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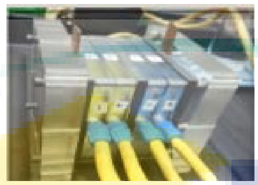

TITLE OF RESEARCH:

EXTENDED KALMAN FILTER (EKF)-BASED MODULAR-STACK VANADIUM REDOX FLOW BATTERY (V-RFB) PREDICTION MODEL DEVELOPMENT FOR REDUCING ELECTRODE CONTACT RESISTANCE AND PARALLELIZATION CURRENT

Name of Project Leader :

ASSOCIATE PROF. TS DR MOHD RUSLLIM BIN MOHAMED

Name of co-researchers:

1. PN. NOOR LINA BINTI RAMLI
2. DR. SAIFUDIN BIN RAZALI
3. DR. MOHD HERWAN BIN SULAIMAN
4. PM. DR. MAZRUL NIZAM BIN ABU SEMAN
5. PROF. DR. AZIZAN AHMAD

IPT/ Faculty / School/ Centre/Unit :

UNIVERSITI MALAYSIA PAHANG/ FACULTY OF ELECTRICAL & ELECTRONICS ENGINEERING

E-mail:

rusllim@ump.edu.my

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ABSTRACT (120 words)

Vanadium Redox Flow Battery (V-RFB) is a type of rechargeable flow battery that employs vanadium ions in different oxidation states. It undergoes oxidation and reduction reaction during discharge and charge process at anode and cathode. Presently, there are lack of publication studies on electrical circuit model for V-RFB. Electrochemical model is commonly use to represent battery due to its detailing in electrochemical process, however, the model is not suitable to identify electrical behavior of V-RFB. Parameter estimation on battery model is a process to fit an equivalent circuit into the battery. This thesis presents equivalent electrical circuit consists of actual and approximate circuit for V-RFB as well as hydrodynamics behavior of the Vanadium redox flow battery (V-RFB) by using 3D computational fluid dynamics (CFD) models. The aim of this project is to propose equivalent electrical circuit for V-RFB that represents excellent adaptableness to any circuitry analysis and design and to study the pump power (pump energy consumption) and electrolyte flow distribution required within the cell.

1. INTRODUCTION

Energy is one of the most important properties in human lives. While it presents everywhere and it has the capability to make changes to the surrounding, it can neither be created nor destroyed as stated in the law of conversion of energy and statement for the First Law of Thermodynamic (Law & Law, 2009). The production of energy that is captured for a later use is known as energy storage. There are many types of energy storage and electrochemical energy storage is one of it (Oberhofer, 2012). Electrochemical energy storage is a conversion of chemical to electricity potential and vice versa for storage. This storage describes various types of batteries and almost all of them are technically advanced for application (Iec, 2009).

Batteries store energy from hours to days, the storage capacity can be extended without the need to upgrade the power generation system so it is easily scalable. There are two basic types of batteries; primary (non-rechargeable) and secondary (rechargeable) batteries (Vutetakis, 2001). Secondary or rechargeable battery is the type of electrical battery which is charged by applying electric current and is discharged when being used (Doughty, Butler, Akhil, Clark, & Boyes, 2010).

Studies have found that energy storage is significant and is a potential solution to stabilise load level and strengthen the power network. There are various types of energy storage that transfer and distribute energy, such as compressed air energy storage (CAES), flywheel energy storage (FES), pumped hydro energy storage (PHES), superconducting magnetic energy storage (SMES), and battery energy storage (BES) (Mahlia, Saktisahdan, Jannifar, Hasan, & Matseelar, 2014). There are many possible techniques or types of storage in this world, but this work focuses on one of the battery energy storage technologies. Among various battery energy storage technologies, vanadium redox flow battery (V-RFB) offers promising advantages because of its supreme features including effective and simple operation, capability of high power independent of energy and power capacities, fast response and recharging contenders, excellent chemical stability that shows an extremely long-round-trip cycle, operationality at room temperature, long discharge times exhibited for highly reversible redox kinetics, suitable for large-scale applications, and reasonable and controlled maintenance cost compared to conventional battery (Miyake & Tokuda, 2001; Park, Jeon, Ryu, & Hwang, 2017).

