Applied Energy 222 (2018) 244–256

Contents lists available at ScienceDirect

Applied Energy

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

Optimized response to electricity time-of-use tariff of a compressed natural gas fuelling station[☆]

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HIGHLIGHTS

- A model for optimization of compressor scheduling based on demand is presented.
- 59.3% cost reduction for a studied gas station fuelling 143 vehicles over a high demand season.
- 25% cost reduction a studied gas station fuelling 146 vehicles over a low demand season.
- Compressor switching frequency is minimized by different strategies.

ARTICLE INFO

Keywords:
Compressed natural gas
Fast-fill
Demand response
Optimization

ABSTRACT

Compressed natural gas propulsion of vehicles has been shown to have advantages over petrol and diesel propulsion due to lower carbon dioxide emissions as well as the increased durability of vehicle engines. The growth of compressed natural gas as an alternative fuel to petrol and diesel can be accelerated by implementing strategies that result in the economical operation of the distribution infrastructure. Economic scheduling of power consumption is a useful strategy for reducing the cost of energy for both industrial and domestic consumers who operate in time-of-use based electricity pricing environments. In this paper, an optimal energy management strategy is proposed for the operation of a compressed natural gas fuelling station. The compressor energy consumption, being the main component of the total operating cost of the fuelling station, presents a cost saving opportunity through which optimal scheduling of operation can be used to lower cost of operation of the station. The developed model shows potential average savings of 59.3% in daily electricity costs while maximizing compressor life through minimization of compressor cycling.

1. Introduction

Compressed Natural Gas (CNG) is one of the alternatives to liquid hydrocarbon fuels that have been promoted to address the challenges of air pollution, energy dependence and climate change [1–4]. CNG, which is largely made up of methane and small quantities of other hydrocarbons such as propane butane and ethane could be considered a clean fuel in comparison with gasoline and diesel because it has the lowest emissions among hydrocarbon fuels [5,6]. Furthermore, CNG vehicles have been shown to have lower total cost of ownership (TCO) than gasoline or diesel fuelled cars [7–9]. In recent years, the use of CNG for vehicle propulsion has been increasing worldwide in both developed and developing countries, especially in countries that have suffered severe air pollution from rapid industrialization in the past three decades such as India and China [10,11]. The expanding adoption of CNG has corresponded to a simultaneous growth of CNG distribution infrastructure for vehicular end users [12]. In South Africa for example, the Department of Energy recognizes compressed natural gas as one of the possible energy options for transportation that will contribute to the reduction of the country's carbon footprint [13]. In view of the long way to large-scale adoption of electric vehicles, CNG is viewed as an appropriate transition fuel towards a greener transportation sector [14]. Introduction of public service vehicles powered by CNG as well as growth in the number of CNG fleet customers has resulted in the growth in number of vehicle fuelling station in the city of Johannesburg and Pretoria. Being consumers of electric power, CNG fuelling stations are subject to the availability and pricing conditions of the electricity environment in which they operate [15]. While the expansion of CNG distribution infrastructure is a sign of investor confidence in the future of the industry, the distribution infrastructure is subject to challenges

[☆] The short version of the paper was presented at ICAE2017, Aug 21–24, Cardiff, UK. This paper is a substantial extension of the short version of the conference paper.

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https://doi.org/10.1016/j.apenergy.2018.04.017
Received 31 December 2017; Received in revised form 3 April 2018; Accepted 5 April 2018

Nomenclature

J	objective function (currency)
Mw_a	molecular weight of the air (g)
Mw_g	molecular weight of the gas (g)
m_{hp}^{max},m_{mp}^{max},m_{lp}^{max}	maximum mass for high pressure, medium pres sure and low pressure reservoirs (kg)
m_{hp}^{min},m_{mp}^{min},m_{lp}^{min}	minimum mass for high pressure, medium pressure and low pressure reservoirs (kg)
m_{ohp}^{max},m_{omp}^{max},m_{olp}^{max}	mass demand from high pressure, medium pres sure and low pressure reservoirs (kg)
$\dot{m}_{co}$	compressor outlet mass flow rate (kg/h)
N	total samples over the control horizon
n	gas quantity (moles)
p	pressure (bars)
P_{co}	compressor motor power rating (kW)
p_e	price of electricity under TOU tariff (currency/ kW h)
p_{hp}^{max},p_{mp}^{max},p_{lp}^{max}	maximum pressure for high pressure, medium pressure and low pressure reservoirs (bars)
p_{hp}^{min},p_{mp}^{min},p_{lp}^{min}	minimum pressure for high pressure, medium pressure and low pressure reservoirs (bars)
Q_{std}	capacity of the compressor under standard conditions (N m^3/h)
R	universal gas constant (L bar/K mol)
T	absolute temperature (K)
u	state of compressor switch
u_{hp},u_{mp},u_{lp}	state of reservoir valves for high pressure, medium pressure and low pressure reservoirs
V	volume of cascade reservoir tanks (L)
z	compressibility factor of CNG
$\rho_{a,std}$	density of air under standard conditions (kg/m^3)

arising from the supply of electricity and must implement adaptive strategies to remain energy efficient and economically attractive.

