Journal of Natural Gas Science and Engineering 22 (2015) 551–570

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Modeling and state estimation for gas transmission networks

Hesam Ahmadian Behrooz, R. Bozorgmehry Boozarjomehry*

Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form
17 December 2014
Accepted 1 January 2015
Available online 8 January 2015

Keywords:
High-pressure gas networks
Orthogonal collocation
Flow reversal
Discontinuity
Kalman filtering
Distributed parameter system

ABSTRACT

In this paper, a non-isothermal model of natural gas in pipelines including mass, momentum and energy balance equations are used as model equations for modeling and state estimation in gas pipeline systems. It is shown that differential equations describing the dynamic behavior of a high-pressure and long-distance gas transmission network (GTN) can be solved efficiently using the orthogonal collocation method. The issues corresponding to the presence of discontinuities in the dynamic model is substantially discussed and studied. The non-isothermal model of a GTN can experience discontinuities during transient operations, which causes challenges in simulation and state estimation in this system. An algorithm is proposed to handle the discontinuities that appear in the dynamic model of a GTN. The states of GTN are estimated using the continuous/discrete form of the extended Kalman filter for two benchmarks and some heuristic rules for sensor placement in a GTN are concluded. To avoid the singularity in the observability analysis of GTNs, a recursive method for the observability analysis of these networks is used.

1. Introduction

Natural gas suppliers and recipients are usually connected through a large-scale, high pressure and integrated transmission pipeline network. These transmission systems are the most cost effective ways to transmit fluid products over long distances (Uraikul et al., 2000), and are usually supplied from multiple sources and use inline compression units to deliver gas to the end users. Adaptation to the varying demands of customers plays an important role, and it is the responsibility of the dispatchers in gas transmission systems to supply adequate amounts of natural gas to meet consumers' requirements and maintain the pressure level above the minimum required values. Safe operation of transmission pipeline systems despite load changes is an important topic and requires the assessment of both the current and future status of the system. The lack of reliable information about many streams and instrumentation errors create additional challenges in assessment of the current state of the transmission network. Other distribution networks such as electrical networks, nitrogen/oxygen and hydrogen networks suffer from these issues as well (Sarabia et al., 2012). Considering several hundred up to several thousand variables of a GTN model, it is possible to measure only a fraction of these variables from cost and feasibility point of view, and there are several unmeasured variables. Hence, it is essential to use an online estimator to obtain unknown variables using available measurements and smooth the measured variables.

GTN is an example of a process with frequent changes, due to the ever changing fluctuations in customer demands and unnoticed load changes from natural gas-fired power plants (Carter et al., 2004). Real time optimization (RTO) of gas pipelines in transient conditions is considered to be a challenging problem. For a process with frequent disturbances, dynamic-RTO can be an effective replacement for steady state RTO (Chaudhary, 2009) while the successful implementation of dynamic-RTO also requires a dynamic data reconciliation module. The quantity of gas contained in a given pipeline segment is defined as the line–pack (Aalto et al., 2005; Menon and Menon, 2013), which is a crucial parameter in gas transmission systems (Pietsch et al., 2001), considering its use in the compensation of abrupt load changes.

As a result, state estimation techniques play a key role in several problems related to the gas industry such as dynamic data reconciliation, determining the line-pack of the pipelines, the appropriate calculation corresponding to natural gas transactions (Bagajewicz and Cabrera, 2003), leak detection, demand

---

* Corresponding author.
E-mail addresses: ahmadian@che.sharif.edu (H. Ahmadian Behrooz), brbozorg@sharif.edu (R.B. Boozarjomehry).

