H_2/Br_2 Flow Battery System Architecture and Control System Analysis

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Abstract

This M.Sc. dissertation aims at implementing a system architecture, dynamic behavior analysis, component selection and experimental study for the Elestor hydrogen bromine flow battery to develop its control system. To reach this goal, different considerations on the system architecture design are proposed. Moreover, components such as a current sensor and an electrolyte pump for the Elestor H_2/Br_2 flow battery were selected and tested. In addition, a first experimental study on the performance of the first Elestor H_2/Br_2 flow battery was done at different hydrogen pressure and electrolyte pump speed. In the theoretical analysis, the transfer function for both open and closed loop electrolyte subsystem are investigated from dynamic mass balance; and also the step responses are premeditated. From the theoretical analysis it was found that the open loop step response of the electrolyte subsystem behaves as a pure capacitive process. The result from the analysis carried out also shows that the closed loop step response of electrolyte subsystem behaves as first order system. The stability analysis of the closed loop electrolyte subsystem under (P) controller shows that the system is stable when the value of the proportional gain of the controller is greater than zero and unstable when the value of proportional gain of the controller is less than zero.

Keywords: H_2/Br_2 flow battery, System Architecture, Transfer function, Proportional controller, Electrolyte flow rate

Nomenclature

$d(s)$ Load current in terms of *s* function

$G_c(s)$ Transfer function of the controller

$G_p(s)$ Transfer function of electrolyte subsystem

I Current, A

K_c Proportional gain of the controller

n Amount of electrolyte in the active area, mol

$\dot{n}_{in}$ Total input molar flow rate, mol/s

$\dot{n}_{out}$ Total output molar flow rate, mol/s

$N(s)$ Output flow rate of electrolyte in terms of *s* function

$N_{set}(s)$ Set point electrolyte flow rate in terms of *s* function

$N(t)$ Output flow rate of electrolyte at time (t), mol/s

$N*(t)$ Amount of electrolyte in the active area at time (t), mole

$V(I)$ Calculated voltage, V

Constants

F Faraday constant, (96485 Col/mol)

G_{th} Theoretical sensitivity LEM 25 CRKS, (25 mV/A)

1. Introduction

The production of electricity from renewable energy resources, such as wind and solar, has been highly encouraged, and intense research activities have been carried out to harness the power from wind and solar. As reported in (Cho, et al., 2012) by 2020, there will be a production of 474 GW power from wind farms throughout the world that will be more than five times the 2007' production. The growth rate of wind capacity all over the world was quite low from 2000-2006, with a total increment of 57 GW over 7 years period. However, it has increased radically from 94 GW in 2007 to 318 GW in 2013 (REN21. 2014).The power produced from wind in the world was 318 GW in 2013, showing 12 % increment compared to 2012 (REN21. 2014).

Simultaneously, the production of electricity from solar is also increasing. The solar photovoltaics capacity of the world was almost negligible in 2004, and slowly growing till 2009. Since 2010, the installed capacity was increased by more than 30 GW per year and reached 139 GW in 2013 (REN21. 2014). This implies that more attention has been given to the use of wind and solar energy. However, the intermittency and unpredictability of wind and solar have been driving demand for energy storage technologies.
Nowadays, energy storage technologies based on flow batteries became a promising technology to manage and to use efficiently the energy from solar and wind. Flow batteries are relatively easy to scale up and work efficiently as energy storage systems (Nguyen & Savinell, 2010). As result, attention has been given to this issue by a number of research institutes, manufacturing companies and universities to develop and to commercialize efficient and affordable energy storage system.
One of the KIC Innoenergy start-up companies, Elestor BV., works on the development of H_2/Br_2 flow battery. Elestor BV. is located in Arnhem, The Netherlands. The mission of the company is to develop electrical energy storage solutions with reasonable price, by using abundant and relatively cheap materials (H_2 and Br_2), easily manufactured compact cells, simplified system architectures and robust control systems. Through these advantages Elestor expects to deliver a revolutionary H_2/Br_2 flow battery with an approximate cost of € 0.05 /kWh.

After NASA discovered the redox flow battery concept in 1974, the hydrogen/bromine fuel cell system has been widely studied for large scale energy storage. Yeo and Chin were the first to thoroughly investigate H_2/Br_2 flow battery (Cho, et al., 2012).

