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Optimization of a compressed natural gas station operation to minimize energy cost

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Abstract

Compressed natural gas (CNG) is one of the growing alternatives to liquid petroleum fuels for propulsion of motor vehicles. Lower greenhouse gas emissions as well as increased durability of vehicle engines are the main properties of CNG that make it a better alternative to petrol and diesel. CNG refueling infrastructure is vital to the expansion of consumer adoption of CNG vehicles. The economical operation of CNG fueling stations is beneficial to the station operators and consumers, by reducing cost of fuel delivery. The present study is concerned with the optimal scheduling of compressor operation in a CNG fueling station to achieve reduced cost of energy in a time-of-use electricity tariff environment. The cascade fast fill station is modelled as a single storage mass flow system with storage refilling optimally controlled to achieve minimum cost of electricity in supplying a typical day gas demand profile. The open loop optimization strategy shows the potential to achieve savings of 59.28% in cost of electricity for operating the compressor, while also minimizing compressor wear and tear.

Keywords: *Compressed natural gas; optimal control; time-of-use*

1. Introduction

The need to address the global challenges of climate change, air pollution and energy dependence brought about by the use of different liquid petroleum fuels has resulted in an increase in the adoption of Compressed Natural Gas (CNG) for motor vehicle propulsion [1]. CNG has the lowest greenhouse gas emissions among hydrocarbon fuels, making it a suitable option for cleaner combustion energy which also results in a lower total cost of ownership (TCO) of CNG powered vehicles when compared with petrol or diesel alternatives [2]. The expansion in the number of CNG powered motor vehicles has corresponded with an expansion in CNG refueling infrastructure, some of which has been implemented domestically by vehicle owners and commercially at roadside refueling stations [3]. CNG fueling points are operated using

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either the time-fill or fast-fill strategy with the time-fill strategy being adopted for applications that can allow for longer filling times while the fast-fill strategy is used in fueling stations with vehicle filling times of less than 5 minutes, comparable to filling times at petrol or diesel filling stations [4]. Electricity powered gas compressors used at CNG refueling points are a significant electrical load and efficient operation strategies are necessary to achieve minimum operation costs [5].
In literature, the fast-fill station has been modelled by different researchers starting with [6] who modelled the fast-fill process based on the first law of thermodynamics between the vehicle reservoir and a single reservoir storage. [6] has been expanded by other researchers who modelled the fast-fill process with consideration for gas flow with respect to different system components and operating conditions [7–9]. Research on the interaction between CNG refueling infrastructure and the electricity distribution networks is still scarce and more investigations should be done in this area [5].
The present study seeks to minimize the operation cost of a fast-fill CNG fueling station by reducing energy cost through the use of an open loop optimization of the switching of the compressor in a time-of-use (TOU) electricity tariff environment. To the best of the authors' knowledge this introductory study is the first attempt to implement a controller to achieve electric load shifting for CNG fueling stations taking advantage of TOU electricity pricing programs implemented by utility companies for demand response.

2. Problem Formulation

Figure 1 shows the schematic diagram of a fast-fill refueling station. The compressor on/off status is set through switch u. When the compressor is turned on, compressed gas flows into the cascade storage through

