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Transient simulation of gas pipeline networks using intelligent methods

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ABSTRACT

Simulation of gas pipeline network has an important role in control and design of the natural gas transmission system. Transient simulation provides several advantages in energy consumption optimization where compressor stations variables are manipulated regarding to contract pressures. In this paper, a novel approach based on intelligent algorithms and three basic functions is proposed for dynamic simulation of gas pipeline networks. An optimization tool is used to find the inlet flow rates of the network. If the inlet flow rates are calculated correctly, all network variables can be computed using three basic functions. In each sample of time, the optimization tool called particle swarm optimization gravitational search algorithm (PSOGSA) offers some candidate solutions for inlet flow rates of the network. For each of these candidate solutions, the network is analyzed using three basic functions and then, outlet pressures are calculated. The differences between calculated outlet pressures and the reference values are considered as an error or fitness function of optimization tool. Finally, the optimization tool finds the optimum inlet flow rates at that sample of time which lead to minimum error. The proposed method is straight forward and easy to implement while its error percentage is near zero and converges faster than some well-known optimization algorithms. Numerical results confirm the accuracy and efficiency of the suggested algorithm.

1. Introduction

Natural gas is one of the most important energy resources in the world and has an important role in global industry and economy. For several decades, natural gas networks have been stimulating extensive interest (Ríos-Mercado and Borraz-Sánchez, 2015; Marques and Morari, 1986; Zavala and Victor, 2014; Gopalakrishnan and Biegler, 2013; Sanaye and Mahmoudimehr, 2012; Erdener et al., 2014). The response of the gas pipeline networks is achieved from a time-space dependent problem including time and space derivatives. Hence, the outlet flow rate of a pipeleg obeys the inlet flow rate changes with a time delay depending on the pipeleg length. Longer networks cause to longer delay. There is a large delay in these networks that makes them more sophisticated. To analyze the transient behavior of these networks, it is necessary to solve each pipeleg governing equation considering its boundary values. Several research studies have dealt with the unsteady analysis of a pipeleg (Erdener et al., 2014; Osiadacz, 1984; Pfetsch and et al., 2015; Helgaker and Fredriket al, 2014; Abbaspour and Chapman, 2008; Brouwer et al., 2011; Oosterkamp et al., 2015) that offer the methods which aimed at increasing speed and accuracy of analyses. Kiuchi (Kiuchi, 1994) proposed a fully implicit discretization method in the isothermal condition for natural gas which later was improved by abbaspour et al. (Abbaspour and Chapman, 2008) by considering the non-isothermal condition, and incorporating convective inertia term as well as non-constant compressibility and friction factors. The differences between isothermal and nonisothermal models of gas pipeline networks are investigated in (Osiadacz and Chaczykowski, 2001). The boundary values of the pipelegs in the network are related to each other. One strategy for network transient analysis is to consider a system of equations that contains all pipelegs equations. In this approach, discretized variables of one pipeleg should be considered as the boundary values in the other pipelegs. Therefore, construction of such system of equations is time consuming and it is not straight forward.

Ke and Ti (Ke and Ti, 2000) proposed a model to analyze isothermal gas pipeline network based on electrical circuit analogy method by combining resistance with theoretically derived model

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of capacitance and inductance. This model is more tractable than the similar model investigated by Tao and Ti (Tao and Ti, 1998). However, it is expressed by a set of first order ordinary differential equations that are simplified version of original Navier-Stokes PDEs. Behbahani-Nejad et al. (Behbahani-Nejad and Bagheri, 2008) proposed a MATLAB Simulink library for transient flow simulation of gas network using transfer functions of nonlinear governing equations. The accuracy and efficiency of this model were investigated in (Behbahani-Nejad and Bagheri, 2010). The nodes through the pipelegs are not accessible by this model and only the endpoints results are given. To address these issues, a powerful intelligent method based on a pipeleg transient analysis is proposed. The latest improvement of transient analysis of single pipeleg (such as (Helgaker and Fredriket al, 2014; Abbaspour and Chapman, 2008; Brouwer et al., 2011; Oosterkamp et al., 2015)) can be directly used in the proposed approach while the models presented in (Ke and Ti, 2000; Tao and Ti, 1998; Behbahani-Nejad and Bagheri, 2008, 2010) are based on some simplifications of governing equations. Generalization of one pipeleg analysis to the whole network analysis that is based on one pipeleg unsteady behavior is much more complicated than single pipeleg analysis. However, the speed and precision of networks analysis is directly affected by single pipeleg analysis. In the networks where the inlet and outlet pressures are known if the true input flow rates can be found at all times, then the whole network variables will be computed at any time through an organized and straight forward procedure. The proposed method precisely and efficiently finds the true input flow rates by minimizing the difference between the reference output and the computed output using suggested input flow rates. The organization of the paper is as follows. In the next section the governing equations are discussed. In the Section 3, GA, GSA, PSO and PSOGSA as the intelligent algorithms are reviewed. The proposed method to analyze transient behavior of gas pipeline network are introduced in Section 4. The numerical results are given in Section 5 and finally the paper is concluded in Section 6.

