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Design Space Approach for Storage Sizing of Hydrogen Fuel Cell Systems through Pinch Analysis

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Fuel cell based systems can be used effectively to supply electricity to an isolated power system. With variations in electricity demand, fuel cell as well as the reformer operates in part load condition and a buffer storage tank is provided to cater to this fluctuating. Efficiency of a reformer deteriorates with part load operations. On the other hand, efficiency of a fuel cell improves during part load operations. It is important to size the buffer tank properly to improve overall system performance. The primary objective of this work is to optimize reformer size and storage volume for a given load profile. In this paper, a methodology, based on the principles of Pinch Analysis, is proposed by dividing the entire load cycle into several time intervals. The net energy balance in every interval is calculated and various design constraints, such as the turndown ratio of the reformer, electricity demand, and no wastage of hydrogen, are imposed. Set of all feasible configurations of the overall system, known as the design space, is identified on a graphical representation between reformer size and storage volume. In addition a sensitivity analysis is also carried to understand the variation of design space with variations in turn down ratio.

1. Introduction

Increasing fuel cost, depleting fossil fuel, and stringent environmental laws necessitate researchers to develop cleaner and efficient energy systems. Fuel cell based systems can be used effectively for transportation as well as for isolated energy systems. Among different types of fuel cells, Polymer Electrolyte fuel cell (PEFC) is considered to be the most promising candidate for such applications. Generation of hydrogen from the fossil fuel through reforming process is considered as short-term solution to meet the hydrogen demand for such applications. Hydrogen is produced mainly by steam reforming, partial oxidation, and auto-thermal reforming. The maximum reforming efficiency occurs at thermo-nuclear point (Ahmed and Krumpelt, 2001). Dutta (2013) carried out a review on various methods to produce and store hydrogen. Mori and Hirose (2009) talked about the various method how to store hydrogen for fuel cell vehicle and found an increase in 2.5 times in storage volume for metal hydride tank in comparison to high pressure tank. Oosthuizen et al., (2009) studied the performance of an autothermal reformer numerically for use in a fuel cell powered auxiliary power unit for transport applications. Ravey et al., (2015) developed a control strategy for fuel cell electric vehicle with hybrid tank. Ampelli et al. (2012) developed sensors for safety purpose for fuel cell transportation. Beside the cost efficiency another important field of research is sizing of the overall system. Several researchers have adopted different methodology for sizing the storage such as economic criteria which includes levelized cost of energy (LCE) (Paliwal et al., 2014),net present value (Ghosh, 2003), and annualized cost (Yang et al., 2008). Vosen and Keller (1999) found that the cost of storing energy is minimum for battery-hydrogen storage system in comparison to only battery storage and only hydrogen storage. Sopena et al. (2006) carried out a study to estimate the design parameter for feeding the fuel cell with 5 kW. Verhasselt et al. (2014) designed and tested 1.2 kW fuel cell vehicle.

Pinch Analysis is another important optimisation method used in several system sizing problems. Kulkarni et al. (2007) applied the concept of Pinch Analysis for sizing solar thermal system and Arun et al. (2009),

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applied it for sizing photovoltaic-battery system. Pinch Analysis is also explored for wind – battery systems (Roy et al., 2009) and photovoltaic-thermal (PVT) systems by Krishna Priya et al. (2013).
In present work, design space methodology, developed based on the principles of Pinch Analysis, is adopted for optimizing the reformer size and hydrogen storage for a known electrical load profile. The choice of reformer and storage sizes influence the overall system cost.

2. System description

For present study a reformer based fuel cell system is considered (Figure 1). The system consists of a reformer to produce hydrogen, a fuel cell to produce electricity to supply the load. A buffer storage tank is also incorporated in the system to cater a fluctuating hydrogen demand from fuel cell due to variable electrical load. It should be noted that the efficiency of a fuel cell varies with the load to be supplied. It has the unique characteristic of having higher efficiencies at part load than full load. Present study essentially aims in sizing of hydrogen generator (reformer) and storage tank for a given electrical load profile.

