KALMAN FILTER-BASED PARAMETER ESTIMATION FOR VANADIUM REDOX FLOW BATTERY (V-RFB) EQUIVALENT CIRCUIT WITH PARASITIC INDUCTANCE

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ABSTRAK

Vanadium redoks aliran bateri (V-RFB) adalah sejenis bateri boleh dicas semula aliran yang menggunakan ion vanadium dalam pengoksidaan yang berbeza. Ia menjalani tindak balas pengoksidaan dan pengurangan semasa proses pelepasan dan caj pada anod dan katod. Pada masa ini, terdapat kekurangan penerbitan kajian ke atas model litar elektrik untuk V-RFB. Model elektrokimia biasanya digunakan untuk mewakili bateri kerana ia memperincikan proses elektrokimia, Walau bagaimanapun, model ini tidak sesuai untuk mengenal pasti tingkah laku elektrik V-RFB. Penilai parameter untuk model bateri ialah satu proses untuk memuatkan satu litar setara ke dalam bateri. Tesis ini membentangkan litar elektrik setara yang terdiri daripada litar sebenar dan anggaran untuk V-RFB. Matlamat projek ini adalah untuk mencadangkan litar setara elektrik untuk V-RFB yang mewakili kebolehsuaian yang sangat baik untuk mana-mana litar analisis dan reka bentuk. Bilangan perintang boleh-kapasitor (RC) yang banyak boleh meningkatkan ketepatan dan perwakilan dalam bateri. Walau bagaimanapun, ia meningkatkan kerumitan model dan mengurangkan pengurangan kelajuan ralat. Litar sebenar terdiri daripada satu potensi sel litar terbuka, dua cawangan perintang boleh-kapasitor (RC), siri RC, rintangan dalaman dan peraruh. Daripada model ini, beberapa parameter disusun semula untuk membina litar anggaran yang terdiri daripada potensi sel litar terbuka, galangan cawangan RC dan rintangan dalaman dengan peraruh. litar anggaran dibina untuk membentangkan hasil kurang kompleks dari segi menilai parameter. Semakin kurang bilangan parameter yang dinilai, semakin kurang masa diperlukan untuk simulasi. Penapis Kalman Lanjutan (EKF) digunakan untuk penilaian parameter bagi kedua-dua litar. Litar sebenar dan anggaran diperolehi dengan sewajarnya. Daripada hasil simulasi melalui rekursi EKF algoritma, terbitan untuk kedua-dua litar menunjukkan setiap parameter lancar menghampiri keadaan stabil dengan ralat 0.6% dan 2.0%. Kedua-dua potensi sel eksperimen dan simulasi EKF bertindih dengan perbezaan kecil untuk litar sebenar dan anggaran. Jadi, ia membuktikan bahawa kedua-dua litar boleh disesuaikan dengan V-RFB.

ABSTRACT

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. The aim of this project is to propose equivalent electrical circuit for V-RFB that represents excellent adaptableness to any circuitry analysis and design. Higher number of Resistor-Capacitor (RC) branches can increase the accuracy and representation within the battery. However, it increase the complexity of the model and decrease the reduction of error speed. 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 in terms of estimation of parameter. As less parameter is estimate, it can save time computationally. Extended Kalman Filter (EKF) is used for parameter estimation for both circuit. Actual and approximate circuit are derived accordingly. From simulation result through recursive EKF algorithm of the derivation for both circuit shows each parameters smoothly approaching steady state with 0.6% and 2.0% of error, respectively. Both cell potential experiment and EKF-based estimation overlaps with minor differences for actual and approximate circuit. So, it proven that both circuit are adaptable for V-RFB.

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LIST OF SYMBOLS

A	Ampere
C_a	Capacitance activation polarization
C_c	Capacitance concentration polarization
C_m	Capacitance mass transfer
E_a	Activation polarization
E_c	Concentration polarization
E_m	Mass transfer
E_{cell}	cell potential; measured across unit cell stack
$E_{cell(orp)}$	open-circuit cell potential
R_a	Resistance activation polarization
R_c	Resistance concentration polarization
R_m	Resistance mass transfer
R_o	Internal resistance
s	seconds
V	Voltage
X_L	Parasitic inductance
Z_a	Impedance activation polarization
Z_c	Impedance activation polarization
Z_L	Impedance parasitic inductance
Z_m	Impedance mass transfer
%	Percentage

LIST OF ABBREVIATIONS

EKF	Extended Kalman Filter
FC	Fuel cell
GaN	Gallium Nitride
KF	Kalman Filter
OCV	Open Circuit Voltage
PCU	Power Conditioning Unit
PDNs	Power Distribution Networks
RC	Resistor-Capacitor
RFB	Redox Flow Battery
SOC	State of charge
UKF	Unscented Kalman Filter
V-RFB	Vanadium Redox Flow Battery

CHAPTER 1

INTRODUCTION

1.1 Chapter Overview

This chapter presents the following components: introduction of the project, problem statement, objective, contribution, scope of the project, and the thesis outline. Introduction will focus on energy storage, battery, V-RFB, and Kalman filter. Objectives are discussed in the project's aim, while the flow of the project from where it began to the end is explained in the project's scope. Finally, the thesis outline which briefly describes each chapter of the thesis concludes the chapter.

1.2 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).

Redox Flow Battery (RFB) is a type of rechargeable battery and it is also an electrochemical energy storage device. Redox Flow Battery (RFB) was established in 1970s (Fedkiw & Watts, 1984; Weber et al., 2011). There are many types of RFB that had been invented for instance, soluble lead acid, iron/chromium, vanadium, vanadium bromine, zinc bromine, and etc. RFBs. RFB is a device that stores electrochemical energy straight into the electrolyte solution where it undergoes the chemical reaction reduction and oxidation which will discharge and charge. Although RFBs density of current is low in comparison to fuel cells, it has several advantages for example, its cost is low, it is easy to handle and its power density are higher than(Mohd R Mohamed, Member, Sharkh, & Walsh, 2009). At anode, oxidation occurs from a high chemical potential state that the electron release through an external circuit and at cathode electron is accepted by reduction reaction from low chemical potential state while during charging the current and reaction direction is reversed (US Department of Energy, 2012).

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 is no losses of system integrity.

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.

Parameters in circuit model can be estimated in various method and Kalman Filter (KF) is one of the techniques. KF uses measured input and output to estimate the states of a system. It is an optimal and best linear estimator (Kleeman, 1996). In practice, Kalman Filtering illustrates best outputs, it is convenient form for online real time processing due to optimality and structure and also do not invert the measurement equations (Kleeman, 1996). There are many types of Kalman Filter such as Unscented Kalman Filter (UKF), and Extended Kalman Filter (EKF) (Banani, 2007). EKF is the common application of KF in a nonlinear system and is also known as one of the best estimators, from noisy data amount to filtering out the noise. EKF can gauge parameter data accordingly which results in time and cost saving.

This project presents equivalent electrical circuit model consist of actual and approximate circuit for V-RFB. The approximate circuit is constructed from the proposed circuit by grouping together some of the parameters. By grouping the parameters the complexity in represent the simulation result is less. KF is used to estimate parameters of both circuit. The purpose of this study is to suggest equivalent electrical circuit model for V-RFB system that is precise and adaptable in any V-RFB designs.

1.3 Problem statement

Battery model can be categorized into thermal, electrochemical and electrical (Hall & Fasih, 2006). Electrochemical model is mostly accurate to represent battery due to its detailing in electrochemical process in the system on the electrodes. However, the model is not suitable to identify electrical behavior of V-RFB. Furthermore, more analysis is required due to this model desires detailing on kinetic reaction and materials (H. Chen, Cong, et al., 2009). Electrochemical models suitable for optimization of the physical design aspects of electrodes and electrolytes (Dees et al., 2002; Caiping Zhang, Jiang, Zhang, & Sharkh, 2012). On the other hand, the equivalent circuit model has widely been used and researched due to its simplicity and adaptability on any circuitry design systems. Complexity to perform performance analysis of a battery is in proportional to the level of complexity of the equivalent circuit model (YIlmaz & Yuksek, 2008). Approximate circuit has a simpler model derivation, less computational time, and a smooth graph shape.

The equivalent electrical circuit model publication studies for V-RFB are limited. To date, Chahwan et al. (2007) and M. R. Mohamed et al. (2013) proposed the equivalent electrical circuit for V-RFB. The former presented an equivalent circuit with parasitic and pumped losses with no Resistor-Capacitor (RC) network but there was no explanation on how the losses being estimated whereas the latter presented an equivalent circuit with a pair of RC network for a better representation within battery but there was no explanation on transient behaviour and mass transport. Parasitic inductance will have a major effect on battery model if a high current discharge is applied (Salerno & Korsunsky, 1998). Inductor contributes the transient behaviour of small voltage overshoot or undershoot (Yu & Yuvarajan, 2005).

Estimation of parameters is carry out in order to fit the equivalent circuit into battery. There are various method in estimating parameter such as Artificial Neural Network (ANN), spline technique, current change method and etc. ANN can be used for pattern extraction or complex trend that are hard to be noted by computer technique or human being. It can transform complicated and imprecise data to meaning derivation, however, ANN in a way are non-conventional method and the input output dataset are hard to identify because sufficient data training and testing are required in dataset (YIlmaz & Yuksek, 2008). Spline technique is piece wise polynomials of degree 'n' and it easy to handle because represent by simple polynomials. Overshooting can occur at intermediate point as the high degree of polynomial is used. Although it good for behaviour of the actual system the overshooting will affect the estimation with the production of error (Wold, 1974). Current change method is a simple technique that changes the output current in order to obtain the transient waveform of the terminal voltage. It not a problem for the current change method to perform for single, small, and even larger stack of battery, however, the load current changes causes the related voltage change (Chang, 2013). So due to this matter, for this research Extended Kalman Filter (EKF) is used to estimate the parameters of actual and approximate circuit. Thus, it can verify the stability and adaptability of the equivalent circuit model of V-RFB system.