As shown in figure 1, during charging and discharging of the hydrogen bromine flow battery reduction and oxidation reactions take place in the cathode and in the anode. More precisely, at the anode, hydrogen is oxidized during discharge, while it is reduced during charge. At the cathode of the cell, bromine is reduced and oxidized during discharge and charge, respectively. The ideal electrochemical cell reactions of H_2/Br_2 battery at 25ºC are presented as follows (Cho, et al., 2012):

At the positive electrode/ cathode:

$$Br_2(aq) + 2e^- \underset{Charge}{\overset{discharge}{\rightleftharpoons}} 2Br^-(aq) \qquad (1)$$
$$E^0 = 1.098\,V$$

At the Negative electrode/ anode:

$$H_2(g) \underset{Charge}{\overset{discharge}{\rightleftharpoons}} 2H^+(aq) + 2e^- \qquad (2)$$

$$E^0 = 0.0V$$

Overall cell reaction:

$$Br_2(aq) + H_2(g) \underset{Charge}{\overset{discharge}{\rightleftharpoons}} 2HBr \qquad (3)$$

$$E^0 = 1.098\,V$$

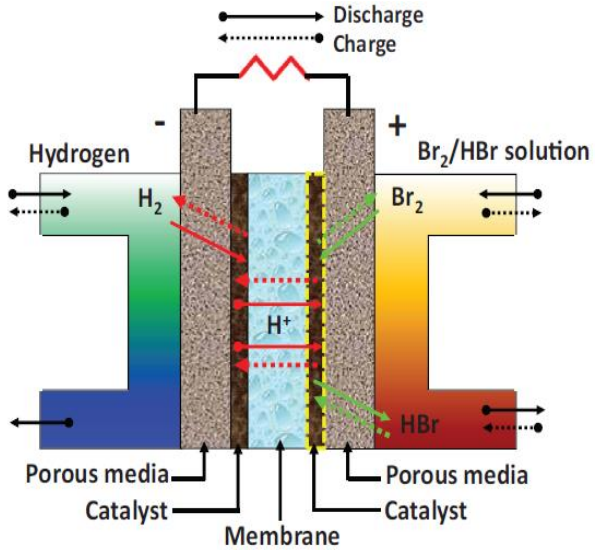

Figure 1. Cross section view of hydrogen/bromine flow battery (Cho, et al., 2012)

H_2/Br_2 flow battery presents the following benefits (Yeo & Chin, 1980) and (Savinell & Fritts, 1986).

i) The electrode reactions are fast which enables high efficiency;

ii) The system tolerates both over discharge and charge, therefore the probability of damaging the cell due to these effects is reduced;

iii) It has low self-discharge and thus the cell has high columbic efficiency;

iv) Since Br_2 has low vapour pressure and is dangerous for health, the electrolyte and Br_2 electrode can operate at ambient pressure.

H_2/Br_2 flow battery is an attractive technology for large scale electrical energy storage due to high power density, high round trip efficiency and its low cost (Nguyen, et al., 2014). Recent findings at the Lawrence Berkley National Laboratory also showed that H_2/Br_2 flow battery has high energy storage efficiency, nearly 88% (Tucker, et al., June 2015). As result, hydrogen bromine flow battery becomes one of the most promising electrical energy storage system.

This M.Sc. dissertation aims at implementing a system architectures, dynamic behavior analysis, component selection and experimental study for the Elestor H_2/Br_2 flow battery in order to develop a control system.

2.System Architecture Design Considerations

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3. Theoretical Dynamic Behavior Analysis

The control system will be developed only for the electrolyte subsystem and it will be developed based on the current and the electrolyte flow rate. Meanwhile, hydrogen pressure will be measured to know the state of charge (SOC) of the battery, but it will not be controlled.

Using the mass conservation equation the dynamic, mass balance of the electrolyte subsystem is given by:

$$\frac{dn}{dt} = \dot{n}_{in} - \dot{n}_{out} + \frac{I}{2F} \qquad (4)$$

By considering a steady state condition and following mathematical arrangement of equation (4), the transfer function of the electrolyte subsystem becomes:

$$G_p(s) = \frac{1}{s} \qquad (5)$$

For a step change of the input, the output of the open loop electrolyte subsystem as function of time (t) becomes:

$$N^{*}(t) = t \quad (6)$$

3.1 Transfer Function of the Closed Loop Electrolyte Subsystem with a Proportional (P) Controller

The control system of the Elestor H_2/Br_2 flow battery will contains measuring devices (current sensor, electrolyte flow rate sensor and hydrogen pressure sensor), final control element (pump) and the controller.

The flow field in the cell stack has a channel and thanks to this; there is electrolyte inside the field, even if the pump stops for a short period of time. Thus, it is assumed that the effect of measurement lag is negligible.