http://dx.doi.org/10.1016/j.jngse.2015.01.002
1875-5100/

Nomenclature

A_c	cross section area of the pipe[m^2]
c_v	valve conductance at fully open [GPM]
C_p	heat capacity at constant pressure [J/kg K]
D	inner diameter of the pipe [m]
f_r	friction factor [−]
g	standard gravity [m/s^2]
$\widehat{h}$	specific enthalpy [J/kg]
I	identity matrix of dimension $n \times n$
$\kappa(\lambda)$	flow characteristic of the valve
k	index of the sampling time
m	number of measurements
$\dot{m}$	mass flow rate [kg/s]
n	number of states
N	compressor adiabatic power [kW/MMSCMD]
n_i	number of inlet streams
n_o	number of outlet streams
N_c	number of internal collocation points
p	pressure [Pa]
P	covariance matrix
q_i	volumetric flow rate [MMSCFD]
q_{demand}	volumetric flow rate to a demand node [MMSCFD]
q_{supply}	volumetric flow rate from a supply node [MMSCFD]
R	specific gas constant [J/kg K]
t	time [s]
T	temperature [K]
$u \in R^{m \times 1}$	known input
$\widehat{u}$	specific internal energy [J/kg]
v	velocity along the axis of the pipe [m/s]
V_w	isentropic sound wave speed [m/s]
x	spatial coordinate [m]
$X \in R^{n \times 1}$	state of the system
Z	compressibility factor [-]
$\gamma = C_p/C_v$	ratio of constant pressure and constant volume heat capacities
η_{id}	thermodynamic efficiency of compressors
Ω	heat flow into the pipe per unit length of pipe and per unit time [J/m s]
λ	valve opening percentage [$\lambda = 100\%$ for max flow]
τ_w	shear stress at the wall [kg/m s^2]
ρ	density of the gas [kg/m^3]
ε/D	relative roughness of the pipe
υ_s	inlet specific volume [m^3/kg]
υ_{avg}	average specific volume [m^3/kg]
θ	angle of inclination of pipe to the horizontal [radian]
$\frac{d\upsilon}{dT}$	derivative of specific volume with respect to temperature [m^3/kg K]

Subscripts

s	discharge side of a compressor or valve
d	suction side of a compressor or valve

estimation, optimal sensor placement (Musulin et al., 2005) and as an aid to control or optimum design of the system. Estimating line-pack of the network is essential in the evaluation of its current status and can be helpful in a reliable planning for the future. Increasing and decreasing pipeline inventory, called line packing and drifting, respectively, is one of the key tools available for the gas dispatchers to balance the time-varying demands with supplies.

The available measurements are mostly pressure and mass flow at the inlet and outlet of the pipeline sections. In compression units, apart from pressure and mass flow, the inlet and outlet temperatures are measured as compression of the gas increases its temperature. For a gas dispatcher, it is desirable to have an accurate measurement of the customer demand flows as the basic information required in the operation of the network. However, mass flow meters are much more expensive than pressure sensors to install, so a method capable of estimating the flow demands from pressure measurements is an economically attractive alternative. There are several standard numerical methods that can be used to simulate the dynamic behavior of a gas transmission system such as spectral method (Battarra et al., 1985; Dorao and Fernandino, 2011; Lang, 1991), the method of characteristic (Kessal, 2000; Poloni et al., 1987), explicit and implicit finite difference (Herrán-González et al., 2009; Thorley and Tiley, 1987; Wylie et al., 1974), the finite volume (Chaiko, 2006; Greyvenstein, 2002), finite element (Bisgaard et al., 1987; Osiadacz and Yedroudj, 1989) and high order approaches such as third order Runge-Kutta discontinuous Galerkin method (Gato and Henriques, 2005). Some of the main characteristics of most common methods used in transient analysis of GTN are discussed in Thorley and Tiley (1987). The literature review reveals that although many methods have been proposed for numerical simulation of dynamic behavior of GTNs, but they mostly focus on isothermal models and transient behavior of fluid in a single pipe. Furthermore, flow reversal arising either from inverse pressure gradient or sudden valve opening or closing is not addressed in them. Including energy equation in the dynamic model of a GTN, introduces a difficulty in the modeling as the governing equations of the boundary points depend on the flow direction or network connectivity. The direction of flow in a specific equipment might change during flow reversals. On the other hand, opening or closing a valve might also alter the connectivity of the network, which leads to connecting or isolating different compartments of a GTN.

Here, we are motivated by discontinuities that appear in the model obtained from the spatial decomposition of a GTN as a result of the flow reversal occurrence or valve position changes. Flow direction changes in the pipelines due to the sudden changes of pressure gradient result in discontinuity in the governing equations. Discontinuities can also arise from the opening or closing of different types of valves, which exist in a GTN, where the governing equations at some points are altered. A common approach to solve this problem is first to use a root finding algorithm to detect and then locate the discontinuity which might lead to restarting of the integration (Mao and Petzold, 2002; Preston and Berzins, 1991).

To tackle these issues, a computationally efficient algorithm is proposed to handle discontinuities in simulation and estimation of a GTN. The key features of the proposed methodology are: (i) long distance transmission systems are considered where the effect of temperature is significant, (ii) discontinuities resulting from flow reversal or valve status changes are handled, (iii) the location of the discontinuity is not needed to be known before the integration takes place, (iv) integration is not necessary to be restarted, (v) common equipment used in natural gas transmission systems such as compressors or valves are included, and (vi) sharp transients resulting from sudden opening or closing of valves can be handled easily.