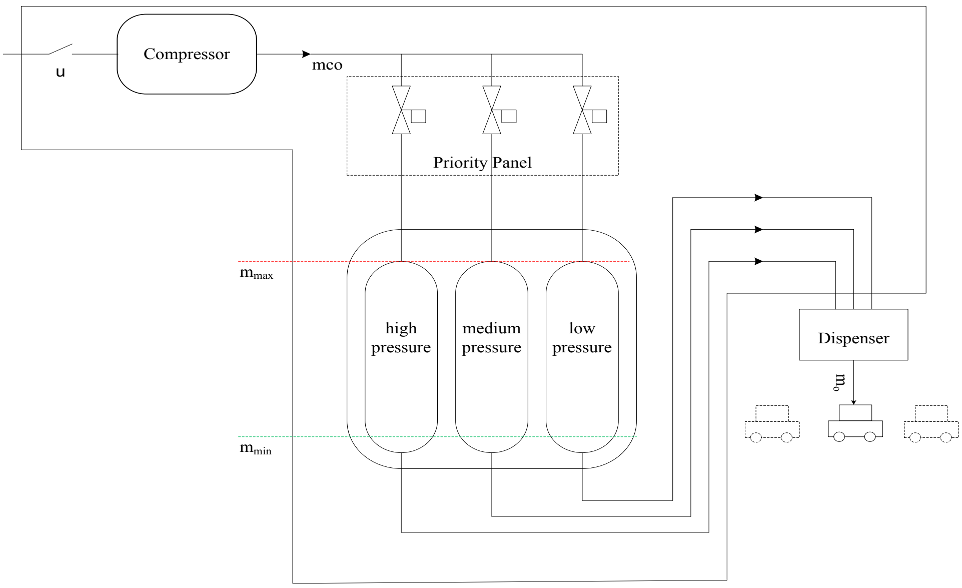

Figure 1: Schematic diagram of a fast-fill CNG refuelling station

the priority panel at a mass flow rate m_{co}. The priority panel runs on an algorithm that determines the reservoir connected to the compressor between the low pressure, medium pressure and high pressure reservoirs [9]. The storage in the present study is modelled as a single mass storage system with a maximum storage mass m_{max} and a minimum mass m_{min}. Gas in the storage is transferred to the vehicle tank through the dispenser whose algorithm determines the reservoir to which the vehicle tank is connected depending on the mass flow rate [10]. The mass flow rate between the reservoir and the vehicle tank changes with the change in the vehicle tank pressure as the filling process takes place. Gas flow to the vehicles is metered by mass for sale. The dispenser is designed with compensation for temperature variation to ensure accurate quantities are delivered to the vehicle tank and charged to the consumer. The gas mass demand at the dispenser determines the gas levels in the cascade storage and therefore the pressure. When the pressure of gas in storage falls such that mass in storage is m_{min}, the compressor switches on and fills the three levels of reservoirs to a pressure level such that mass in storage is m_{max}, and the compressor is turned off subsequently.

In order to minimize the cost of electricity, the present study proposes to optimize the on/off operation of the compressor based on typical daily gas demand profile. The status of the compressor switch u is the control variable such that

$$u(t) \in \{0,1\} \quad (1 \le t \le N) \tag{1}$$

the objective function can therefore be expressed as

$$J = \sum_{t=1}^{N} P_c P_e(t) u(t) \tag{2}$$

where P_c is the compressor motor power rating, $P_e(t)$ is the electricity price per kWh in a sampling interval t and N is the total number of samples in the control horizon. If the compressor is switched on and off too frequently, mechanical stress induced in the compressor will increase resulting in an increase in wear and tear, increase in maintenance cost, as well as reduction in the life of the compressor. To prevent frequent on/off switching of the compressor, the objective function can be modified to include an element minimizing the change in status of the compressor switch such that

$$J = \mu \sum_{t=1}^{N} P_c P_e(t) u(t) + (1-\mu) \sum_{t=1}^{N-1} (u(t+1) - u(t))^2 \tag{3}$$

where μ is a weighting factor. The objective function is subject to the storage capacity constraint and the terminal condition constraint so that

$$m_{min} \le m(t) \le m_{max} \tag{4}$$

$$m(t) = m(0) + t_s \sum_{i=0}^{t-1} m_{co} u(i) - \sum_{i=0}^{t-1} m_o(i) \tag{5}$$

$$m(N) = m(0) + t_s \sum_{i=0}^{N-1} m_{co} u(i) - \sum_{i=0}^{N-1} m_o(i) \tag{6}$$

where $m(t)$ is the mass of gas in the cascade storage at a sampling interval, t_s is the sampling time, m_{co} is the mass flow rate of gas from the compressor, $m_o(i)$ the gas demand in a sampling interval, m_{min} is the mass of gas corresponding to the minimum pressure limit for the cascade storage and m_{max} is the mass of gas corresponding to the maximum pressure limit for the cascade storage. The values of m_{min} and m_{max} are obtained from the gas property constants and pressure limit values using the equation of state