2. Governing equations

The gas pipeline network consists of pipelegs and compressors. Therefore, the transient behavior of the gas pipeline networks is based on the unsteady responses of the pipelegs and the output of compressor stations which are described in the following subsections.

2.1. Pipeleg equations

The governing equations set of gas flow in the pipelegs are momentum, continuity and energy conservation. Since the isothermal condition is considered in this paper, the governing equations are only continuity and momentum equations (Osiadacz, 1984):

$$\begin{cases} \frac{\partial P}{\partial t}+\frac{ZRT\rho}{A}\frac{\partial Q}{\partial x}=0 \\ \frac{\partial Q}{\partial t}+\frac{A}{\rho}\frac{\partial P}{\partial x}+\left(\frac{fZRT\rho}{2DA}\right)\frac{Q\,|Q|}{P}=0 \end{cases} \tag{1}$$

where P and Q are gas pressure and volume flow rate. The convective inertia in the momentum equation is neglected due to the assumption of low flow velocity with respect to wave speed (ZRT). The parameters Z, R, T, and ρ are compressibility factor, gas specific constant, gas temperature, and gas density in the standard condition, respectively. Also, t refers to time and x indicates space dimensions. To discretize the governing equations, totally implicit method can be used which makes the discrete scheme quite stable (Abbaspour and Chapman, 2008) (see appendix A for more details):

$$\begin{cases} \frac{P_{j+1}^{n+1}-P_{j+1}^{n}+P_{j}^{n+1}-P_{j}^{n}}{2dt}+\frac{ZRT\rho}{A}\frac{Q_{j+1}^{n+1}-Q_{j}^{n+1}}{dx}=0 \\ \frac{Q_{j+1}^{n+1}-Q_{j+1}^{n}+Q_{j}^{n+1}-Q_{j}^{n}}{2dt}+\frac{A}{\rho}\frac{P_{j+1}^{n+1}-P_{j}^{n+1}}{dx}+\left(\frac{fZRT\rho}{2DA}\right)\frac{\left(\frac{Q_{j+1}^{n+1}+Q_{j}^{n+1}}{2}\right)\left|\frac{Q_{j+1}^{n+1}+Q_{j}^{n+1}}{2}\right|}{\frac{P_{j+1}^{n+1}+P_{j}^{n+1}}{2}}=0 \end{cases} \tag{2}$$

Where superscript n indicates the time samples and subscript j denotes space samples. It is usually solved by numerical algorithm such as Newton-Raphson method. For example when the number of nodes in the pipeleg is equal to N+1, system of equations includes 2*N equations with 2*N unknown values should be solved by numerical algorithm such as Newton-Raphson.

In the cases whose boundary values are pressure and flow rate in one side of pipeleg, the discrete scheme can be simplified to speed up the procedure. In this case, the totally implicit scheme with the following modification is used to linearize the equations:

$$F=\frac{F_{j+1}^{n+1}+F_{j}^{n+1}}{2}\rightarrow F=F_{j}^{n+1} \tag{3}$$

Therefore, it leads to the following system of linear equations:

$$\begin{cases} \frac{P_{j+1}^{n+1}-P_{j+1}^{n}+P_{j}^{n+1}-P_{j}^{n}}{2dt}+\frac{ZRT\rho}{A}\frac{Q_{j+1}^{n+1}-Q_{j}^{n+1}}{dx}=0 \\ \frac{Q_{j+1}^{n+1}-Q_{j+1}^{n}+Q_{j}^{n+1}-Q_{j}^{n}}{2dt}+\frac{A}{\rho}\frac{P_{j+1}^{n+1}-P_{j}^{n+1}}{dx}+\left(\frac{fZRT\rho}{2DA}\right)\frac{Q_{j}^{n+1}\times\left|Q_{j}^{n+1}\right|}{P_{j}^{n+1}}=0 \end{cases} \tag{4}$$