Vanadium Redox Flow Battery (V-RFB) is a rechargeable flow battery that employs vanadium ions to store chemical potential energy in different oxidation states. It undergoes oxidation and reduction reaction during discharge and charge processes at anode and cathode. Both sides of V-RFB system selective membrane use vanadium compound because it is fundamentally reliable and it has simple maintenance procedures which are different from the other flow batteries (Blanc & Rufer, 2010). By eliminating cross-contamination the electrolyte does not require to be changed, it lasts indefinitely and it is highly efficient as the charge acceptance of the system is optimal and nominal (Tokuda et al., 1998). Hence, it lasts long and there are no losses of system integrity. More attention has been given on V-RFB rather than other chemical batteries because V-RFB has unique features which consist of decoupled energy storage and power component. These features give V RFB an independent control of capacity and power and are attractive for optimisation of power and energy in Electric Vehicle (EV) applications (Mohamed, Sharkh, & Walsh, 2010). In addition, V-RFB employs the same element in both the positive and negative half-cells, so it does not affect battery capacity as the problem of cross-contamination of ions is avoided.

Battery's circuit need to be model properly. It is vital to acquire precise simulation and result. By modelling complex circuit into simplify form, analyzation can take place smoothly. Furthermore, it will reduce cost and time. A proper way to describe dynamic process of chemical reaction on the system electrodes of V-RFB is based on electrochemical model (Dees, Battaglia, & Bélanger, 2002; Shah & Walsh, 2009; Caiping Zhang, Liu, Sharkh, & Zhang, 2009). However, to describe V-RFB electrical behaviour is not well appropriate due to the requirement of battery chemical parameters. Thus, an equivalent electrical circuit that signifies excellent adaptability and simple realization of V-RFB system is required.

2. RESEARCH METHODOLOGY

1.1 Modelling

Equivalent electrical circuit has widely been researched and used due to its simplicity and adaptability on any circuitry design system. The connection at the battery terminal between voltage and current is known as an electric circuit. The proposed equivalent electrical circuit for V-RFB resembles (Choi, Enjeti, & Howze, 2004) and (Chang, 2013). Both researchers used the circuit for Fuel Cell (FC) (Chang, 2013) to estimate parameter of the circuit for FC using current change method, whereas (Choi et al., 2004) used it to evaluate current ripple effect for Power Conditioning Unit (PCU). FC and RFB are similar theoretically. However, in the FC system the electrolyte remains in the cell stack, whereas in RFB redox reaction occurs as the electrolyte flows through the cell stack. The equivalent circuit is also proposed based on the design consideration in

(Salerno & Korsunsky, 1998) with the present of parasitic inductance. Parasitic or stray inductance is an unintended inductance in a circuit and has undesired effect in a way. However, in some applications parasitic inductance give desired effect; helical resonators and battery protection circuit. Equivalent circuit model presented has two types actual and approximate.

The simulation and modelling of V-RFB are evaluated with different V-RFB geometries under three cases which is plain (no flow channel), parallel, and serpentine, at flow rates of 5 - 30 cm3s−1. The controlled flow rates parameter is use in the range as stated above. 5 cm3s-1 is shown as laminar flow, whereas 10, 15, 20, 25 and 30 cm3s-1 present as turbulent flow. These studies are operating in laminar and turbulence flow at the cell geometries that in practise for non-ideal condition. Other parameters such as temperature, current densities and performance of cell laboratory unit of V-RFB at voltage, coulombic, and energy efficiency are not calculated and considered because these studies are focusing in analysing the hydrodynamic behaviour and natural phenomenon inside the V-RFB cells.