1.4 Objectives

The main objectives of the project are:

- To develop equivalent electrical circuit model for V-RFB with consideration of parasitic inductance.

- To propose approximate circuit as an alternative for actual circuit to represent general characterization of V-RFB.

- To estimate the equivalent electrical circuits model parameters by using EKF.

1.5 Scope of project

In this project, the overall scope is discussed in Figure 1.1. The project is expected to propose an equivalent electrical circuit along with the approximate circuit and EKF is used for parameter estimation of the circuit. The experimental data result was taken from Mohamed et al. (M. R. Mohamed, Ahmad, Seman, Razali, & Najib, 2013).

Energy storage can be formed into mechanical (Hebner & Beno, 2002), electrochemical (H. Chen, Ngoc, Yang, Tan, & Li, 2009), and electrical energy storage (Blanc, 2016). Among these energy storages, the project will focus on electrochemical energy storage, because it is more stable, the oldest, and established.

Electrochemical energy storage is the place where various types of batteries were formed and found, for example, lead acid (H. Chen, Ngoc, et al., 2009; Oberhofer, 2012; Vutetakis, 2001), nickel cadmium (Alotto, Guarnieri, & Moro, 2014), RFB (Mahlia, Saktisahdan, Jannifar, Hasan, & Matseelar, 2014), lithium ion (Iec, 2009; Singamsetti & Tosunoglu, 2012), and fuel cell (Pires, Romero-cadaval, Vinnikov, Roasto, & Martins, 2014). Rechargeable battery, RFB is chosen in the current study.

There are many types of RFB; bromide-polysulphide (Díaz-González, Sumper, Gomis-Bellmunt, & Villafáfila-Robles, 2012; Weber et al., 2011), zinc bromine (Le & Walsh, 2006; Smith, Smith, & Mccann, 2015), iron chromium (Weber et al., 2011), vanadium bromine (Le & Walsh, 2006), and vanadium (Skyllas-kazacos, 2003). Vanadium type of RFB is used because of its high energy density, less cross-contamination, and will not damage due to overly discharged.

In theoretical section, the project will be based on literature review and fundamental theory. For the circuit modelling section, the circuit model has been categories into thermal, electrical, and electrochemical model. For this project, the electrical circuit model is used because of its less complex model. The circuit model is divided into two; equivalent and approximate circuit. Equivalent circuit has widely been researched because it is simple and reliable. Approximate circuit is formed from the equivalent circuit because a less complex result can be presented. As for the simulation section, the circuits is verified by using EKF for parameter estimation in MATLAB. EKF can linearized the circuit and measure data though it is full of noise.

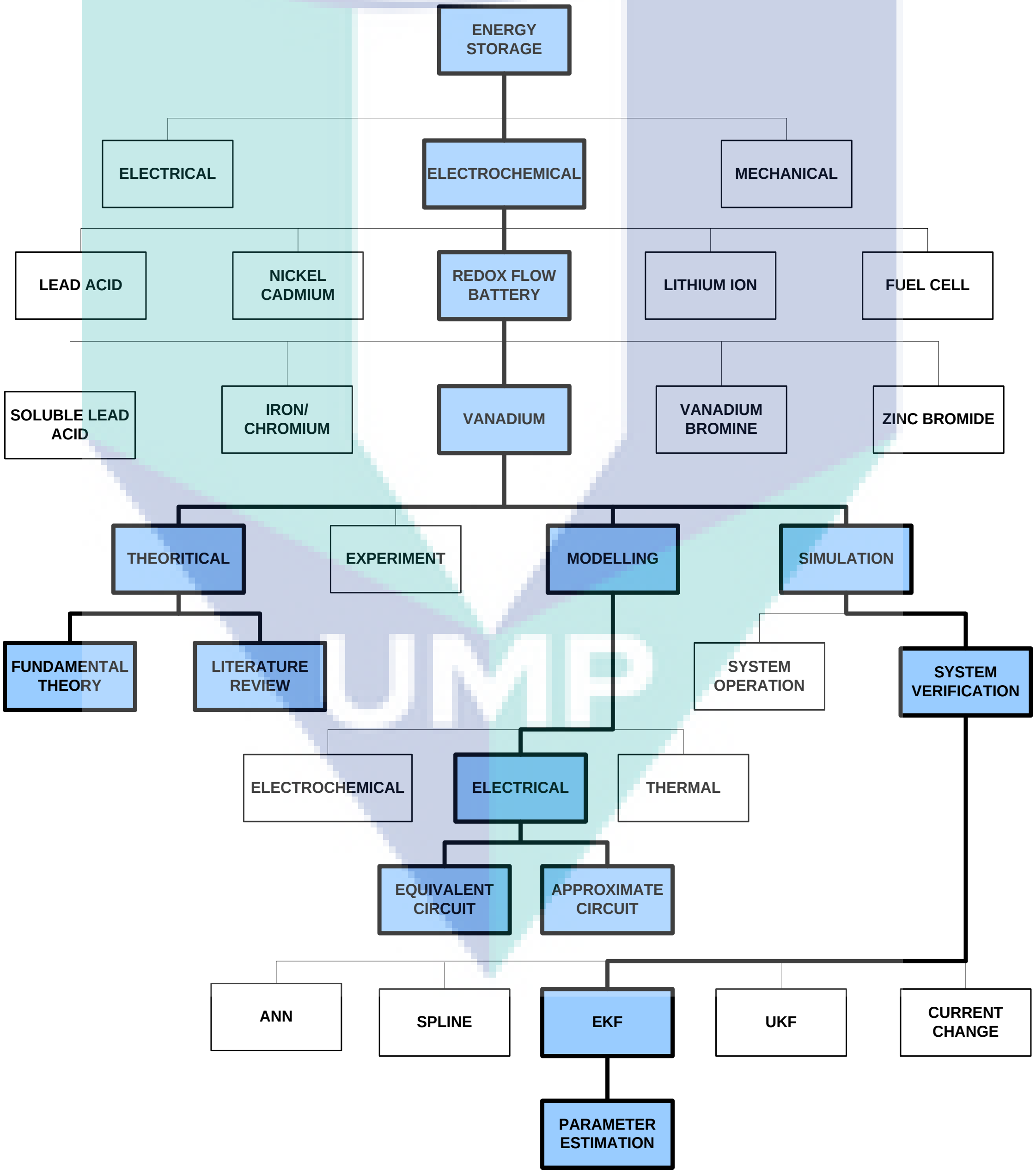

Figure 1.1 Fill of energy storage of equivalent circuit for V-RFB

1.6 Thesis outline

This thesis contains five chapters. Each chapter illustrates:

Chapter 1 briefly describes the overview of the project; introduction, problem statement, the objectives and the scopes of this project.

Chapter 2 provides studies previously conducted by others researchers in the same area and appropriate issues related to the energy storage, RFB, V-RFB, circuit models, parameter estimation methods, and parasitic inductance. This includes an overview of battery types used in the scope of study. The different types of circuit models and parameter estimation method are presented to justify the best method chosen for the project. Effect of parasitic inductance in circuit is also discussed.

Chapter 3 describes a wide description of the research methodology in this project. It begins with the description of the flow chart of the project. The actual circuit and approximate circuit for V-RFB are proposed as part of this project. The equivalent circuit is derived. The simulation using EKF for parameters estimation of the equivalent circuit is described later.

Chapter 4 presents the result and discussion of the parameters estimation for the actual circuit and approximate circuit for V-RFB by using EKF.

Chapter 5 provides general conclusion based on the project's results. The future works for improving the project is emphasized.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter overview

This chapter discusses the literature review based on the project scope. Related articles published within the area were reviewed. Energy storages are discussed and the focus is on the type of RFB. Description of RFBs leads to the explanation on the choice of V-RFB. From the chosen battery model, the methods of parameter estimation were deliberated. The conclusion of the review of the literature leads to the need of the current project.

2.2 Energy storage

2.2.1 Mechanical energy storage

Mechanical energy storage stores energy by motion. Mechanical energy storage systems are compressed air energy storage (CAES), hydraulic accumulator, and flywheel energy storage. CAES uses air as a storage due to viability and it has a large capacity, however it has efficiency with low round-trip and limitation of locations geographically (Iec, 2009; Koshizuka, Ishikawa, Nasu, Murakami, & Matsunaga, 2003; Oberhofer, 2012). Hydraulic accumulator very important in generates electricity and had been installed worldwide but high cost and give a big impact to the environments and also lack of available sites (Hebner & Beno, 2002.) Flywheel energy storage store energy through flywheel, it used to store grid energy as emergency power source(Hebner & Beno, 2002; Luo, Wang, Dooner, & Clarke, 2015; Mahlia, Saktisahdan, Jannifar, Hasan, & Matseelar, 2014). These storage systems has been widely use in numerous residential, industrial, and commercial uses for backup and store energy (Luo et al., 2015). The system is environmentally friendly but highly maintenance cost (Mahlia et al., 2014).

