Computers and Chemical Engineering 88 (2016) 145–156

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Online performance tracking and load sharing optimization for parallel operation of gas compressors

Andrea Cortinovis[a,*], Mehmet Mercangöz[a], Matteo Zovadelli[b], Diego Pareschi[c], Antonio De Marco[d], Sergio Bittanti[d]

[a] ABB Corporate Research, Segelhofstrasse 1K, CH-5405 Baden-Dättwil, Switzerland
[b] Tecnimont Spa, Process Control and Automation, Via G. De Castillia 6/A, 20124 Milan, Italy
[c] ABB Spa, Process Automation, Oil, Gas and Petrochemicals, Via L. Lama 33, 20099 Sesto San Giovanni, Milano, Italy
[d] Politecnico di Milano, Dipartimento di Elettronica e Informazione, Via Ponzio, 34/5, 20133 Milano, Italy

ARTICLE INFO

Article history:
Received 13 July 2015
Received in revised form
17 December 2015
Accepted 19 January 2016
Available online 22 February 2016

Keywords:
Centrifugal compressor
Compressor load sharing
Performance monitoring
Process optimization
Natural gas transport

ABSTRACT

Compressor stations on natural gas pipelines are typically composed of multiple parallel compressors for operational flexibility. The aim of load sharing optimization is to operate the compressor units of a gas compression station in an energy efficient way while satisfying the varying gas demand. This paper presents a problem formulation for compressor load sharing optimization, as well as a novel method to track the performance characteristics of gas compressors using thermodynamic models and historical operating data. An implementation of the proposed algorithm together with a dedicated case study concerning a station with 10 gas turbine driven compressor units are presented. The optimization results, which are based on simulations with actual operating data spanning over a 1 year duration, indicate an annual fuel saving potential of over 5% potentially leading to improved profitability and to a significant reduction of CO_2 emissions from the gas turbine drivers.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

The recent development of compressor stations on natural gas pipelines has been characterized by upgrading compressor units with drivers that provide a wider operating range such as variable speed gas turbines and electrical variable frequency drives in order to satisfy the demand for more flexibility in the operation of the stations (Devold, 2006). In the older type of plants based on fixed-speed drivers, throughput or pressure control of the boosting stations was mainly performed by acting on the number of active compressors, while the fine regulation was achieved via throttling or recirculation of the compressed gas. With the introduction of variable speed drivers, the overall station efficiency can be improved by exploiting the possibility of acting separately on individual compressor speeds but since compressor stations contain multiple parallel units, realizing this potential requires the solution of an optimization problem, consisting of deciding on the number of active units and the speeds of the corresponding drivers. This is a complex problem, often referred to as compressor load sharing optimization.

Load sharing optimization can be considered as the equivalent of real-time optimization used in the process industries (Seborg et al., 2010) and in the context of compressor station operation it is an extension of what is generally referred to as load sharing control (Staroselsky and Mirsky, 1984). As illustrated in Fig. 1-1, the compressor station receives a general target from the dispatch center, typically in form of an hourly pressure or flow set point depending on the role of the station. This set point is then realized via a station performance control system by allocating a target to each individual compressor. In turn, the individual compressor performance control systems pursue their targets by adjusting the operating speeds. The load sharing control operates between the station and the individual machine performance controllers in order to distribute the load according to the operating limits of each machine by using approaches that keep equal load or an equal distance to the surge instability for all compressors. Load sharing optimization extends the task of load sharing control by considering the individual performance characteristics of each machine and by achieving a specific objective such as minimizing the overall energy consumption of all machines. In an extended arrangement, the load sharing optimization can automatically choose the compressors in operation depending on additional objectives such as minimizing start-up and shut-down operations or equalizing the total operating hours of the different compressors.

* Corresponding author.
E-mail address: andrea.cortinovis@ch.abb.com (A. Cortinovis).

http://dx.doi.org/10.1016/j.compchemeng.2016.01.012
0098-1354/© 2016 Elsevier Ltd. All rights reserved.

