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Techno-economical and environmental optimization of natural gas network operation

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abstract

In the present study, a multi-objective approach is proposed to find optimum operating condition of natural gas network. For this purpose, a thermodynamic modeling of natural gas through the main elements of the network i.e. pipelines and compressor stations (CSs) is performed. This study aims to find optimum values of three conflicting objective functions namely maximum gas delivery flow and line pack, and minimum operating cost (sum of fuel consumption and carbon dioxide emission costs), simultaneously. Here, fast and elitist non-dominated sorting genetic-algorithm (NSGA-II) is applied by considering fourteen decision variables: number of running turbo-compressors (TCs) and rotational speed of them in compressor stations as well as gas flow rate and pressure at injection points. The results of multi-objective optimization are obtained as a set of multiple optimum solutions, called 'the Pareto optimal solutions'. Furthermore, a set of typical constraints, governing the pipeline operation, is subjected to obtain more practical solutions. To control the constraints satisfaction and to find better solutions in optimization process, the penalty functions are defined and applied. Sensitivity analysis of change in the objective functions, when the optimum decision variables vary, is also conducted and the degree of each parameter on conflicting objective functions is investigated.

Keywords: Natural gas pipeline network operation; Compressor station; Modeling; Carbon dioxide reduction; Multi-objective optimization; NSGA-II

1. Introduction

Huge amount of natural gas is transported through pipeline network systems across long distances. A typical gas transmission network is composed of large numbers of pipes, regulators, valves, etc., many injection and delivery points and a few to tens of compressor stations.

In gas transmission networks, the energy and pressure of gas are lost, mostly because of friction between the gas flow and the pipe inner wall. Typically, the compressor stations are located at regular intervals along the pipeline to compensate for the pressure drop and provide demanded gas with required pressure in the downstream elements. They involve one or multiple turbo-compressor units, arranged in parallel or serial arrangement.

Turbines' required energy, provided with a portion of the transported gas, causes a considerable fuel cost as well as a significant contribution to greenhouse gases emission.

Generally, gas network optimization problems are different from conventional optimization ones; first, compressor stations are complex components. They may consist of a remarkable number of active or inactive compressor units in different arrangements and characteristics. In addition, there is a complicated set of non-linear constraints governing the system operation. Furthermore, the problems often include both discrete and continuous variables. Therefore, computer analysis tools are widely applied in pipeline studies.

Many optimization approaches have been developed to make significant improvements in different fields of natural gas networks with a number of general assumptions, but

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Nomenclature

A	pipe's internal cross section area (m^2)
A_1–A_{11}	Dranchuk, Abou-Kassem's Z-equation coefficients
A_e, B_e, C_e, D_e	efficiency coefficients determined by polynomial fit
A_h, B_h, C_h	head coefficients determined by polynomial fit
APW	available power (kW)
Cost	operating cost ($)
CD	estimated annual CO_2 emissions from combustion of fuel (ton/year)
COX	fraction of fuel C oxidized
CW	carbon weight ratio (kg C/kg fuel)
D	internal diameter of pipe (m)
f	Darcy friction coefficient
FAP	fraction of available power
FC	fuel consumption (kg/s)
G	gas relative density
H	compressor head (kJ/kg)
k	ratio of specific heats
L	pipe length (m)
LP	line pack (m^3)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate of natural gas (kg/s)
MAOP	maximum allowable operational pressure (Pa)
MMSCMD	million standard cubic meter per day
MW	molecular weight (kg/kmol)
N	number
OF	objective function
P	pressure (kPa)
PF	penalty function
PW	power (kW)
Q	volumetric flow rate (m^3/s)
R	gas constant (kJ/(kg K))
Re	Reynolds number of the gas flow
SM	surge margin (%)
T	temperature (K)
u	average gas velocity in pipe cross-section (m/s)
Z	compressibility factor

Greek abbreviation

α	cost coefficient ($/kg Fuel)
β	cost coefficient ($/kg CO_2)
ε	wall pipe roughness (m)
η	efficiency
ρ	density (kg/m^3)
ω	rotational speed of compressor station (rpm)

Subscripts

1	pipe inlet
2	pipe outlet
ac	actual
avg	average
cr	critical
CS	compressor station
d	discharge side
dr	driver
e	efficiency
er	erosional
F	fuel
h	head
in	inlet
is	isentropic
max	maximum
min	minimum
mech	mechanical
out	outlet
p	pipeline
r	reduced
R	rated
s	suction side
sc	standard condition
Stonewall	stonewall
Surge	surge
TC	turbo-compressor
Tot	total

still a tremendous potential exists in this field (Farahani et al., 2011). Each of the methods has its own weaknesses and advantages.

Dynamic programming (DP) (Carter et al., 1998; Lall and Percell, 1990; Peretti and Toth, 1982; Tsal et al., 1988; Wong and Larson, 1968) and gradient search techniques (Percell and Ryan, 1987; Wu et al., 2000) have been commonly employed in previous gas network optimization problems.

The first attempt to use dynamic programming in natural gas transmission networks was carried out by Wong and Larson (Wong and Larson, 1968) for a steady-state gas transmission system.

In 1987, a methodology based on a generalized reduced gradient (GRG) nonlinear optimization method was used by Percell and Ryan (1987) for non-cyclic structures.

Larson and Wismer (1971) proposed a hierarchical control approach for a transient operation of a gun-barrel pipeline system. Since then, a number of researches with some degree of success are implemented based on hierarchical control approach for transient models (Anglard and David, 1988; Osiadacz, 1994; Osiadacz and Bell, 1986; Osiadacz and Swierczewski, 1994).

Besides, heuristics were proposed for operation of natural gas transmission pipelines as early as 1961 (Batey et al., 1961). Ríos-Mercado et al. (2006) proposed a two-stage iterative procedure for fuel cost minimization on gas transmission systems.

Also, some studies applied metaheuristic methods in this area. Wright et al. (1988) evaluated using simulated annealing (SA) to find the optimum configuration and power settings for multiple compressors in a single compressor station. Borraz-Sánchez and Ríos-Mercado (2009) combined TS with nonsequential DP in a natural gas transmission network to minimize total amount of fuel consumption. More recently, Chebouba et al. (2009) developed a new evolutionary optimization technique, called ant colony optimization (ACO) algorithm for operations of steady flow gas pipeline to optimize the power consumed by the stations.

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