3. LITERATURE REVIEW

Energy storage is required to store electrical energy during times of low demand at low energy cost and for the surplus energy generated from intermittent energy sources of RES (Alamri & Alamri, 2009). The demand for electricity varies emergently; there may be days or seasons where there is maximum demand of supply which may last for a few hours each year. This leads to the inefficient power supply, over-designed power storage and supply, and expensive costs (D. You, Zhang, & Chen, 2009). So far, energy storage plays an important role in power system operation, control, and management. Efficient energy storage can add the following benefits to power utilities by reducing energy consumption, cost and overcome energy shortages problem (Fisher et al., 2014). Generally, energy storage technologies are categorised into three main types, which are electrical, mechanical, and electrochemical energy storage systems.

Due to system power and capacity can be largely decoupled, RFB seem to be especially attractive system in electrochemical energy (Mohamed et al., 2010). An RFB electrolyte is typically composed of three species: a solvent, supporting electrolyte, and the active species, or redox couple. Redox reactions are reduction and oxidation reactions in which the oxidation states of molecules change. RFB configuration; the characteristics and components are similar to those of fuel cell in the way that electrochemical energy is reserved in the tank that is occupied with active species.

Practically, the RFB mechanism consists of three segments including the cell stack, energy reserve tank, and flow circulation system. The cell stack consists of individual cells where every single cell contains a part where the electrochemical charge transfer reaction happens to store or release energy under redox reaction. Redox reaction is a reduction and oxidation process where the reduction involved the release of electron, and the oxidation involved the gain or recombination of the ions (Kear, Shah, & Walsh, 2012).

The reactants in the tank are recirculated through the redox flow cell. Pumps are used in flow batteries to help flow circulation by circulating the electrolyte for redox reaction which occurs through the cell stack and a porous electrode to generate electrons, which flow through the external circuit (Ponce de León et al., 2006).

On the negative side, flow batteries are rather complicated in comparison with other standard batteries as it is required much component which were pumps, sensors, control unit, reservoir tanks and electrolyte tube. The energy densities are relatively small compared to Lithium ion batteries.

Figure 1.1 represent the components of V-RFB cell to become one complete cell stack. The main parts of a unit cell of V-RFB, which consist of cell membrane, flow frame electrode (cell geometry) and pumping system. V-RFB basically comprises of positive and negative parts containing an anolyte and catholyte with an interposed membrane or ionic separator. So, one-unit cell stack consist of two half-cell is separated by a membrane. V-RFB store energy in two electrolytic solutions containing redox couples. The solutions are circulated through their external tanks by means of two pumps. Similarly, to fuel cell this architecture decouples power rating, which depends on the stack size, from stored-energy rating, which depends on the tanks volume. The overall stack structure is shown in Figure 1.2. Next, a multiple cell can be stacked together in series to produce a modular stack as illustrated in Figure 1.3.

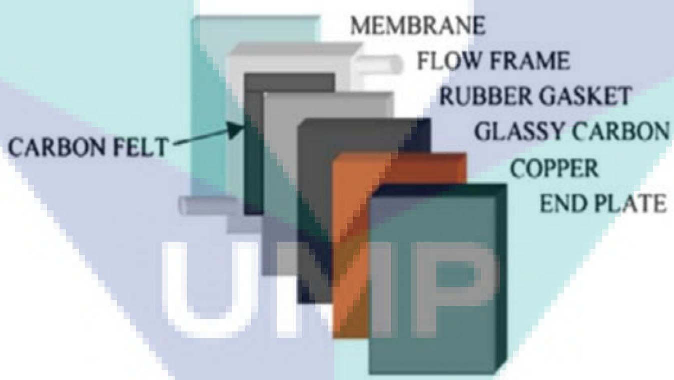

Figure 1.1 Components of V-RFB cell stack

Source: (Parasuraman et al., 2013)