2.2.2 Electrical energy storage

Electrical energy storage has two needs (Iec, 2009). First, as the electricity is generated at the same time it is expended and it will lead to unsatisfied demand if there is imbalance of supply and demand because the stability and the quality of the power supply will be damage. Second, location of electricity generation is from where it had been consumed. Electricity is vital for everyday routine because many tasks require the use of electricity. Magnetic energy storage; Superconducting Magnetic Energy Storage (SMES) and electrostatic energy storage; supercapacitor are basic categories in electrical energy storage (Blanc, 2009). SMES employs magnetic field energy. Although it is fast response, is able to discharge partially and fully, and also environmentally none hazard, the requirement in the cooling process reduces the efficiency, there are high expenses in manufacturing and maintenance, and it involves high energy losses (Koshizuka et al., 2003; Oberhofer, 2012). Supercapacitor stores energy in electrolytes solution between two solid conductors (H. Chen, Cong, et al., 2009). In comparison to conventional capacitor, high energy density can continuously charge and discharge, and can be used in many applications due to its long lifespan, and high efficiency; engine's starter, actuators, electric or hybrid-electric vehicles (H. Chen, Ngoc, et al., 2009; Oberhofer, 2012)

2.2.3 Electrochemical energy storage

Electrochemical energy storage is the most established and oldest energy devices (H. Chen, Cong, et al., 2009). Various types of batteries are described from this energy storage and almost all of them are technologically mature for practical use (Iec, 2009). Battery is a conversion of chemical energy to electrical energy. In today's world, the use of battery is inevitable, from the households to the factories. Anode, cathode and electrolyte are three important components of a battery. There are two basic types of a battery; primary and secondary batteries (Vutetakis, 2001). Primary battery is not rechargeable, inexpensive, can be bought almost everywhere, easy to dispose, and poor performance at low temperature; for examples, alkaline battery, mercury battery, zinc-carbon, and etc. (Arnold, 2011; Singamsetti & Tosunoglu, 2012). Secondary battery is rechargeable, higher initial cost but lower operating cost, requires maintenance but a longer life cycle, durable, and better performance at low temperature; for examples, lead acid, lithium-ion, sodium-sulphur, redox batteries, and etc. (Antonucci & Antonucci, 2011; Singamsetti & Tosunoglu, 2012; Vutetakis, 2001).

2.3 Battery

2.3.1 Lead acid battery

Lead Acid(LA) battery is the type of energy storage battery that is commonly used commercially since 1859 and is applicable in both mobile and stationary applications (Iec, 2009). For over 150 years of development and experience, it has been considered as the most mature and oldest technology. It was widely used to substitute power supplies and is capable of delivering a high voltage of electricity at once but due to high lead density the life cycle and energy density is low (H. Chen, Ngoc, et al., 2009; Oberhofer, 2012; Vutetakis, 2001). It has a large scale energy storage with low cost but it has limited life cycle and recharged ability, chemical reaction cause the corrosion to occur, people and animals can be affected by the exposure of lead this is because lead is toxic(H. Chen, Ngoc, et al., 2009; Oberhofer, 2012).

2.3.2 Nickel cadmium

Nickel cadmium (NiCad) is considered as rechargeable alkaline battery with long life cycle. It can be developed in large scale application; telecommunication system. Compared to LA, it produces a higher energy with low maintenance cost and longer lifespan (H. Chen, Cong, et al., 2009; Pires, Romero-Cadaval, Vinnikov, Roasto, & Martins, 2014). In contrast, NiCad has a low cycle of life, and a high manufacturing cost (Alotto et al., 2014) and can be damaged by overcharging.

2.3.3 Lithium ion battery

Lithium ion battery has a high energy density to store energy in a small space with a larger amount, high efficiency (range between 95% to 98% (Iec, 2009), and relatively long life span (H. Chen, Ngoc, et al., 2009). Lithium ions battery is an important storage in portable and mobile applications (Iec, 2009; Singamsetti & Tosunoglu, 2012). Further care should take place in order to recycle lithium because lithium can combust and some of the electrolytes are toxic (Díaz-González et al., 2012; Pires, Romero-cadaval, et al., 2014; Singamsetti & Tosunoglu, 2012). It has a higher voltage per cell; 3.7V compared to lead acid; 2.0V, low energy lost, and a large amount of lithium and graphite are available. (Oberhofer, 2012; Singamsetti & Tosunoglu, 2012). On the other hand, lithium is expensive, the cell can be destroyed if fully discharged takes place, the cell will fail if not used, and lithium is combustible in contact with atmospheric moisture (Díaz-González et al., 2012; Oberhofer, 2012). In addition, the cost to construct it in a large scale is high due to circuit protection and packaging.

2.3.4 Fuel cell

Fuel cell (FC) is broadly used in various applications such as mobile and stationary (Pires, Romero-cadaval, et al., 2014). There are several types of fuel cell, which include polymer electrolyte membrane, alkaline, phosphoric acid, molten carbonate and solid oxide. FC is harmless to our body. In addition, it has low efficiency although it is conceptually the same with RFB (Alotto, Guarnieri, & Moro, 2013; Mohd R Mohamed et al., 2009). FC and batteries are different, FC consumes reactants which must be reloaded, whereas batteries store electrical energy chemically in a closed system. (H. Chen, Ngoc, et al., 2009; Pires, Romero-Cadaval, et al., 2014). Furthermore, when battery is charged or discharged the electrodes between the batteries are reactant change, while electrodes in FC are relatively stable (H. Chen, Cong, et al., 2009). FC is also difficult to handle and is costly.

2.3.5 Redox Flow Battery (RFB)

Redox Flow Battery (RFB) is a device that stores electrochemical energy. The term redox is the combination of chemical reaction reduction and oxidation which undergo discharge and charge of electrochemical cell in which energy is stored in the electrolyte solution. One of the sources of direct current is RFB for various applications such as household and industry (Mahlia et al., 2014). There are many types of RFB such as zinc bromide, iron/chromium, bromide polysulphide, soluble lead acid, and V-RFB (Alotto et al., 2013; H. Chen, Cong, et al., 2009; Mohd R Mohamed et al., 2009). RFB has a longer life cycle and it is low in maintenance, for instance in circulating the electrolytes between the tanks and cell electrodes in RFBs only two low cost tanks are needed (Alotto et al., 2013; Oberhofer, 2012). However, RFB is unsuitable for mobile applications due to its low energy density, due to the electrolytes is conductive it disposed shunt current and extra losses can occur (Alotto et al., 2013). Table 2.1 shows the comparison of energy storage technologies.

Table 2.1 Comparison of energy storage technologies

Energy storage	Types	Efficiency	Lifetime	Status	Problems
- Mechanical	- Hydraulic accumulator	- 85%	- 30 years	- Commercial products	- Exclusion area
	- Flywheels	- >90%	- 20 years	- Prototypes in testing	- Containment
- Electrical	- Super capacitors	- 95%	- 10 000 cycles	- Some commercial products	- Short period
	- SMES	- 95%	- 30 years	- Design concept	- Short period
- Electrochemical (battery)	- LI-ion	- >95%	- 1000 cycles	- Commercial products	- Thermal runaway
	- V-RFB	- 85%	- 10 years	- In test	- Low energy density
	- FC	- 40%	- 10-20 years	- In test	- Safety
	- Lead acid	- 85%	- 2-10 years	- Commercial products	- Lead disposal

Source: Anderson, Member, & Carr, (2000), Blanc, (2016), Garcia, Gerlich, & Rautiainen, (2016), Hebner & Beno, (2002), & Koshizuka et al., (2003)

2.4 Types of RFB

RFB is one of the potential performance characteristics compared to other battery. The batteries can be discharged completely without damaging the cell. These RFB are significantly different from each other referring to redox potential and electrolytes, except all of them have the same net chemical redox reactions. The principle behind a RFB cell is a couple of electrochemical reduction and oxidation reactions occurring in two liquid electrolytes. The reduction half-reaction at one electrode extracts electrons and ions from one electrolyte, while the oxidation half-reaction at the other electrode recombines them into the other electrolyte. Ions migrate from anode to cathode through an electrolyte that is impermeable to electrons, which are thus forced through an external circuit providing electric energy exchange. Figure 2.1 shows RFB configurations.

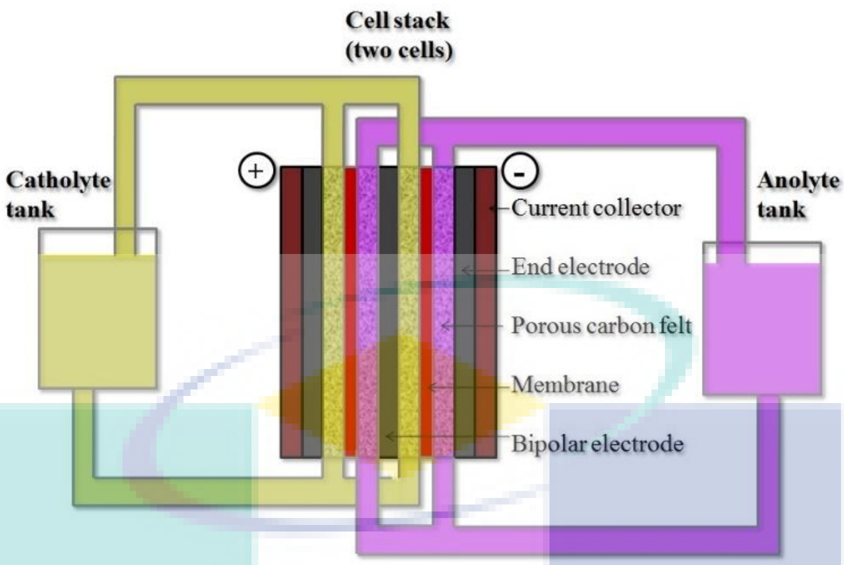

Figure 2.1 RFB configuration
Source: Alotto et al., (2013)

2.4.1 Bromide-polysulphide (PSB) Flow Battery

PSB was introduced by Regenesys Technologies and it is suitable for energy storage in long duration of time because it has no self-discharge (H. Chen, Cong, et al., 2009; Díaz-González et al., 2012). The battery's electrolytes are plentiful in nature and the cost is low (Díaz-González et al., 2012; Weber et al., 2011). Cross-contamination can occur due to the different electrolytes solutions, balance of the electrolytes are hard to maintain, and hydrogen sulphide and bromine gas formation need to be prevented (Le & Walsh, 2006; Smith et al., 2015).

2.4.2 Zinc Bromine Flow Battery

In 1970s Exxon produced hybrid flow batteries; zinc bromide is a hybrid redox flow battery because much energy is stored at zinc metal plate (H. Chen, Ngoc, et al., 2009). It has the highest density among the flow batteries with good energy density. Additionally, the manufacturing cost is low and it can be recycled (Le & Walsh, 2006; Smith et al., 2015). This flow battery electrodes cost and rate of self-discharged are high, and also low lifespan (Le & Walsh, 2006). Although it is used but still can harm health so it need to be maintain.

