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Receding Horizon Operation Control of a Compressed Natural Gas Station

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Abstract

In order to lower the cost of gas delivery to consumers who use compressed natural gas to propel their vehicles, operators of compressed natural gas stations in locations where electricity is sold under time-of-use tariff pricing can adopt station operation strategies that result in lower energy costs to secure their revenue. While finite horizon open loop control has shown the potential for significant savings on electricity costs while meeting the gas demand profile, receding horizon control can increase the robustness of the scheduling optimization by delivering a convergent solution for continuous operation of the plant. The present work shows the performance of the compressed natural gas station when the receding horizon control strategy is implemented achieving savings of up to 56.7% and a solution for continuous operation.

*Keywords:*compressed natural gas; receding horizon control; time-of-use tariff

1. Introduction

The global search for solutions to mitigate air pollution, greenhouse gas emissions and oil dependence has resulted in a drive to expand the use of alternative fuel for transportation [1]. Electric vehicles are seen as the future solution to achieve clean transportation but have still not overcome the perception by consumers of their disadvantages in range and recharging times [2]. Among the reasons expected to result in the ascendance of CNG powered vehicles in the near future are: The abundance of compressed natural gas (CNG), CNG's lowest greenhouse gas emitter status among

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hydrocarbon fuels as well as CNG's better performance in increasing the longevity of internal combustion engines [3]. CNG is compatible with both petrol and diesel engines and therefore serves as a transition fuel as the transport sector migrates from high pollution fuels [4]. Presently, there are over 25 million CNG powered vehicles globally, with China, Iran and India leading in the adoption of CNG for automotive applications. The CNG vehicles are fuelled at over 30, 000 CNG fuelling stations globally with an average annual growth rate of 17% in the number of new stations between year 2000 and 2017 [1].

CNG fuelling stations are vital components of the CNG distribution infrastructure and their continued growth in numbers is useful in driving more consumer adoption of CNG powered automobiles. The CNG fuelling station is reliant on an electrically powered gas compressor which is used to pressurize gas into storage from where consumers fill their vehicles [5]. The most widely used configuration of the CNG stations for roadside refueling is the fast-fill configuration which consists of a compressor and cascade storage, where gas pumped from municipal supply lines by the compressor is stored in the cascade storage from where it is dispensed to vehicles. The compressor is switched on when the level of gas in the cascade storage reaches a minimum quantity and replenishes the storage to the maximum capacity after which it is switched off [6]. The study and modeling of the operation of the fast-fill CNG stations have been performed by various researchers mostly focusing on the modeling of gas flow with respect to different components of the station [3] [5] [7]. Research investigating operation efficiency is still scarce when it comes to energy cost incurred during compressor cycling. The researchers in this work have previously reported results for a finite horizon open loop control strategy for compressor scheduling to minimize electricity costs in a 24 hour period [8].

In the present work, the goal of minimizing CNG fuelling station electricity costs in a time-of-use tariff environment is achieved through a receding horizon closed loop control. This contribution is important in advancing the real time implementation of the optimized compressor scheduling strategy in continuous operation of CNG stations which has not been previously reported. Receding horizon control can allow operators to implement the compressor scheduling strategy with a long term indication of performance and with feedback which allows for system correction in case of change in conditions. Further a strategy for minimizing the rate of compressor on/off switching is proposed by minimizing the difference between the first value of the current control solution and the first value of the computed control sequence in the previous step.