$$pV = znRT \quad (7)$$

where p is the pressure, V the volume of the storage tank, z is the compressibility factor, n is the quantity of gas in moles and T is the absolute temperature. The mass values can be obtained from the quantity of gas value given the relationship between the quantity of gas in moles and the molar mass M, which is

$$n = \frac{m}{M} \quad (8)$$

Gas demand data for the fast-fill CNG fueling station was obtained from a CNG fueling station in Johannesburg, South Africa. The station has two dispensers with four fueling nozzles and is supplied by a single reciprocating compressor with the capacity of 900Nm3/hr and the motor rating of 132kW. The 24 hour gas demand profile was recorded at the sampling interval of 4 minutes which is the average single vehicle fueling time. The cascade storage consists of three reservoirs of 2000L each with a maximum operating pressure of 252 bar and a minimum pressure of 210, 150 and 75 bars for the high pressure, medium pressure and low pressure reservoirs respectively. The gas demand data is shown in Figure 2.

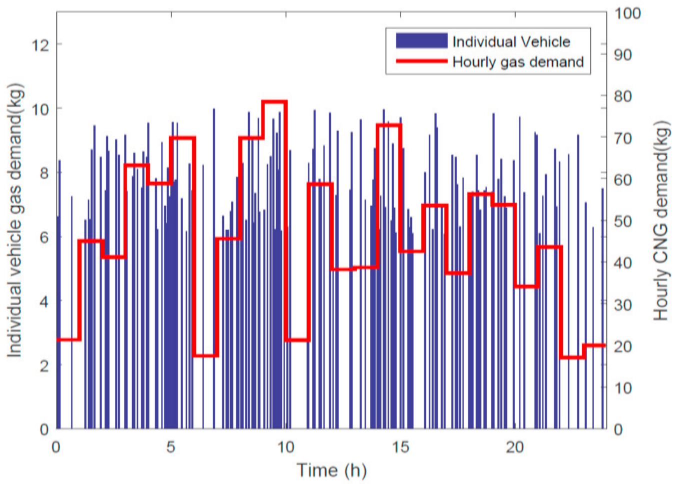

Figure 2 Gas demand at the CNG fuelling station dispenser at every sampling interval

There is high gas demand early morning as vehicles fuel for journeys between 5am and 10am. This coincides with the morning peak electricity pricing which is between 6am and 9am in the Miniflex power tariff from South Africa's power utility, Eskom, shown in Eq. (8)

$$P_e(t) = \begin{cases} P_{offpeak} = 0.5157R/kWh \; if \; t \in [0,6] \cup [22,24] \\ P_{standard} = 0.9446R/kWh \; if \; t \in [9,17] \cup [19,22] \\ P_{peak} = 3.1047R/kWh \; if \; t \in [6,9] \cup [17,19] \end{cases} \quad (9)$$

where $P_{offpeak}$, $P_{standard}$ and P_{peak} are the prices of electricity at the off-peak, standard and peak electricity pricing periods respectively in South African Rands per kilowatt hour (R/kWh). There is a similar peak in demand in the midafternoon in preparation for the afternoon transportation rush hour. Since most CNG

vehicles in Johannesburg are public transport vehicles, the gas demand profile shows an increase in the number of vehicles refueling at the CNG station prior to and during peak people movement times.
In the current study, it is assumed that the initial pressure and therefore mass of gas in the cascade storage is at the maximum value. Figure 3 shows the behavior of the compressor without optimal control, where the compressor switches on only when minimum gas quantities in the cascade storage are reached. This results in the compressor operating during the morning peak electricity pricing period as well as the evening peak electricity pricing period incurring 432.59 South African Rands as the day's cost of electricity. It is desired that the operation of the compressor is optimized so that the total cost of electricity incurred to meet the gas demand is reduced through optimal shifting of compressor actions.