2.4.3 Iron\chromium Flow Battery

In 1970s, iron/chromium system (Fe/Cr) was developed (Weber et al., 2011). On Fe/Cr system, at the positive electrode (Fe^{2+}/Fe^{3+}) an aqueous solution of a ferric/ferrous redox couple; the negative electrolyte is a mixture of chromic and chromos ions (Cr^{2+}/Cr^{3+}); the supporting electrolyte for most system is hydrochloric acid (Weber et al., 2011). With the electrochemical potential of 1.18, it has been considered as a capable RFB (Pawar, Madhale, Patil, & Lokhande, 1988). Nevertheless, the disadvantage of this type of battery is the membrane in which diffusion of cations may occur as a result of cross contamination.

2.4.4 Vanadium/Bromine Flow Battery

There is a limitation in the amount of vanadium that can be stored in V-RFB solution, and hence, the same researchers who established the work on the cell noted that vanadium solubility could be advanced in the presence of halide ions (Le & Walsh, 2006). Even though the efficiency of columbic increases in current density because of the lower self-discharge through the membrane, as the temperature increases, it decreases due to diffusion that occurs rapidly (Weber et al., 2011). This type of battery produces energy density that is suitable for electrical vehicles. However, it will become useless if the production of energy is low.

2.4.5 Vanadium Redox Flow Battery (V-RFB)

V-RFB is a type of rechargeable battery. It undergoes oxidation and reduction reaction during discharge and charge processes at anode and cathode. As the battery is discharged, acid from the electrolytes will combine with the active plate material. Compared to the other type of RFB, V-RFB has a higher energy efficiency and there is no cross contamination because both half-cell use the same type of electrolyte (Skyllas-kazacos, 2003). Vanadium is very convenient, it can increase storage density, respond fast and reduce costs (Smith et al., 2015). The battery will not be damaged due to not overly charged over discharged (Díaz-González et al., 2012).

2.5 Models

2.5.1 Thermal model

In thermal model, by current flowing through resistors the heat is produced and dissipate first order term that signifies the convection out of the battery (Hall & Fasih, 2006). The thermal parameters are very tough to measure, however the overall effect can be approximated to a first order exponential (Hall & Fasih, 2006). Nominal values of both the specific heat and heat transfer rate can be exactly gained by looking at sample values of resistance and temperature changes accompanying currents and with experimental data (Hall & Fasih, 2006). Ohmic heating can occur due to battery's charge transfer because the chemical processes can either be exothermic or endothermic in battery(Pour, 2015). However, thermal model are difficult to precisely quantify, so it is not suitable for identifying electrical behaviour.

2.5.2 Electrochemical model

The electrochemical model is very accurate in modelling battery due to its detailing in the electrochemical processes. For some system design engineers, simulation using electrochemical model is impractical because the chemical composition and material conductivity need to be measured or identified (Cheng Zhang, Li, McLoone, & Yang, 2014). In addition, complex numerical techniques are required to solve the independent partial differential equations and for on-board system it will lead to overwhelming computational expense (Cheng Zhang et al., 2014). Some researchers like Blanc et al. (2016) and You et al. (2009) presented V-RFB's electrochemical model (Blanc, 2016; You, Zhang, & Chen, 2009).However, the model becomes complex and difficult to configure because the description is highly detailed (Jongerden & Haverkort, 2008).

2.5.3 Electrical circuit Model

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 as it leads to better modelling accuracy and presentation. However, it shows no large difference between the errors of the system, as the RC network increases from three or more RC network (S. X. Chen, Tseng, & Choi, 2009; Díaz-gonzález et al., 2012; M. R. Mohamed et al., 2013). 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 2.2 shows the circuit proposed by Chahwan et al. (2007) and Figure 2.3 shows the circuit proposed by M. R. Mohamed et al. (2013). Electrical circuit model is less complex than electrochemical model, less cost computationally, and can do simulation.

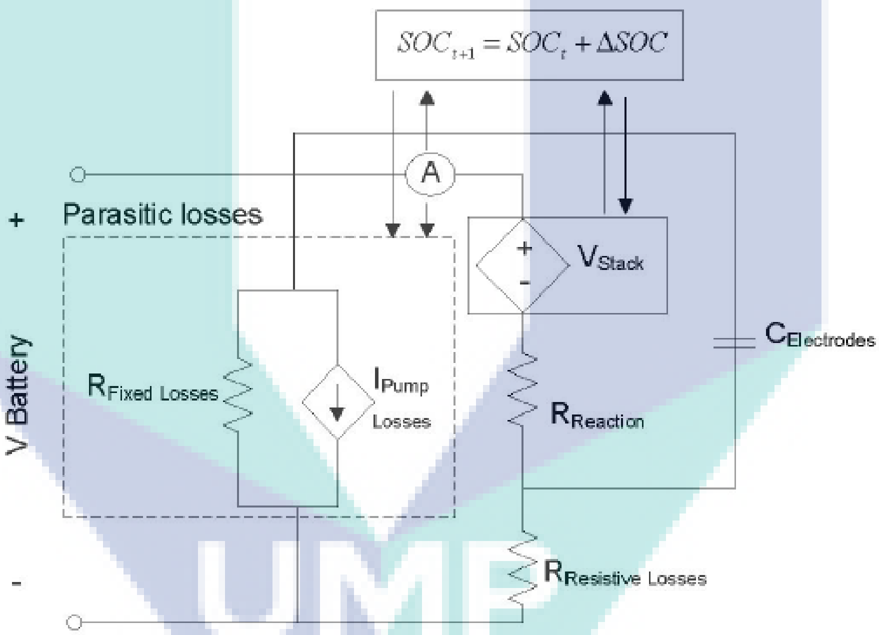

Figure 2.2 Equivalent circuit for V-RFB proposed by Chahwan at el

Source: Chahwan et al.,(2007)

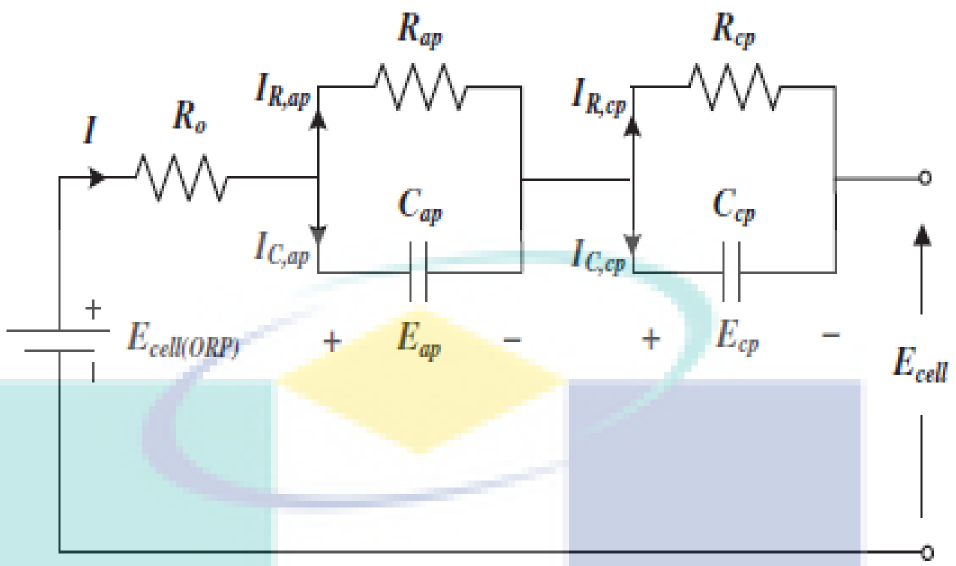

Figure 2.3 Equivalent circuit for V-RFB proposed by M.R.Mohamed

Source: M. R. Mohamed et al., (2013).

2.6 Parameter estimation

To fit an equivalent circuit model to a specific battery cell, parameter estimation is a common process to go through (Jackey et al., 2013). It is also to identify sources of error and discrepancy. To implement parameter estimation, analyse the measured current data to locate the exact pulse transitions, remove noise by filtering the raw data, set the initial values for the equivalent circuit elements, for circuit lookup table the exact State of Charge (SOC) is calculate, the settings for the optimization algorithm need to be choose and gauge, and a series of estimations is perform to determine the optimum parameters (Jackey et al., 2013; Z. Zhang, 1997). Almost all of parameter estimations depend on the applications or design produced error. There are many methods of parameter estimation for example artificial neural network (ANN), spline techniques, linear parameter varying, change current, and Extended Kalman Filter (EKF). Table 2.2 shows parameter estimation methods.

2.6.1 Artificial Neural Network (ANN)

There are some patterns extraction and complex trends which are hard to be noted by computer techniques or human beings and as a solution ANN is used because it has the ability that are outstanding from complicated or imprecise data to meaning derivation (YIlmaz & Yuksek, 2008). More advantages that ANN offers include the ability to learn how to do tasks based on the data given for training or initial experience, it can create its own organization or representation of the information it receives during learning time, its computations may be carried out in parallel, and partial destruction of a network leads to the corresponding degradation of performance of the network(YIlmaz & Yuksek, 2008). However, ANN is a nonconventional method and is quite hard to identify input and output dataset due to this sufficient amount of data for training and testing are required in database (Caiping Zhang et al., 2009).

2.6.2 Spline technique

Spline technique is defined as piecewise polynomials of degree 'n'. This function of degree n is a continuous function with n-1 continuous derivatives (Wold, 1974). Moreover, since the splines computationally easy to handle because of the represent polynomial is simple; their integrals and derivatives are also spline functions of one degree higher and lower, respectively. Also, the definition of splines in terms of polynomials has the statistically important consequence that a spline functions, when fitted to data by least squares, converses the first two moments of the data(Wold, 1974). Spline technique depends on the degree of polynomial but overshooting occurs at an intermediate point as the high polynomial degree is used although it is good for behaviour for actual system (M. R. Mohamed et al., 2013). The overshooting will affect the estimation with the production of error.