2. Formulation

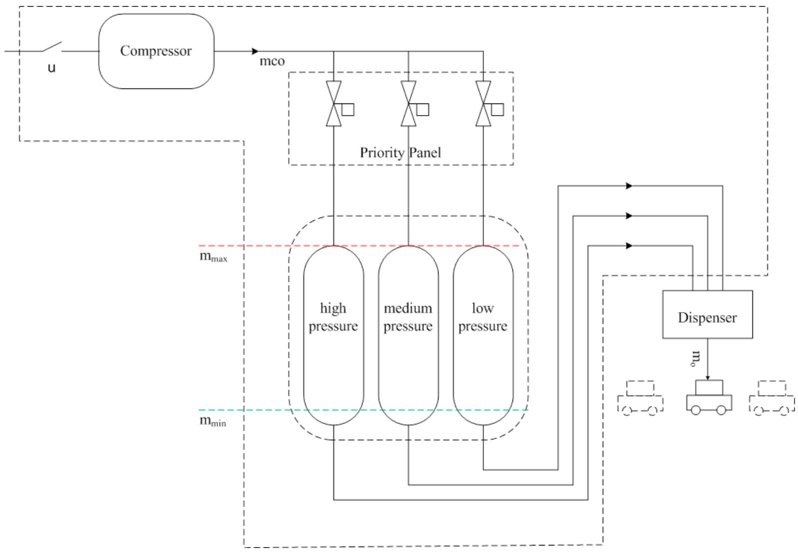

Figure 1: A fast-fill CNG station

The schematic of a fast-fill CNG station is sown in Figure 1. During normal operation, the compressor switch u, is switched on when the quantity of gas in the cascade storage reaches the minimum mass m_{min} corresponding to the minimum pressure. The compressor stays on supplying gas at a flow rate m_{co} until the cascade storage is completely replenished to the maximum mass $m_{max,}$ corresponding to the maximum pressure level. The priority panel coordinates the filling of individual tanks in the cascade storage, while the dispenser coordinates the extraction of gas from the cascade storage to vehicles as they visit the CNG station at different times represented by the gas demand, m_o.

In a time-of-use (TOU) tariff environment, the time at which the compressor is turned on affects the total cost of energy incurred [9]. Scheduling of the compressor-on status can be an effective way to lower energy costs by optimally shifting the operation of the compressor from times during the day where peak electricity pricing applies to times when lower electricity prices apply.

The current study seeks to use a receding horizon control to minimize electricity costs under continuous operation. The objective function is

$$J = \sum_{j=k}^{k+N-1} P_c P_e(j) u(j|k) \tag{1}$$

where the status of the compressor switch $u(j|k)$ is the control variable, P_c is the power rating of the compressor motor and $P_e(j)$ is the price of electricity under the time of use tariff. k denotes the current time instant and j denotes the future time instant in the prediction horizon N. Under the principle of the receding horizon, the controller solves for an optimum operation schedule of compressor switch u for the prediction horizon N [10]. From the solution obtained, only the first element of the control vector is implemented [11]. The mass of gas in storage is measured and fed back to be used as the initial condition for the next control iteration. The mass of gas in storage is expressed as

$$m(j|k) = m(k) + t_s \sum_{i=k}^{j-1} m_{co} u(i|k) - \sum_{i=k}^{j-1} m_o(i) \tag{2}$$

where t_s is the sampling interval.

Further, it is necessary to minimize the rate of change of the compressor switch status to minimize the negative effects of frequent start/stop transition on wear and tear of compressor components [12]. This is achieved by minimizing the difference between the first control element in the current solution, and the first control element in the previous solution. Such that

$$J = \beta \sum_{j=k}^{k+N-1} P_c P_e(j) u(j|k) + \mu \left(u(1|k) - u(1|k-1)\right)^2 \tag{3}$$

Where β and μ are weighting factors. The solution of the receding horizon control is subject to the constraints of the cascade storage such that

$$m^{min} \leq m(j|k) \leq m^{max} \tag{4}$$

The workflow of the controller is,

(1) Define the control horizon N
(2) Find the optimal solution for the control variable $u\epsilon\{0,1\}$ in the control horizon, by minimizing the objective function in Equation (3) with $m(k)$ subject to the constraint in Equation (5)
(3) Implement only $u(k|k)$ to the plant from the solution
(4) Measure the state $m(k + 1)$ for feed back
(5) Set $k = k + 1$ and update system states, inputs and outputs
(6) Repeat step 2-5 until k reaches predetermined value