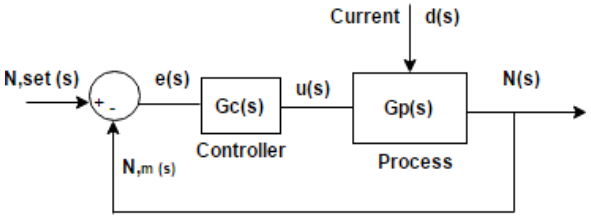

Figure 2. Process block diagram for the electrolyte subsystem with a P controller

To determine the closed loop transfer function of the electrolyte subsystem under the P controller:

$$N(s) = \frac{G_p(s)*G_c(s)}{1+ G_p(s)*G_c(s)}\, N_{set}(s) + \frac{G_p(s)}{1+ G_p(s)*G_c(s)}\, d(s) \quad (7)$$

For a step change of the load current equation (7) after mathematical rearrangement becomes equation (8).

$$N(s) = \frac{\frac{1}{K_c}}{\left(\frac{1}{K_c} * s + * 1\right)} * \frac{1}{s} \quad (8)$$

By Laplace inversion equation (8) becomes:

$$N(t) = \frac{1}{K_c} * (1 - e^{-K_c * t}) \quad (9)$$

From the stability analysis, the closed loop electrolyte subsystem is stable when $K_c > 0$, and unstable when $K_c < 0$.

4. Component Selection and Cell Performance Experimental study

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5. Results and Discussion

5.1 System Architectures

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5.2 Open and Closed Loop Step Response of Electrolyte Subsystem

As it is defined in equation (5), the electrolyte subsystem behaves as a pure capacitive process. If only current is measured and if there is no electrolyte flow rate measurement, there will be accumulation of electrolyte inside the cell that aggravates the crossover of electrolyte to the active site of the cell. As result, poison of the Pt catalyst and decreasing of performance will happen (Cho, Ridgway, Battaglia, Srinivasan, & Weber, 2014).To avoid such kind of problems, the speed of the electrolyte pump must be controlled based on the current load. As result, proportional controller is used to control the speed of the Elestor hydrogen bromine flow battery electrolyte pump.

The open loop and closed loop (with P controller) transfer function of electrolyte subsystem obtained from theoretical analysis are presented in equation (5) and equation (8), respectively. The

trend of the step response of the electrolyte subsystem without controller and with the P controller for a load current variation are depicted in figure 3 and figure 4, respectively.

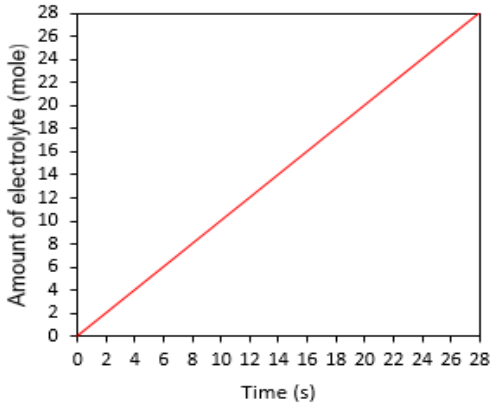

Figure 3.The behavior of the step response of open loop electrolyte subsystem

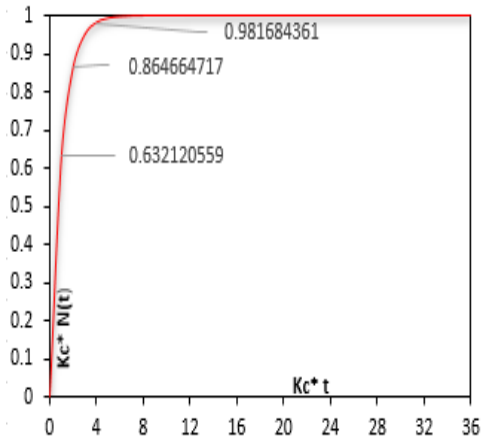

Figure 4.The behavior of the step response of electrolyte subsystem with P controller

5.3 Components selection and Experiment

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5.3.1 Cell Performance

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6. Conclusion

Different system architectures are proposed for the Elestor H_2/Br_2 flow battery. The system architecture proposed with a purge valve was found to be environmentally unfriendly. The system architecture with double tanks has the most expensive initial investment. From dynamic behavior analysis it is found that the electrolyte subsystem without any control mechanisms behaves as a pure capacitive process. However, the step response of the closed loop with P controller behaves as first order system. The closed loop system is stable when $K_c > 0$, and unstable when $K_c < 0$. The result of the performance test shows that there is a slight increase of performance with the pump speed. However, it needs a lot of experiment with multiple cells to better assess the effect the pump speed.

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