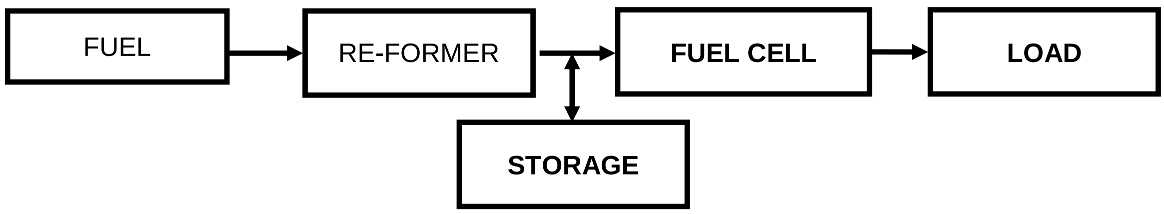

Figure 1: Block diagram of hydrogen fuel cell system

3. Methodology

The proposed system is modelled considering the discretization of the entire cycle of operation into 'n' equal time intervals. The mismatch between the supply and demand mainly influences the stored energy (*St*) and it can be estimated for i[th] interval as follows,

$$\Delta St_i = (g_i - l_i) \forall i \quad (1)$$

Here, g_i is the generation from the reformer and l_i is the hydrogen demand by the fuel cell.
The state of the stored energy level at the end of i^{th} interval is given by,

$$St_i = St_{(i-1)} + \Delta St_i \forall i \quad (2)$$

It should be noted that the storage energy level must always be a positive quantity and can be expressed mathematically as follows:

$$St_i \geq 0 \forall i \quad (3)$$

Moreover, for the system to be at autonomous, the energy level of storage at the beginning and end of a cycle must be the equal, i.e.,

$$St_{(i=0)} = St_{(i=n)} \quad (4)$$

In addition, the energy generated during each interval should be a non-negative quantity and maximum generation cannot exceed the rating of the reformer.

$$g_i \geq 0 \forall i \quad (5)$$

$$g_i \leq g_{ref} \forall i \quad (6)$$

The value of cumulative hydrogen generation must be equal to or greater than the cumulative hydrogen demand during entire cycle can be expressed mathematically as,

$$\sum_0^i g_i \geq \sum_0^i l_i \quad (7)$$

The point at which the cumulative hydrogen production touches the cumulative hydrogen demand, is referred as Pinch Point. The storage capacity is estimated as:

$$\max(St_i); 0 \le i \le n \tag{8}$$

3.1 Limit imposed by load constraint.

For a known load profile and reformer size, Eq(1), Eq(2), Eq(7) and Eq(8) facilitate estimating the storage size. The variation in the storage requirement is illustrated by the dotted line in Figure 2.It should be noted that for any reformer size less than the average load, the net energy generated in a cycle is less than the total energy required. This means that irrespective of the initial level of storage, the system can never ensure the autonomy in the system, as the final amount of energy in storage is always be less than the initial value. Thus, the constraint given by Eq(4) can never be satisfied and it is represented by the infeasible region-I in the Figure 2. For any reformer rating that is greater than the peak demand, storage is unnecessary as the reformer is capable of meeting the hydrogen demand. For any value of reformer size between these two limits, a minimum storage size is needed to ensure the autonomy of the system as illustrated by dotted curve in the Figure 2. It can be seen that as reformer size increases, storage needed decreases. This is very similar to the design space obtained for a PV battery system by Arun et al. (2009). As a PV battery system and a reformer–storage system are very similar in configuration, this trend is expected. In the region below the storage curve denoted by dotted line in the Figure 2, though enough energy is being generated by the reformer, the storage is not sufficient to store and meet the energy demand. This makes region-II also infeasible as far as the autonomy is concerned. Along the curve bordering regions-II and III, the size of reformer and storage are such that all the energy generated by the reformer is either used to meet the load directly or stored. No energy is wasted. In region-III, which lies above the curve, for any given storage volume, the reformer is oversized. This means that for any configuration in region-III, the storage size is overrated ensuring the autonomy of the system utilizing the entire hydrogen generated by the reformer.