3. Case study

A CNG fuelling station located in Johannesburg, South Africa that is used as a public fuelling station is considered in this study. The demand profile for gas over a 24 hour period is shown on Figure 2 with a resolution of 4 minutes and is assumed to be repeated for subsequent days. Gas demand has peaks in the hours corresponding to times of the day just before, and during peak people movement times. The station compressor is a reciprocating compressor with a capacity of 900Nm^3/hr (under normal conditions) and is run by a 132kW motor. The total capacity of the cascade storage is 6000L which is divided equally among the three reservoirs. In the Johannesburg municipality, the CNG station falls under the Miniflex electricity tariff of the South African utility firm Eskom, whose rates are

$$P_e(t) = \begin{cases} P_{offpeak} = 0.5157R/kWh \; for \; t = [0,6] \cup [22,24] \\ P_{standard} = 0.9446R/kWh \; for \; t = [9,17] \cup [19,22] \\ P_{peak} = 3.1047R/kWh \; for \; t = [6,9] \cup [17,19] \end{cases} \quad (5)$$

where $P_{offpeak}$, $P_{standard}$ and P_{peak} are the prices, in South African Rands per kilowatt-hour, of electricity in the off-peak, standard and peak pricing times respectively.

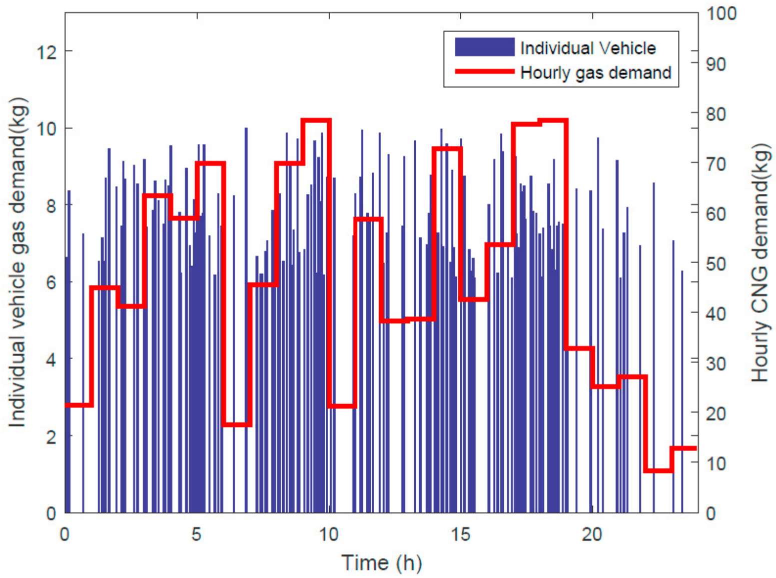

Figure 2: Gas demand profile

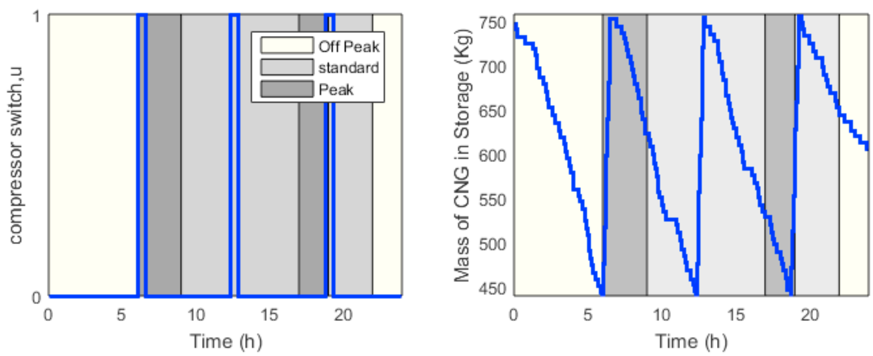

Figure 3: Baseline compressor switch operation and corresponding mass of gas in cascade storage

Under baseline operation shown in Figure 3, the compressor is switched on only when the quantity of gas in storage reaches a minimum and replenishes the cascade storage to maximum level before being switched off. This mode of operation does not consider the period in the time-of-use tariff which the compressor is switched on, hence there is a likelihood that the compressor runs during high electricity pricing time of the day and incurs high electricity costs like in this case where a total electricity cost of R432 is incurred for the 24 hour period.

