period t
$S_{(i,t)}$	= 1, if compressor i starts up at the beginning of time period t
$X_{(i,t)}$	= 1, if compressor i is operating during time period t
$Y_{(i,j,t)}$	= 1, if compressor i serves header $j \in J_i$ during time period t
$W_{(i,t)}$	= 1, if a flexible maintenance task starts in compressor i at the beginning of time period t