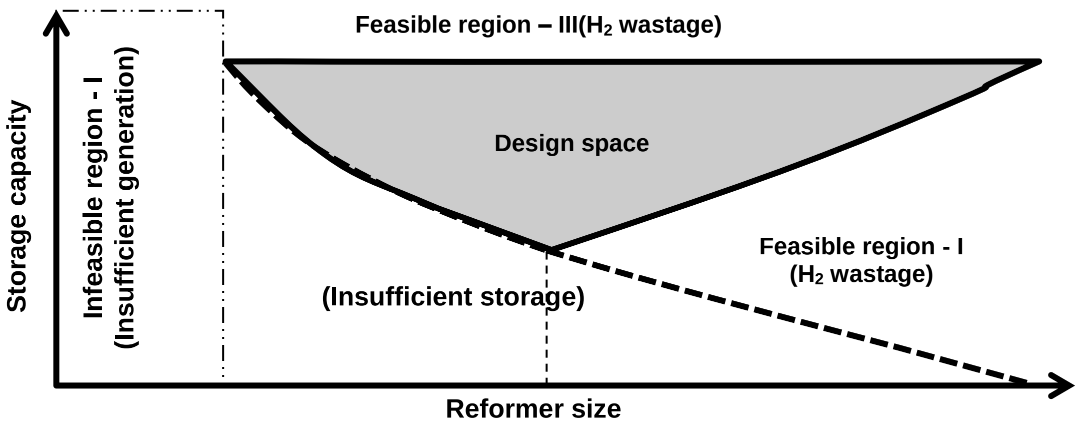

Figure 2: Design space for a hydrogen system

3.2 Constraint due to reformer's turndown ratio

Often, in addition to the constraints mentioned in the last section, an additional constraint arising from the technical capabilities of the reformer known as turndown ratio, may be required to impose in the sizing of the system. Turndown ratio refers to the window of the operational range of the reformer, and is defined as the ratio of the minimum capacity to the maximum capacity. Hence, the inclusion of the turndown ratio in the system can be expressed mathematically as follows:

$$g_i \ge g_{\min} \forall i \tag{9}$$

Here, the minimum value, g_{min} refers to the minimum hydrogen generation capability considering the turndown ratio, f_{td} and is given by Eq(10), where $P_{reformer}$ refers to the rating of the reformer.

$$g_{\min} = P_{reformer} \cdot f_{td} \tag{10}$$

Introduction of the turndown constrain in the estimation process, imposes limit in the minimum operating power of the reformer. In such a situation, the design space is altered accordingly as shown in Figure 2. The storage curve is altered in such a way providing local minima for a particular value of the reformer size. The value of the local minima depends on the turndown ratio. It can be seen that upto a certain value of reformer size, the value of minimum storage volume is the same as before. In these regions, since the reformer size in on the lower side, the reformer must already be operating at or above the minimum value constraint. Beyond the minimum storage point, however, the storage volume has to be increased so that the excess energy generated due to turndown ratio, can be stored to avoid the wastage of hydrogen. The region under design space offers a set of configurations capable of ensuring autonomous system without any excess generation of hydrogen. In feasible region-I, the reformer is forced to operate at the minimum power partly during operation when the demand is less and the storage capacity is insufficient to store the hydrogen casing some amount of hydrogen wastage to maintain the autonomous status of the system. In the feasible region-II, the minimum hydrogen generation capacity of the reformer due to turndown ratio becomes higher than the average hydrogen demand in the system. As a result of that a finite amount of hydrogen must be produced and wasted in every cycle of the operation so that the autonomy of the system is maintained following Eq(4).

4. Illustrative example

In this section, the methodology of design space using Pinch Analysis is applied to meet the daily electrical demand with a profile as illustrated in Figure 3. The average daily electrical energy requirement is 5 kW with peak demand of 10 kW and base load of 2 kW. Since, the efficiency of the fuel cells depends on the load and it increases at partial load, the varying efficiency is considered for the estimation as shown in the Figure 3. The variation in daily hydrogen demand by the fuel cell from the reformer/storage is estimated based on the electrical load and the fuel cell efficiency as shown in Figure 3. The average energy requirement is around 10.2 kWh/d and the peak requirement is around 22.22 kWh.