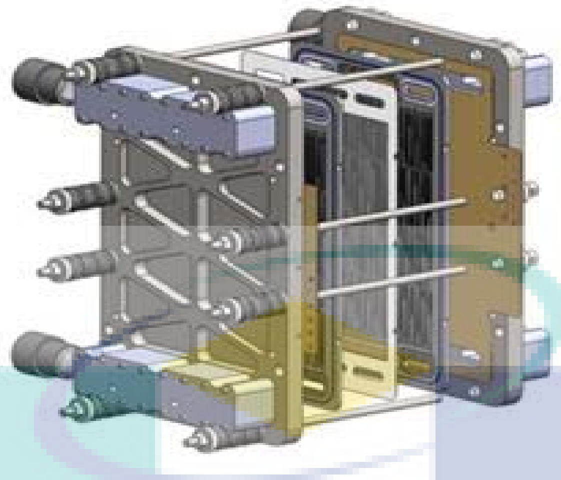

Figure 1.2 Complete single unit of V-RFB cell
Source: (Fisher et al., 2014)

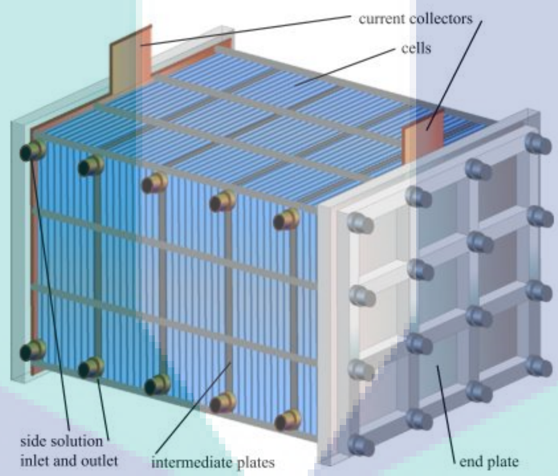

Figure 1.3 Modular stack
Source: (Alotto et al., 2014)

Open Circuit Voltage (OCV) and internal resistance are the elements in the simplest ECM. Some ECM also consist parallel resistance-capacitor (RC) network and the accuracy and complexity increase as the branches of RC network increase (Pour, 2015). Higher number of RC influences the complex nonlinear electrochemical processes within the battery, with better modelling accuracy and presentation, it shows no large difference between the error of the system, as the RC network increases from three or more the error produced decreases but reduction of error speed will become slower and lower (S. X. Chen, Tseng, & Choi, 2009; Díaz-gonzález et al., 2012; M. R. Mohamed et al., 2013) . There is also an equivalent circuit model with parasitic and pumped losses (Chahwan, Abbey, & Joos, 2007). Electrical-circuit model was first proposed by Hageman and nickel-cadmium lead acid and alkaline batteries were stimulated using simple PSpice circuits (Jongerden & Haverkort, 2008). Figure 1.4 shows the circuit proposed by Chahwan et al. (2007) and Figure 1.5 shows the circuit proposed by M. R. Mohamed et al. (2013). Electrical circuit model is simpler model than electrochemical model, so it less costly computationally.