2.6.3 Current change

Current change is a simple technique that changes the output current in order to obtain the transient waveform of the terminal voltage (Chang, 2013). It can be used to get accurate quantitative result and quick qualitative indications, suitable to be performed for standard low-cost electronic measurement equipment, and it is not a problem for the current change method to perform for single, small, and even larger stack of battery (Chang, 2013). However, the load current changes causes the related voltage change (Chang, 2013). For this project the current is constant, and hence, current change method is not suitable.

2.6.4 Extended Kalman Filter (EKF)

EKF is an extension of Kalman Filter (KF) that can be applied to nonlinear systems. It works by transforming the nonlinear models at each time step into linearized systems of equations (Ribeiro, 2004). EKF known as one of the most used and best estimators in filter out the noisy data amount (Sun & Chen, 2014). It is also very convenient for real-time processing and is quite straight forward to be implemented if a priori information of the measurement and process noise covariance matrices are available (Banani, 2007; Caiping Zhang et al., 2012). EKF linearized nonlinear model to linear model (Banani, 2007; Grewal & Andrews, 2001; Kleeman, 1996; M. R. Mohamed et al., 2013). EKF can measure data even though the data is full of infected noise. Table 2.2 shows the differences of parameter estimation methods.

Table 2.2 Comparison of parameter estimation methods

Methods	Advantages	Disadvantages
- Artificial Neural Network (ANN); can be used for pattern extraction or complex trend that are hard to be noted by computer or human.	- Can transform complicated and precise date to meaning derivation.	- Input and output dataset hard to identify
- Spline technique; piece wise polynomial of degree 'n'	- Easy to handle because of simple polynomials - Good for the behaviour of actual system	- Overshooting occur at high polynomials degree at intermediate poinT
- Current change; simple technique that changes the output current to obtain the transient waveform at the terminal voltage	- Can be used to get accurate quantitative result and quick qualitative indication - not a problem for the current change method to perform for single, small, and even larger stack of battery	- changes in load current causing related voltage to change
- Extended Kalman Filter (EKF); common application of Kalman Filter	- Minimize system error - Can gauge parameter data accordingly which can save time - Low cost	

Source: Banani, (2007), Chang, (2013), Grewal & Andrews,(2001, M. R. Mohamed et al., (2013), Wold, (1974), & YIlmaz & Yuksek, (2008)

2.7 Chapter conclusion

In this chapter, review of literature is given emphasis and some studies were used as a guide to complete this project. RFB was chosen due to low maintenance, fast response time, and longer lifespan. V-RFB was used for this project because it had a lesser chance for cross-contamination, the battery would not be affected for overly discharged, and high energy density. The equivalent electrical circuit model was chosen to represent V-RFB because of easy to derive, simulate and also less complex. To adequate proposed equivalent circuit into V-RFB, parameter estimation took place by using EKF which can measure data accordingly and also can save time.

CHAPTER 3

METHODOLOGY

3.1 Chapter overview

This chapter explains the research methodology on equivalent circuit model for V-RFB. For equivalent circuit model, it has two types actual and approximate. Construction of equivalent circuit model are presented along with method and software used for parameter estimation.

3.2 Project review

Based on the project, research about the related project has been conducted. Every related article or journal has been through to find the best methods that will be used in this project. The methods used for this project will be following the flow chart below. Figure 3.1 below displays the project flow from the beginning to the end of the project.

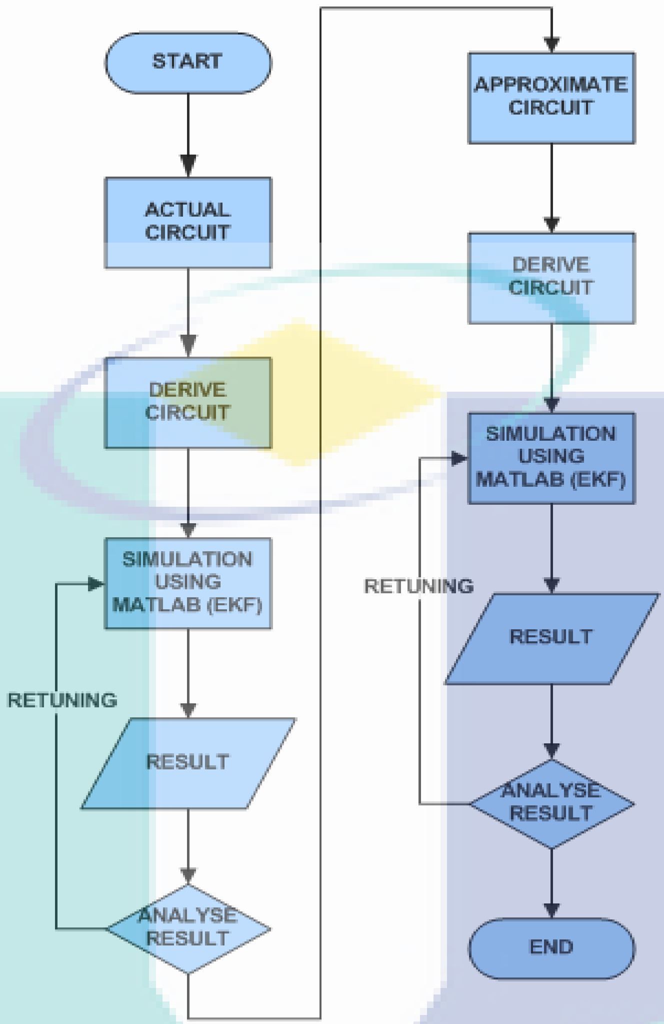

Figure 3.1 Flow chart of project methodology

Equivalent electric circuit models for V-RFB was proposed which consist of actual and approximate circuit. From actual circuit, the circuit was derive thoroughly and from the derivation recursive EKF algorithm was construct. Simulation using EKF method in MATLAB software take place to estimate each parameter of both actual and approximate circuit. Based on the result through the simulation, if the expected result are not achieved, the simulation will be continuously retuning to obtain better result.

3.3 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.

3.3.1 Actual circuit

Equivalent electrical circuit in Figure 3.2 contains of an open circuit cell potential, $E_{cell(orp)}$ that signifies the SOC and temperature of the V-RFB, an internal ohmic resistance, R_o that corresponds to the effect of current excitation, inductor for battery performance, X_L the polarization resistance is R_{a1}, R_{a2}, R_{c1}, R_{c2}, and R_m, where R_{a1} and R_{a2} represent effective resistance describing activation polarization, R_{c1} and R_{c2} represent effective resistance describing concentration polarization, Rm for mass transfer resistance; while C_a, C_c, and C_m represent effective capacitance parameters. Compare to Figure 2.3, Figure 3.2 has additional resistors and capacitors for activation, concentration, and mass transport polarization and also an inductor for battery performance.

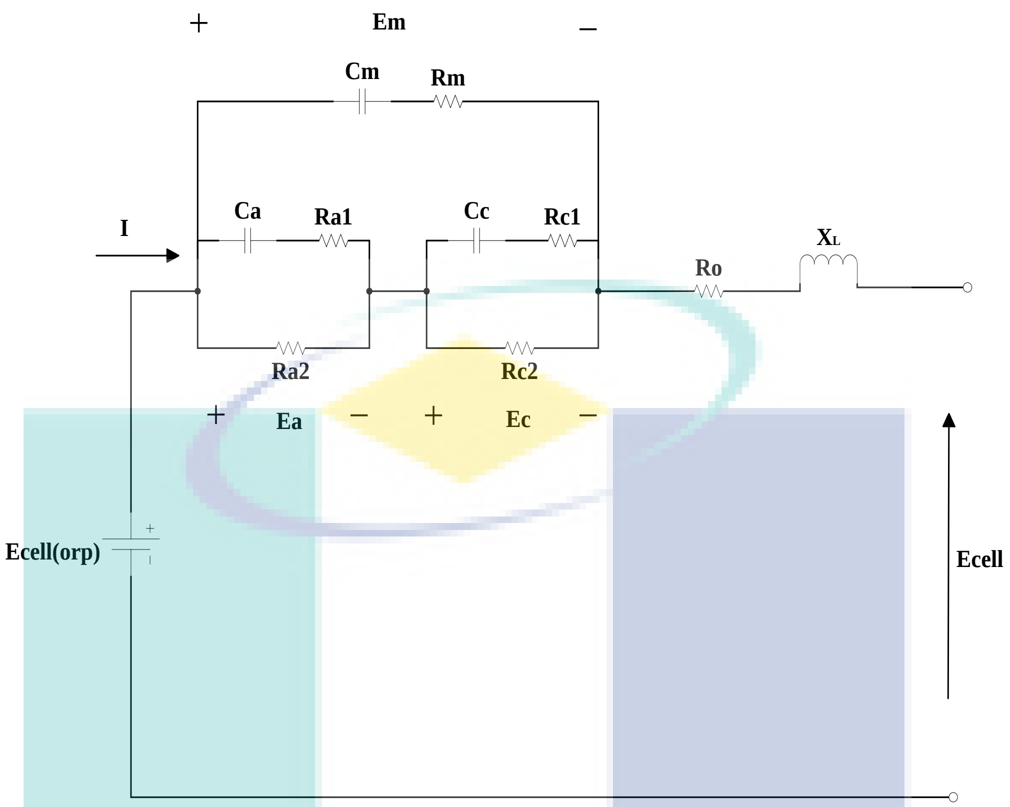

Figure 3.2 Actual circuit for V-RFB system

This part describe modelling equation for proposed circuit. The electrical behaviour of the actual circuit can be stated by applying Kirchhoff's Voltage Law (KVL):

$$E_{cell} = E_{cell(orp)} - I(X_L + R_o) - E_m - E_a - E_c \qquad 3.1$$

The ordinary differential equation across the polarizations is:

$$E_m = \frac{I}{C_m + R_m} - \frac{E_m}{(C_m + R_m)(C_a + R_{a1} + C_c + R_{c1})} \qquad 3.2$$

$$E_a = \frac{I}{C_a + R_{a1}} - \frac{E_a}{C_a R_{a2} + R_{a1} R_{a2}} \qquad 3.3$$

$$E_c = \frac{I}{C_c + R_{c1}} - \frac{E_c}{C_c R_{c2} + R_{c1} R_{c2}} \qquad 3.4$$