The optimum energy required for the system is estimated following the methodology explained in the previous section. The estimations of the storage size for three different sizes of reformer with two different turndown ratios are shown in Figure 4. In this figure, the cumulative plot of hydrogen generation by the reformer, hydrogen demand by the fuel cell and meeting point of these two curves refer to the Pinch Point, i.e. at this point the hydrogen generation is just sufficient to satisfy the hydrogen demand. So the storage requirement at this point is zero. Basically Pinch Point signifies a point at which driving force is minimum (zero in this case). The demand curve cannot go beyond this point, (as the storage cannot be negative).

The cumulative mismatch between the hydrogen generation and the demand is referred as Grand Composite Curve (GCC), which falls to zero at a reformer size corresponding to the Pinch Point. The storage capacity is determined from GCC based on the Pinch Point on the plot. It is seen that when the reformer capacity is equal to the average load (10.17 kW in this example) a storage capacity of 36 % of the total daily hydrogen demand It should be noted that no turndown constrain of the reformer is imposed during the sizing of the storage as mentioned above. The variation in system behaviour with a turndown ratio of 0 % and 40 % is presented in Figure 4. Here, the reformer size is considered to be 16.67 kW (75 % of peak load). It is observed that the requirement of the storage size is increases with the introduction of the turndown ratio.

It is observed that the storage size is increased from 10 % to 16 % in a system with minimum reformer size having a turndown ratio of 40 %.The variation in the storage requirement with reformer size is shown in Figure 5. It represents the variation in the storage size for different turndown ratio of the reformer. From the figure it is clear that the storage requirement decreases monotonously with the increase in the reformer size. However, with the inclusion of the turndown ratio constrain in the estimation of the storage size, a local minima is observed. In other words, for every reformer size there is a specific turndown ratio.

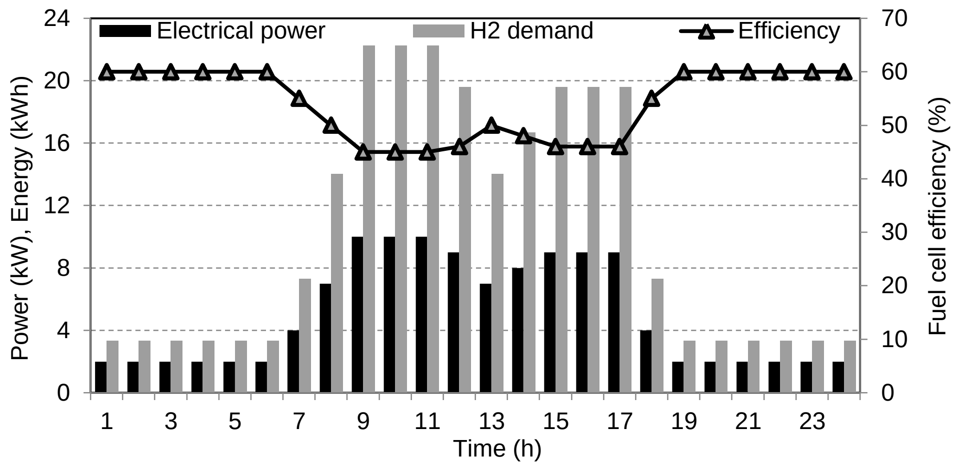

Figure 3: Daily behaviour of the load profile, H_2 demand and corresponding fuel cell efficiency