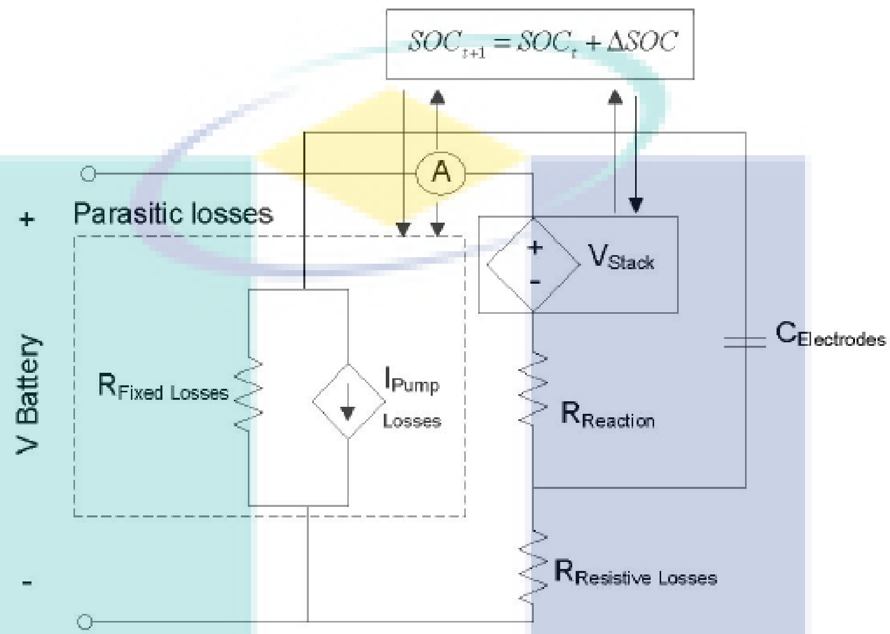

Figure 1.4 Equivalent circuit for V-RFB proposed by Chahwan at el (Chahwan et al., 2007)

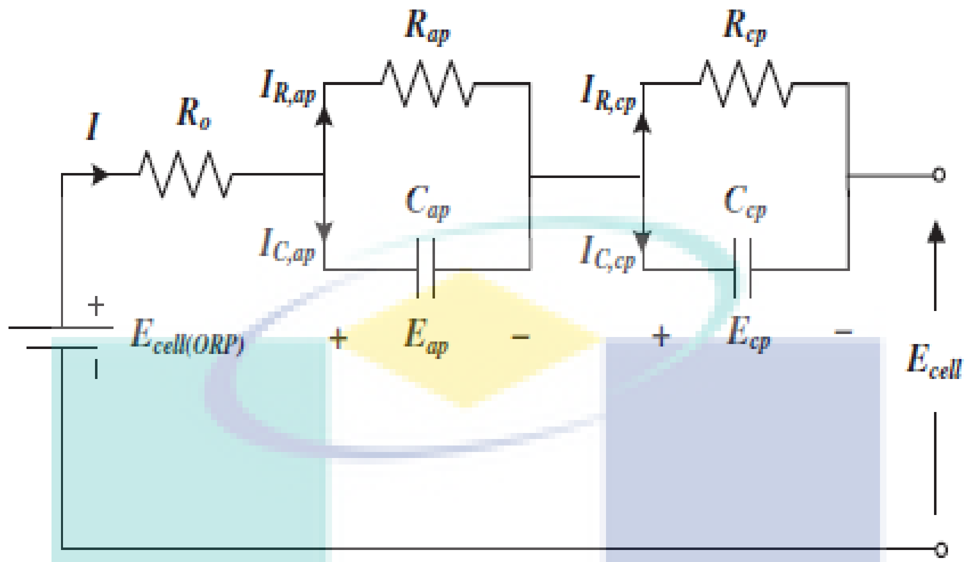

Figure 1.5 Equivalent circuit for V-RFB proposed by M.R.Mohamed (M. R. Mohamed et al., 2013).

Research on parasitic inductance does not only focus on battery but also converter, electrical vehicles, and power network among others. Several researchers presented the equivalent circuit with the present of parasitic inductance. (Pan et al., 2016) designed Power Distribution Networks (PDNs) to decrease the parasitic inductance between power/ground pads on PCB and junction point to PDNs because it can limit high frequency performance and as a result, equivalent lumped circuit is developed to extract parasitic inductance of the PDNs. (Salerno & Korsunsky, 1998) designed protection circuit for Lithium-ion battery system loads effects and parasitic elements. This is to avoid over-charge and over-discharge when there is presence of current. However, at high transient current the parasitic element will affect the operation and performance of the system. (Affanni, Bellini, Franceschini, & Guglielmi, 2007) also mentioned voltage drop can mislead the protection circuit causing under-voltage, and as such, it is necessary to consider parasitic elements during transient state.