State variables of V-RFB

$$
\begin{aligned}
E_{cell} = & -\left[\frac{1}{C_m + R_m} + \frac{1}{C_a + R_{a1}} + \frac{1}{C_c + R_{c1}} + \frac{L}{C_c R_{c2} + R_{c1} R_{c2}}\right] I \\
& + \left[\frac{1}{(C_m + R_m)(C_a + R_{a1} + C_c + R_{c1})} - \frac{1}{C_c R_{c2} + R_{c1} R_{c2}}\right] E_m \\
& + \left[\frac{1}{C_a R_{a2} + R_{a1} R_{a1}} - \frac{1}{C_c R_{c2} + R_{c1} R_{c2}}\right] E_a \\
& + \left[\frac{1}{C_c R_{c2} + R_{c1} R_{c2}}\right] E_{cell(orp)} - \left[\frac{1}{C_c R_{c2} + R_{c1} R_{c2}}\right] E_{cell}
\end{aligned} \qquad 3.5
$$

3.3.2 Approximate circuit

Equivalent electrical circuit of V-RFB shown in Figure 3.2 has a potential to approximate some of the parameters which can be lumped together for a simpler circuit due to complexity in representing the simulation results. Figure 3.3 shows the approximate equivalent circuit for V-RFB. It also consists of an open circuit cell potential, $E_{cell(orp)}$, an internal ohmic resistance, Ro and inductor, X_L which as impedance of inductance (Z_L) same as circuit shown in Figure 1, impedance of mass transfer, Z_m (C_m and R_m), and a pair of Resistor-Capacitor (RC) branches that represent the time-dependent V-RFB's dynamics of activation, Z_a (C_a, R_{a1} and R_{a2}) and concentration, Z_c (C_c, R_{c1} and R_{c2}) polarizations. Overall, the polarization in the circuit shown in Figure 3.2 and 3.3 are used to describe the transient response at power transferring of the battery.

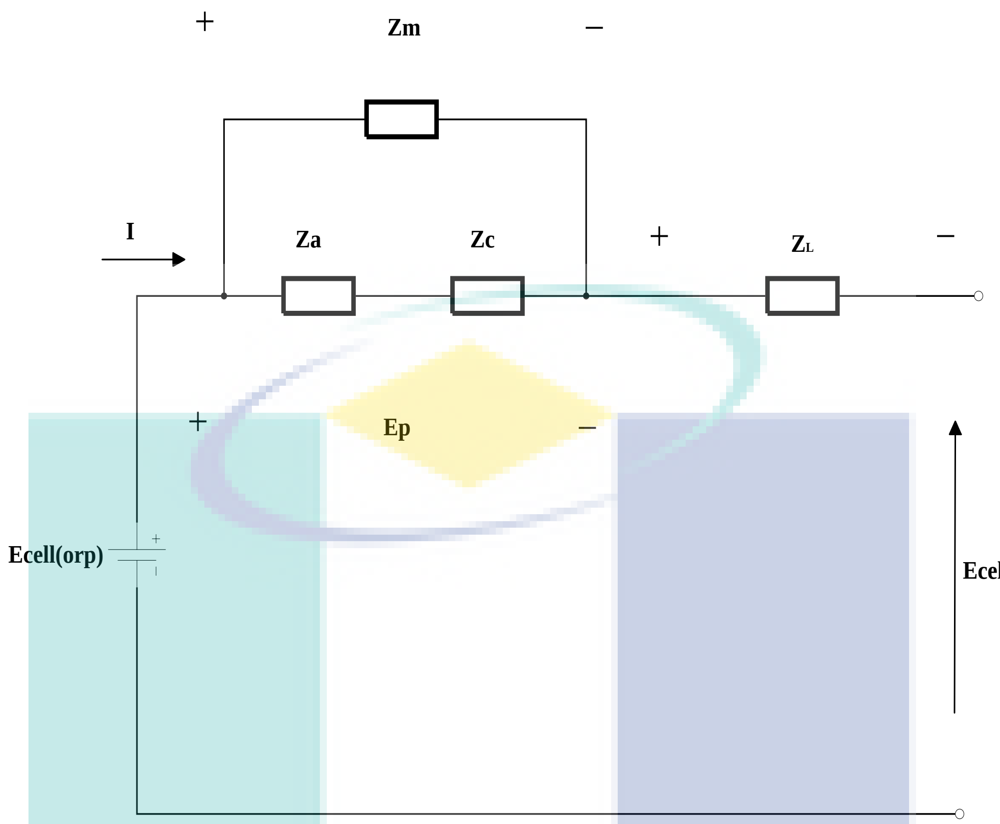

Figure 3.3 Approximate circuit of V-RFB

The following equation is the expression of the approximate circuit:

$$E_{cell} = E_{cell(orp)} - E_p - IZ_L \quad 3.6$$

The ordinary differential equation across the polarization is:

$$\dot{E_p} = \frac{I}{Z_m} - \frac{E_p}{Z_m(Z_a + Z_c)} \quad 3.7$$

State variables of V-RFB:

$$E_{cell}^{\cdot} = -\left[\frac{1}{Z_m} + Z_L\right] + \left[\frac{1}{(Z_a+Z_c)Z_m}\right] E_p + E_{cell(orp)} \;\; - E_{cell} \quad 3.8$$

3.4 Parameter estimation

EKF is the common application of Kalman Filter (KF) in nonlinear system and one of the best estimators from noisy data amount to filter out the noise. It is also very convenient for real-time processing and is quite straight forward to be implemented if a priori information of the measurement and process noise covariance matrices are available (Banani, 2007). EKF in MATLAB was used to estimate parameters of the proposed electrical circuit for V-RFB. EKF linearized nonlinear model to linear model. By reducing the state covariance it can minimize the estimation error. Clarification of continuous-time with discrete-time measurement are per below (He, Xiong, Zhang, Sun, & Fan, 2011):

$$\left.\begin{aligned} x_k &= f_k(x_{k-1}, u_k, w_k \\ z_k &= h_k(x_k, v_k) \\ w_k &\sim (0, Q_k) \\ v_k &\sim (0, R_k) \end{aligned}\right\} \qquad 3.9$$

System output current is u_k, the process noise in continuous-time Gaussian zero mean white noise with covariance of Q_k is w_k whereas the measurement noise in discrete-time Gaussian zero mean noise with covariance R_k is v_k. Figure 3.4 the operation of EKF in estimating optimal or quasi-optimal value of V-RFB parameters.

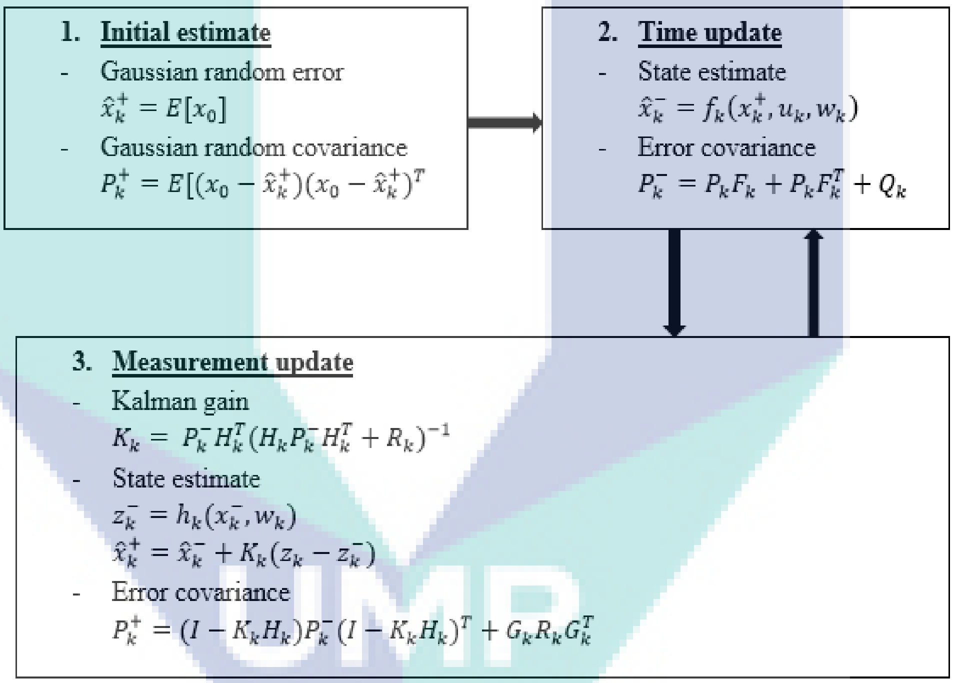

Figure 3.4 Implementation flowchart of EKF algorithm in estimating optimal or quasi-optimal of V-RFB parameters.