CNG is stored under high pressure in on-board vehicle tanks, from where it flows to the combustion engine under regulation [16]. CNG powered vehicles receive their fuel from high pressure reservoirs at CNG fuelling stations. Although refuelling of vehicles with natural gas can take a long time, the fast-fill process which is used at most CNG fuelling stations has been developed to achieve fuelling times of less than five minutes, which is comparable to the fuelling time of diesel or gasoline powered automobiles [17]. Fast-fill fuelling stations use reservoir tanks in a cascaded storage system divided into low pressure, medium pressure and high pressure levels [18]. The dispenser at the fast-fill station has electronic sequencing valves that are controlled by a microprocessor algorithm as well as sensors for measuring mass flow from each of the three reservoirs [19]. A vehicle typically arrives with low pressure in its tank and the dispenser starts the filling of the tank by connecting it to the low pressure reservoir. The differential pressure causes gas to flow into the vehicle tank and as the vehicle tank fills up, the mass flow rate between the reservoir and the vehicle tank falls to a limit after which the dispenser switches the filling to the medium pressure reservoir for a higher mass flow rate [20]. The vehicle tank continues to fill up from the medium pressure reservoir which results in the mass flow rate falling until a limit is reached and the dispenser switches the filling from the medium pressure reservoir to the high pressure reservoir. The high pressure reservoir completes the filling of the vehicle tank [21]. It is possible in some scenarios for the vehicle to arrive with a high tank pressure that can only be filled from the high pressure reservoir since it is almost full or from the medium pressure reservoir followed by the high pressure reservoir. The dispenser algorithm determines from initial vehicle tank pressure which reservoir to start with [22]. It is also possible in some scenarios for the customer to request a quantity of gas that does not result in filling of the vehicle tank and therefore receive gas from the low pressure reservoir and medium pressure reservoir only, or even the low pressure reservoir alone. This means that the demand of gas from one reservoir is not always synchronized with demand from the other two reservoirs. The CNG station dispenser runs a vehicle filling algorithm that is compensated for temperature and pressure to ensure that correct quantities of gas demanded by consumer are dispensed to the vehicle tank. This isolates the consumer vehicle tank from the fluctuations in the pressure and temperature that may occur in the cascade storage as a result of vehicle gas demand itself or as a result of operation control [23–27].

A priority panel controls the filling of the three reservoirs of the cascade storage, by switching the gas flowing from the outlet of the compressor between the reservoir valves [28]. The priority panel is operated through a PLC, which runs an algorithm that controls the sequence of opening the three reservoir valves during charging of the cascade storage by the reciprocating compressor [29]. The compressor is a vital part of the fast-fill operation and is the main contributor to the CNG fueling station's operating cost through its power consumption as well as wear and tear [30]. The sizing of the station compressor and other station components is based on the expected inlet flow rate from the municipal supply line and the quantity of gas expected to be dispensed at the station [31]. Efficient operation of the compressor in a CNG fuelling station presents an opportunity for the reduction of operating costs. The savings that are realised can be passed on to consumers in the form of reduced price of CNG per unit of sale.

Energy efficiency of energy converting systems falls into four general categories of equipment efficiency, technology efficiency, performance efficiency and operation efficiency [32–35]. CNG fuelling station operators, just like other commercial electricity consumers, must make careful consideration for all the four categories of energy efficiency in order to increase the economic performance of these installations [36–39].

Research into the efficient operation of CNG fuelling stations has been greatly aided by the work of previous researchers. Kountz [40] modelled the fast-fill process based on the first law of thermodynamics for gas behaviour between a single reservoir and the on-board vehicle cylinder. Other researchers have expanded the modelling of the fast-fill CNG fueling station by considering the individual components of the station infrastructure and their interaction with the flowing gas. These include [41,42] whose work advanced the thermodynamic modelling of the fast-filling process. The research on further minimization of filling time has been studied by [43]. Using thermodynamic laws and mass balance, [44] studied the effects of initial conditions and ambient temperature on the filling of the vehicle on-board cylinder and achieving of the target pressure. The effects of the connecting pipe on the process of vehicle filling was also studied by [45]. Research on the complete filling of on-board vehicle cylinder through the development of dispenser algorithms for the fast-fill process has been conducted by [46,19]. Research has also been undertaken in relation to the thermodynamic behaviour of the reciprocating compressor in achieving different performance goals for the CNG fuelling station [47–50]. Frick et al. [51] studied the optimization of the distribution of CNG refuelling stations in Switzerland. The study applied cost benefit analysis to determine optimal location of new CNG fuelling stations among the existing petrol filling stations as well as existing CNG filling stations. CNG self-fuelling of vehicles and fuelling from homes has also been the subject of other research towards efficient delivery of the gas [16,52]. The significant effect that domestic refuelling of CNG vehicles in consumer homes could have on the electric power infrastructure has been studied by [53]. Their study recognized limited infrastructure as a major technological barrier to the market penetration of CNG vehicles in the United States of America. This limitation was also shown to result