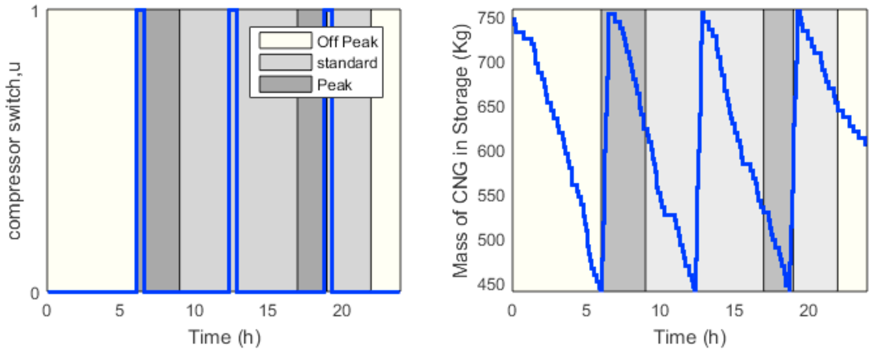

Figure 3: Compressor switch operation and mass of gas in the cascade storage without optimal control

3. Results and Discussion

This optimization problem is solved in Matlab using the SCIP solver in the OPTI toolbox interface over a sampling time of 4 minutes for the horizon of 24 hours starting at 00.00.

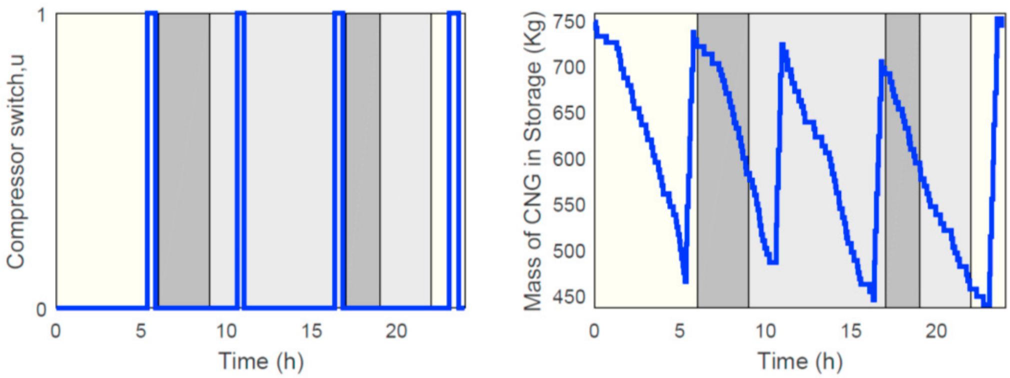

Figure 4 Compressor switch operation and mass of gas in the cascade storage under open loop optimal control

Figure 4 shows the compressor switch operation and the state of mass of gas in the cascade storage under open loop optimization. The compressor is switched on to maintain a high level of gas in the cascade storage before the onset of the peak electricity pricing period at 6:00am. This ensures that the compressor stays in the off state during the morning peak period and therefore does not incur the higher cost of energy. In order to meet gas demand during the mid-morning and afternoon, the compressor is switched on at 10:00 to restore high levels of gas in the cascade storage. The restored level of gas in storage sustains the gas demand until the late afternoon when the controller switches on the compressor to raise gas levels prior to the onset of the evening peak electricity pricing period between 17:00 and 19:00 as well as in the subsequent standard electricity pricing period between 19:00 and 22:00. The compressor is then switched on to meet the terminal conditions of a replenished storage at the end of the control horizon. By minimizing compressor activity in the peak and standard pricing time bands, the strategy reduces the cost of electricity required to meet the day's gas demand to 176.13 South African Rands which is a 59.28% reduction from the baseline. This reduction represents significant savings which raise the economic efficiency of the CNG fueling station.

4. Conclusion

The present paper introduces the application of a load shifting strategy for a CNG fueling station in order to minimize the cost of operation of the station. With the results showing significant savings in cost of electricity, the efficiency of CNG fueling infrastructure can be greatly improved which can avail resources for product price reduction. This can contribute to the economic incentive to encourage consumer adoption of lower emission CNG vehicles. The use of the proposed strategy can also reduce the contribution of CNG fueling infrastructure to carbon emission from power utility companies by helping them meet the objectives of time-of-use electricity pricing as a demand response strategy.

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