3.4.1 EKF of actual circuit for V-RFB

Form of Eq. 3.9 is used to illustrate state variable of the parameter of actual circuit for V-RFB by applying Eq. 3.2, 3.3, 3.4 and 3.5 for model development. State x_k as:

$$x_k = [E_m \;\; E_a \;\; E_c \;\; E_{cell} \;\; R_m \;\; C_m \;\; R_{a1} \;\; R_{a2} \;\; C_a \;\; R_{c1} \;\; R_{c2} \;\; C_c \;\; X_L]^T \qquad 3.10$$

From state model with deliberation of input variable:

$$f(x_k, u_k) = [f_1 \;\; f_2 \;\; f_3 \;\; f_4 \;\; f_5 \;\; f_6 \;\; f_7 \;\; f_8 \;\; f_9 \;\; f_{10} \;\; f_{11} \;\; f_{12} \;\; f_{13}]^{\mathrm{T}} \qquad 3.11$$

$$z_k = h_k(x_k) = [0 \quad 0 \quad 0 \quad E_{cellk} \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}} \qquad 3.12$$

Where $u_k = I$, f is the transition matrix of V-RFB system, and h_{k} is measurement matrix. Thus, $f_s(s = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13)$ are describe as:

From Eq. 3.2:

$$f_1 = -x_1/(x_6 + x_7)(x_9 + x_7 + x_{12} + x_{10}) + (x_6 + x_5)u_k$$

From Eq. 3.3:

$$f_2 = -x_2/(x_8(x_9 + x_7)) + (x_9 + x_7)u_k$$

From Eq. 3.4:

$$f_3 = -x_3/(x_{11}(x_{12} + x_{10})) + (x_{12} + x_{10})u_k$$

From Eq. 3.5:

$$\begin{aligned} f_4 = -x_4/(x_{11}(x_{12} + x_{10})) + x_2((1/(x_8(x_9 + x_7))) - (1/(x_{11}(x_{12} \\ + x_{10})))) + x_1((1/(x_6 + x_5)(x_9 + x_7 + x_{12} + x_{10})) \\ - (1/(x_{11}(x_{12} + x_{10})))) - ((x_6 + x_5) + (x_9 + x_7) + (x_{12} \\ + x_{10}) + (x_{13}/(x_{11}(x_{12} + x_{10})))) uk \\ + E_{cell(orp)}/(x_{11}(x_{12} + x_{10})) \end{aligned}$$

Thus,

$$f_5 = f_6 = f_7 = f_8 = f_9 = f_{10} = f_{11} = f_{12} = f_{13} = 0 \qquad 3.13$$

From Eq. 3.15 the matrix representation of the model, F is calculated as:

$$F = \frac{\partial f}{\partial x} | x = \hat{x}$$

$$= \begin{bmatrix} a_{11} & 0 & 0 & 0 & a_{15} & a_{16} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{22} & 0 & 0 & 0 & 0 & a_{27} & a_{28} & a_{29} & 0 & 0 & 0 & 0 \\ 0 & 0 & a_{33} & 0 & 0 & 0 & 0 & 0 & 0 & a_{3,10} & a_{3,11} & a_{3,12} & 0 \\ a_{41} & 0 & 0 & a_{44} & a_{45} & a_{46} & a_{47} & a_{48} & a_{49} & a_{4,10} & a_{4,11} & a_{4,12} & a_{4,13} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad 3.14$$

Where,

$$a_{41} = \frac{1}{(C_m + R_m)(C_a + R_{a1} + C_c + R_{c1})} - \frac{1}{R_{c2}(C_c + R_{c1})}$$

$$a_{44} = -\frac{1}{R_{c2}(C_c + R_{c1})} \qquad a_{45} = \frac{E_m}{(C_m + R_m)(C_a + R_{a1} + C_c + R_{c1})}$$

$$a_{46} = \frac{E_m}{C_m + R_m} - I \qquad a_{47} = \frac{E_a}{R_{a2}(C_a + R_{a1})}$$

$$a_{48} = \frac{E_a}{C_a + R_{a1}} \qquad a_{49} = \frac{E_a}{R_{c2}} - I$$

$$a_{4,10} = \frac{E_c}{R_{c2}(C_c + R_{c1})} \qquad a_{4,11} = \frac{E_c}{C_c + R_{c1}}$$

$$a_{4,12} = \frac{E_c}{R_{c2}} - I$$

$$a_{4,13} = -\frac{1}{R_{c2}(C_c + R_{c1})}\left[E_{cell} + E_m + E_a + (X_L + R_0) - E_{cell(orp)}\right] - I$$

And the measurement matrix, H as:

$$H = [0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0] \qquad 3.15$$

3.4.2 EKF of approximate circuit for V-RFB

Form of Eq. 3.9 is used to illustrate state variable of the parameter of actual circuit for V-RFB by applying Eq. 3.7 and 3.8 for model development. State x_k as:

$$x_k = [E_p \quad E_{cell} \quad Z_a \quad Z_c \quad Z_m \quad Z_L]^T \qquad 3.16$$

From state model with deliberation of input variable:

$$f(x_k, u_k) = [f_1 \quad f_2 \quad f_3 \quad f_4 \quad f_5 \quad f_6\,]^T \qquad 3.17$$

$$z_k = h_k(x_k) = [0 \quad E_{cellk} \quad 0 \quad 0 \quad 0 \quad 0]^T \qquad 3.18$$

Where $u_k = I$, f is the transition matrix of V-RFB system, and h_k is measurement matrix. Thus, $f_s(s = 1, 2, 3, 4, 5, 6)$ are describe as:

From Eq. 3.7:

$$f_1 = -x_1/((x_3 + x_4) * x_5) + u_k/x_5$$

From Eq. 3.8:

$$f_2 = -x_2 + x_1/((x_3 + x_4) - (x_6 * u_k) - u_k/x_5 + E_{cell(orp)}$$

Thus,

$$f_3 = f_4 = f_5 = f_6 = 0 \qquad 3.19$$

From Eq. 3.18 the matrix representation of the model, F is calculated as:

$$F = \frac{\partial f}{\partial x}|x = \hat{x} = \begin{bmatrix} a_{11} & 0 & a_{13} & a_{14} & a_{15} & 0 \\ a_{21} & 0 & a_{23} & a_{24} & a_{25} & a_{26} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad 3.20$$

Where,

$$a_{11} = -\frac{1}{(Z_a + Z_c)Z_m} \qquad a_{13} = -\frac{E_p}{Z_m(Z_a + Z_c)}$$

$$a_{14} = -\frac{E_p}{Z_a + Z_c} \qquad a_{15} = -\frac{E_p}{Z_m} - I$$

$$a_{21} = \frac{1}{(Z_a + Z_c)Z_m} \qquad a_{23} = \frac{E_p}{Z_a + Z_c}$$

$$a_{24} = \frac{E_p}{Z_a + Z_c} \qquad a_{25} = \frac{Ep}{Z_m} - I$$

$$a_{26} = -\left[E_{cell} + E_p + \left(\frac{1}{Z_m} + Z_L\right) - E_{cell(orp)}\right] - I$$

And the measurement matrix, H as:

$$H = [\,0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0\,] \qquad 3.21$$

3.5 Simulation and result analyzation

MATLAB software was used to simulate the circuits using EKF method. EKF algorithms were formed based on the derivation from both actual and approximate circuits. Simulation for both circuits was conducted respectively to estimate the parameters. Tuning process was involved as the graphs obtained from the simulations diverged. This process needed to be carried out constantly until the graph of each parameter of both circuits approaches a steady state and achieve expected result. The graph simulation for the circuits is analysed accordingly.

3.6 Chapter conclusion

This chapter begins with the discussion of the flow of the project; from the derivation of the equivalent circuits for V-RFB to the analyses of the results. Both actual and approximate circuit for V-RFB were derived accordingly. From the derivation of the circuits, EKF was used as parameter estimation to simulate both circuits. The graph of each parameter of actual and approximate circuit was observed and analysed. Tuning processes continuously took place until a steady state graph of each parameter for both circuits was obtained. As the parameter in each graph approaches a steady state, it shows the compatibility of the circuit itself. The processes then continued until the objectives of the project were achieved.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Chapter overview

This chapter focuses on the results of both actual and approximate circuit for V-RFB. The result shows the graph for each parameter of circuits is in a steady state. All data were capture at 80% SOC. Result of an error is also shown to see the efficiency of the equivalent circuit for V-RFB.

4.2 Open Circuit Voltage

OCV or $E_{cell(orp)}$ refers to as State of Charge (SOC) function and directly related. To validate the model, verification of the OCV curve is one of the options. The accuracy of OCV estimation influences the battery SOC accuracy. Simulation was conducted for both circuits and tuning process was also taken place in order to gain a steady state graph of each parameter of both circuits. All data were capture at 80% of SOC. Figure 4.1 shows a comparison between EKF-based estimated and experimental E_{cell} of equivalent electrical circuit that charged at 1.5 V and discharged at minimum 1.46 V. Meanwhile, Figure 4.2 shows a comparison between EKF-based estimated and experimental E_{cell} of approximate circuit which was also charged at 1.5 V while discharged at minimum 1.35 V. It can be observed that for equivalent electrical circuit that $E_{cell\,EKF\,estimation}$ and $E_{cell\,experiment}$ are overlapped with minor within 50s, whereas for approximate circuit that $E_{cell\,EKF\,estimation}$ and $E_{cell\,experiment}$ are overlapped with minor differences within 100s. Based on this observation it is proven that both circuits are suitable for V-RFB, even though there is inconsistency at the first 50s. This inconsistency occur due to high measurement noise covariance, however both circuit achieved steady state within 50s and 100s respectively. Constant current (1.5A) is applied for both circuit due to the parasitic inductance which can affect the immediate voltage drop of cell voltage during discharge and could cause under voltage if high current density is used. It takes some times for the cell voltage of experiment and EKF estimation to stabilize as the inductor oppose changes.