List of symbols

C_{SU}	startup cost [−]
C_{SD}	shut-down cost [−]
c_{pNG}	specific heat capacity [J/(kg K)]
D_i	efficiency coefficient matrix [−]
g	linear term in QP cost function [−]
H	Hessian matrix of QP problem [−]
$f(\vec{\alpha})$	nonlinear constraint on eigenvalues of D_i [−]
$\tilde{f}(\vec{\alpha})$	simplified constraint on eigenvalues of D_i [−]
$h(\vec{x}, \vec{z})$	nonlinear constraint of MINLP [−]
i	index [−]
j	index [−]
LHV	lower heat value [J/kg]
M	measurement matrix [−]
N_g	maximum length of global buffer [−]
N_l	length of local buffer [−]
N_a	number of active compressors [−]
n_{update}	number of updates [−]
P_{actual}	actual power [W]
p_d	discharge pressure [Pa]
p_s	suction pressure [Pa]
q_c	compressor flow [kg/s or m^3/s]
q_{rec}	recycle flow [kg/s or m^3/s]
q_{ST}	station flow [kg/s or m^3/s]
$q_{ST,SP}$	station flow set point [kg/s or m^3/s]
T_a	ambient temperature [°C]
T_d	discharge temperature [°C]
T_s	suction temperature [°C]
$t_{arr,i}$	arrival time in global buffer [samples]
W	diagonal weight matrix [−]
W_{iso}	isentropic work [J]
W_{actual}	actual work [J]
W_{fuel}	thermodynamic fuel work [J]
WH	working hours [h]
WD	working days [d]
ω_i	weight for sample i [−]
$\vec{x}$	real valued optimization variables [−]
$\vec{z}$	integer valued optimization variables [−]
$\vec{\alpha}$	isentropic efficiency map coefficients [−]
$\vec{\beta}$	gas turbine efficiency map coefficients [−]
$\vec{\gamma}$	total efficiency map coefficients [−]
a_j, b_j, c_j	constraint coefficients for compressor j [−]
Δq_j	user limit on compressor flow variation j [−]
$\Delta\omega_j$	set point corrections [−]
γ	specific heat ratio [−]
λ_i	eigenvalues of D_i [−]
Π	pressure ratio over compressor [−]
Π_{ST}	station pressure ratio [−]
$\bar{\Pi}_{UB}$	upper bound on constraint [−]
η_{iso}	measured isentropic compressor efficiency [−]
η_{gt}	measured gas turbine compressor efficiency [−]
η_{tot}	measured total compressor efficiency [−]
$\hat{\eta}_{iso}$	predicted isentropic compressor efficiency [−]
$\hat{\eta}_{gt}$	predicted gas turbine compressor efficiency [−]
$\hat{\eta}_{tot}$	predicted total compressor efficiency [−]
$\tilde{\eta}_{tot}$	modified total efficiency map for estimation of fuel consumption [-]
$\omega_{SP,j}$	corrected machine set point of compressor j [−]
ω'_{SP}	uncorrected machine set point [−]

For this particular optimization problem, the availability of up-to-date performance information of the machines is fundamental. As expected, the performances of compressors and gas turbine drivers are subject to significant drifts due to external and mostly untraceable factors (Saxena, 2000). Typically, the compressor map (relationship between head and flow at various speeds) and the performance map (efficiency at varying operating points) are tested only after a major overhaul of the machines, which could happen every 10–20 years or after major failure of some components in the turbomachinery train. Due to the infrequent nature of these tests, it is rather common to have inaccurate performance models, such that the optimization task can be hardly fulfilled (Petek and Hamilton, 2005).

In the literature, various approaches for the optimization of compression networks can be found starting as early as the mid 19th century, where Hax (1967) investigated the optimization of natural gas transmission. In late 70s, Edgar et al. (1978) focused on the optimal design of natural gas transmission networks and Marques and Morari (1988) showed first promising results on pipeline optimization in the late 80s. Compressor station optimization was considered, for example by Murphy (1989), Jenícek and Kralík (1995) and Wright et al. (1998) in the late 80s and 90s.

More resent research on this topic is discussed in the following. Nguyen et al. (2008) consider the problem of active compressor selection in natural gas pipeline operations. This selection deals with the choice of the number of operating compressors and no optimal set-points for compressor speeds are computed. Abbaspour et al. (2005) derive a detailed mathematical model of compressor networks, and use the model as a basis for solving a nonlinear programming (NLP) problem. The decision variables are constituted by the compressor steady-state speeds and the objective function to be minimized is the total fuel consumption. The NLP problem is solved numerically by a sequential unconstrained minimization technique. Moritz (2007) considers a mixed integer linear programing (MILP) approach for the transient optimization of compression networks, where the nonlinearities are approximated by means of piece-wise linear functions. There are two studies, which consider optimization with multiple objectives related to compressor stations. In Xenos et al. (2014) several different objectives in connection with both operations and maintenance are all combined for a 30 day window with 1 day intervals to formulate a single MINLP resulting in a schedule for the next month. In contrast, in Hawryluk et al. (2010) a formal multi-objective optimization to minimize energy consumption and to maximize station throughput is carried out and the results are presented in the form of various Pareto fronts. Kurz et al. (2012) investigated different influence factors affecting costs and economic potential of compressor stations.

It is important to note that in all the studies listed above, the load sharing optimization problem is not posed and treated as an RTO problem in the context of an automation system, which is the main approach of the present article. A recent paper by Xenos et al. (2015) comes close with the main difference of the present work being the formulation of the related optimization problems tailored for practical industrial implementations on embedded devices. Moreover, in the present article a more challenging case of dual-axis gas turbine drivers for the compressors is considered instead of electrical drivers, which have a relatively constant efficiency with respect to both operating points and in time. Finally, this article presents a considerably richer case study with respect to the number of compressors and the duration of the considered time period. Preliminary results on this approach are presented in Paparella et al. (2013) and Cortinovis et al. (2014).

In this paper, a load sharing strategy is proposed based on a two stage procedure of on-line adaptation of compressor performance characteristics followed by the solution of the load sharing optimization problem. After discussing the algorithmic details and the implementation of the performance tracking and load sharing optimization steps, a novel case study, based on simulations

Download English Version:

https://daneshyari.com/en/article/172020

Download Persian Version:

https://daneshyari.com/article/172020

Daneshyari.com