4. Results

The receding horizon control problem is solved with the SCIP solver of the OPTI toolbox interface with a 4 minute sampling interval and a prediction horizon of 24 hours. Figure 4 shows the control solution and the corresponding mass of gas in storage over the 24 hour control horizon. The controller is able to keep the compressor from being switched on during both the morning and evening peak electricity pricing periods, by replenishing the cascade storage just before the onset of the peak electricity pricing time and thus meet the demand without the need to switch on the compressor. At the end of the control horizon, the controller switches on the compressor because the receding horizon approach predicts operation beyond the horizon under observation.

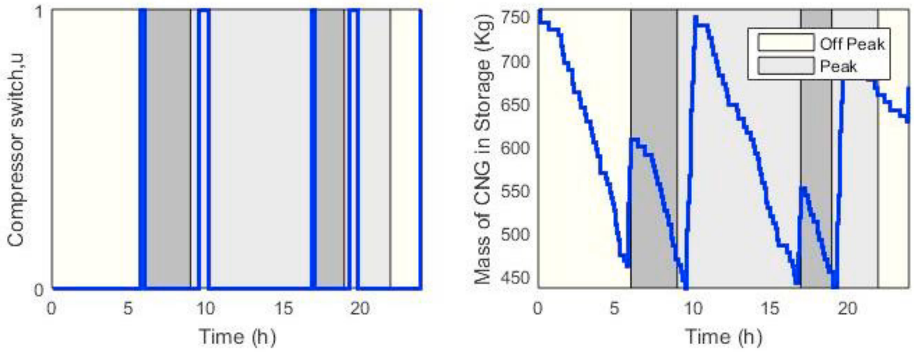

Figure 4: Optimal operation for a 24 hour control horizon

When a control horizon of 6 days is implemented, the optimized operation of the compressor and the corresponding quantity of gas in storage is shown in Figure 5. The controller is able to prevent the compressor from operating during the peak electricity pricing times and the control solution obtained repeats itself every 48 hours showing convergence of the control actions [13]. The cost of electricity incurred for the first 24hours of the repeating pattern of operation is R186.69 while that of the second 24 hour period is R188.94. This is as a result of the difference in initial conditions between the two periods that results in a small difference in total compressor operation time for the two back to back 24 hour periods.

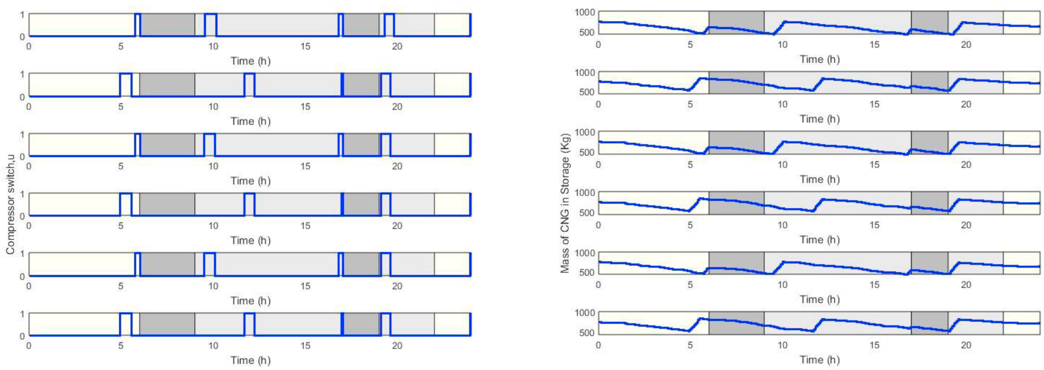

Figure 5: Optimized operation for a 6 day control horizon

The savings in electricity cost from the approach are significant and can raise the level of economic performance of the CNG station.

5. Conclusion

This paper is a presentation of the outcomes of a study that applies a receding horizon control approach to minimize the cost of energy, through shifting of compressor operation from high electricity price times of the day to lower electricity price times. The approach is successful in achieving savings of up to 56.7%. Further, the study achieves a convergent solution that is repeated every 48 hours. The participation of CNG stations in the load shifting strategy not only saves the CNG operators money but also helps in achieving the wider goals of the utility companies having the time-of-use tariff, which is stabilizing the grid and improving reliability of supply.

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