4. FINDINGS

For equivalent circuit, the actual circuit consists of an open-circuit cell potential, two Resistor-Capacitor (RC) branch, a series RC, internal resistance, and inductor. From the circuit, some of the parameters are lumped to construct approximate circuit consists of open-circuit cell potential, impedance of RC branches and internal resistance with inductor. Approximate circuit is built in order to present less complex result and save time. Extended Kalman Filter (EKF) is used for parameter estimation for both circuit. Actual and approximate circuit are derived accordingly. The simulation result through recursive EKF algorithm of each parameters of both circuits shows approaching steady with 0.6% and 2.0% errors, respectively. So, it proven that both circuit are adaptable for V-RFB. On the other hands, three different cell geometries of V-RFB cell, namely square-, rhombus- and circular cell designs are evaluated at three different cases i.e. no flow (plain) channel, parallel channel and serpentine channel. Furthermore, the work has been extended in modular stack of 100 cm^2 of V-RFB. The stack has been developed and tested to observe the pump power within the stack in the three designs which directly related to performance of the cell with respect to power distribution and power losses. Based on the findings, the cell exhibits different characteristics under different geometries of V-RFB cell at no flow channel application. Conversely, based on the scaling up of the cell geometry, the relationship between pump power and cell geometry for 100 cm^2 of V-RFB has been developed. Optimum flow distribution within the cells without fluid flow channels were recorded; highest and lowest pump consumption at 25.6% and 18.4% respectively. Extended reduction of power losses by 53% were recorded as parallel flow channels has been applied to the V-RFB. Proportionate correlations were observed for modular V-RFB as a result of scaling up of the cell and potential for further analysis of extension to the n^{th} cell. Further works are presented for future research in geometry study of V-RFB.

5. CONCLUSION

The result of parameter estimation by using EKF method of estimated EKF-based and experiment cell voltage for both circuit are overlapped and estimation of each parameter for both circuits shows approaching steady state. Therefore, it is proven that actual and approximate circuit are adaptable for V-RFB and also approximate circuit as an alternative for actual circuit. The effectiveness of the model simulation verifies where the error is closer to zero; 0.6% and 2.0% errors, respectively. Thus, it is also proven that EKF mothed is one of the best choices for parameter estimation. Furthermore, the work summarizes for critically considers design, construction and cell features together with their benefits and problems, leading to good practice through improved cell performance. This work presented a new design and development of single cell and modular stack of V-RFB. The newly developed 100 cm^2 conventional square, rhombus and circular cell geometries with flow channel added have been presented in details; in which the cell geometries and flow channel were suitable for expanding the studies on V-RFB. Notably, the optimum results of the V-RFB cell indicate that the circular geometric cells design without fluid flow channels record evenly electrolyte distribution within the cells and shows the lowest pump power consumption reduction is 25.6% at the lowest and 18.4% at the highest flow rate. In addition, circular geometry cells show the rate of percentage is decreasing 53% with parallel flow channels applied.

ACHIEVEMENT

i) Name of articles/ manuscripts/ books published

ii) Title of Paper presentations (international/ local)

1. S.F.M. Ibrahim, M.R. Mohamed, S. Razali, H. Ahmad, M.H. Sulaiman, "Kalman filter-based parameter estimation for vanadium redox flow battery (V-RFB) equivalent circuit with parasitic inductance" In: The 9th International Meeting on Advances in Thermofluids (IMAT 2017), 25 January 2017, Universiti Teknologi Malaysia, Skudai.

2. S. Sujali, M.R. Mohamed, A.N. Oumer, and A. Azizan and P.K. Leung (2018) “Study on architecture design of electroactive sites on Vanadium Redox Flow Battery (V-RFB”. International Conference on Renewable Energy and Environment Engineering (REEE 2018), 29-31 October 2018, Paris, pp. 1-5.

3. S. Sujali, M.R. Mohamed, S.A. M.Don, N. Yusoff “Method Approaches to prevent leakage cell stack of Vanadium Redox Flow Battery (VRFB)” 4th IET Clean Energy and Technology Conference (CEAT 2016) 14th -16 th November 2016 pp. 1-7

iii) Human Capital Development : **2 MSc Graduated**

iv) Awards/ Others

v) Others

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APPENDIXES

N/A