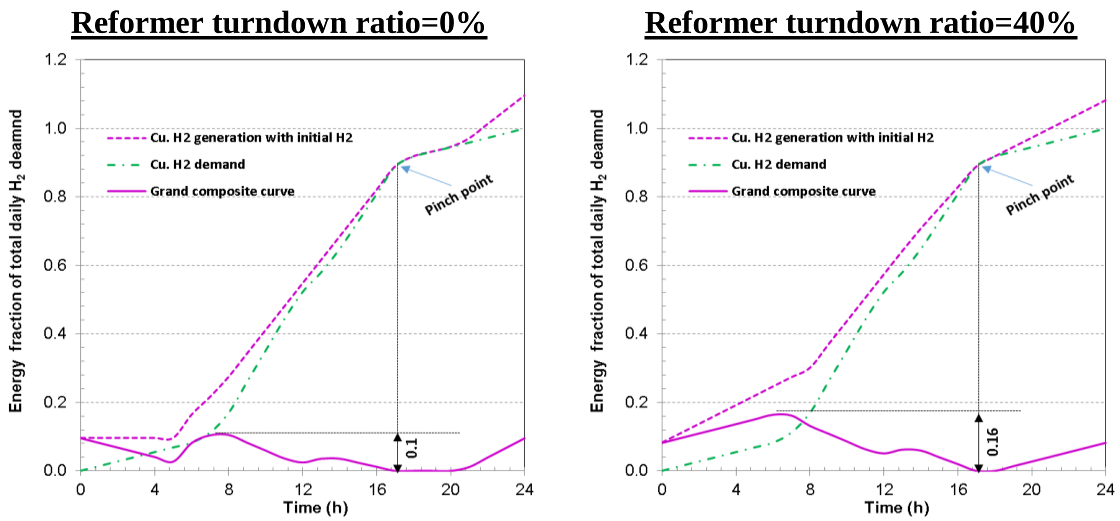

Figure 4: System behaviour with a turndown ratio

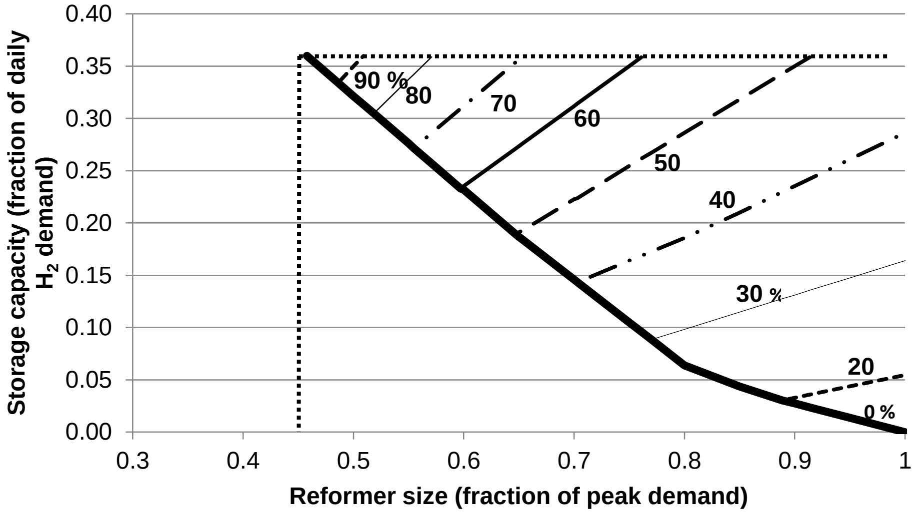

Figure 5: Design Space with variation in turndown ratio.

5. Conclusion

In this paper, a design space method based on Pinch Analysis is applied successfully to size a hydrogen storage supported reformer based fuel cell system. In order to do so, a hydrogen fuel cell system is studied and a mathematical formulation is done considering various constraints involved in sizing such a system. It is observed that for a given load profile, the size of the reformer must at least be equal to the average load. Also, the size of the storage decreases monotonously with the increase in the reformer size. This plot of reformer size vs. storage volume is found to deviate if the reformer turndown ratio of the reformer is introduced. If so, beyond a point, the storage volume increases to accommodate the increase in energy generation. This solution is also verified using GCC. This study can be further expanded to include a sensitivity analysis to the minimum reformer limit, load characteristics etc. The major benefit of the proposed methodology is that is does not needs any special optimisation tools or software for getting the optimal solution. As this work is the first adaptation of pinch analysis and design space for hydrogen system sizing, a comparison is not possible at the moment. It can however be seen that in addition to being a useful sizing technique, this method provides insights into the system behaviour, such as the relation of reformer size vs. storage volume plot to turn down ratio. Economic optimization can also be carried out to find the most cost effective solution.

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