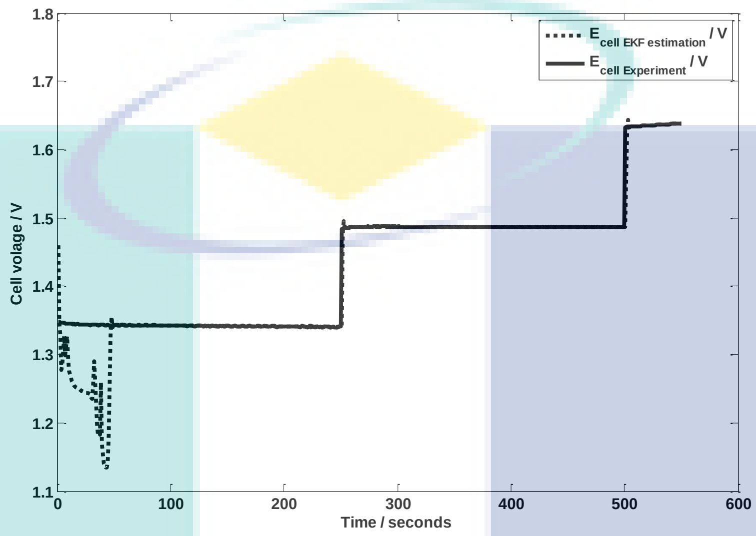

Figure 4.1 Comparison of EKF-based estimated and experimental E_{cell} of equivalent electrical circuit at 80% of SOC.

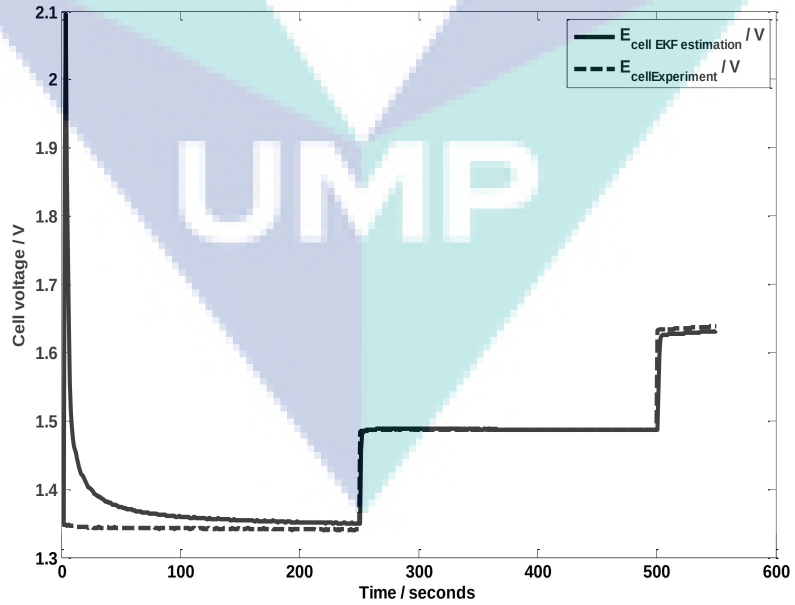

Figure 4.2 Comparison of EKF-based estimated and experimental E_{cell} of approximate circuit at 80% of SOC

The accuracy state vector estimation performance also refer as degree of uncertainties is illustrated in Figure 4.3 and Figure 4.4. Figure 4.3 shows the degree of uncertainties of state estimation covariance for actual circuit, and as observed all state estimation approach steady state at the end. Figure 4.4 shows the degree of uncertainties of state estimation covariance for the approximate circuit, and in the end all state estimations approach steady states. Both circuit states estimation shows approaching steady state so it depicts the performance and accuracy of the estimated state.

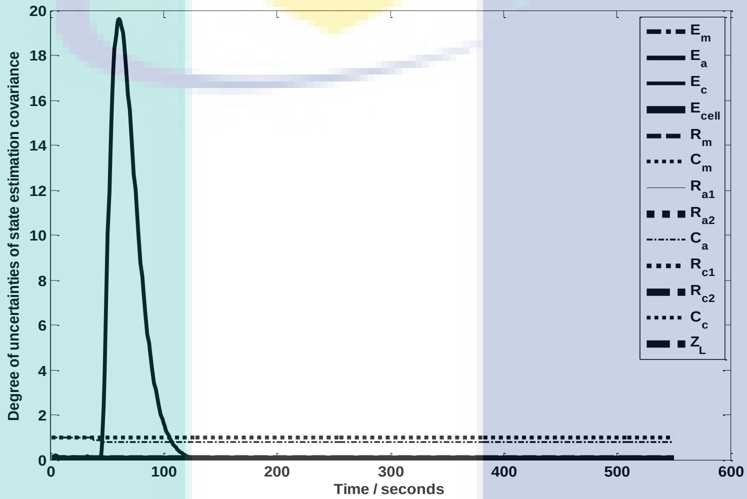

Figure 4.3 Degree of uncertainties of state estimation covariance for equivalent electrical circuit at 80% of SOC.

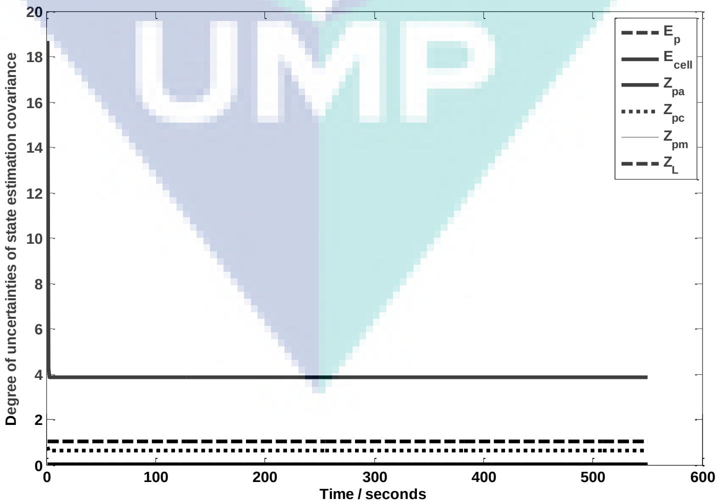

Figure 4.4 Degree of uncertainties of state estimation covariance for approximate circuit at 80% of SOC.

4.3 Polarization

Polarization is also known as losses which usually occurs at activation, concentration, and ohmic polarization (Yu & Yuvarajan, 2005). Current density influences the losses to occur, as a high current transient is applied, parasitic elements can affect the systems performance. As for activation polarization, the losses increase as the current increases and shows the slowest step in electrochemical reaction. Concentration polarization occurs at only high current and can be reduced as the formation large positive ions at electrode/electrolyte interface. Resistor is referred as the losses of ohmic from the electrodes and electrolyte electrical resistance. Ohmic resistance loss and the relaxation period voltage drop related before the transient mode start although the capacitance and the battery transient behaviour can be related. Mass transfer is essential in controlling the success and rate any preparative electrochemical reaction easily measureable and predictable. Subtopic 4. 3. 1 and 4. 3. 2 shows the results of activation, concentration, and mass transport polarization of both actual and approximate circuit.

4.3.1 Actual circuit

The estimation of parameters of the V-RFB based on the implemented EKF model against time and all the data recorded at discharging mode at 80% of SOC are illustrated as capacitance mass transfer (C_m), resistance mass transfer(R_m), capacitance activation polarization(C_a), resistance activation polarization$(R_{a1}\ and\ R_{a2})$, capacitance concentration polarization (C_c), resistance concentration polarization $(R_{c1}\ and\ R_{c2})$, parasitic inductance (X_L) and estimation error$(E_{cell}\ error)$ respectively in Figure 4.5 until Figure 4.14. Tuning process of the simulation continuously takes place until the graph of each parameter approaches a steady state.

The tuning of covariance of P (initial state), Q (process noise), and R (measurement noise) are expressed as follows:

$$P = \begin{bmatrix} 4e^{-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 5e^{-8} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 8e^{-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1e^{-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1e^{-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1e^{-1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1e^{-1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1e^{-1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1e^{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q = \begin{bmatrix} 1e^{-4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1e^{-4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1e^{-4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1e^{-4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$R = [1e^{-5}]$$

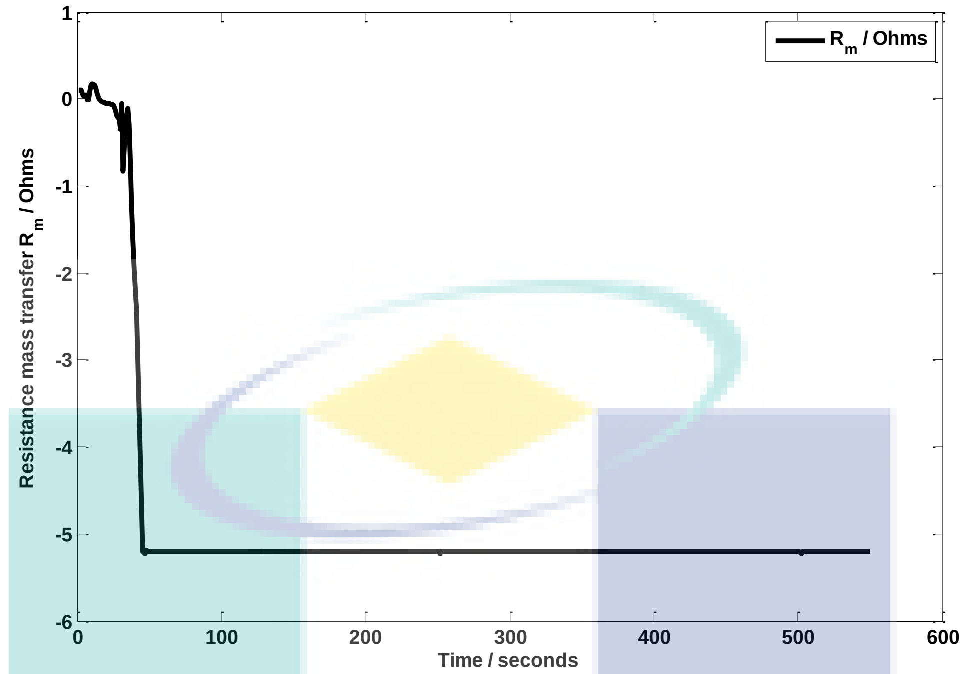

Figure 4.5 Estimation result of resistance mass transfer polarization of equivalent electrical circuit for V-RFB

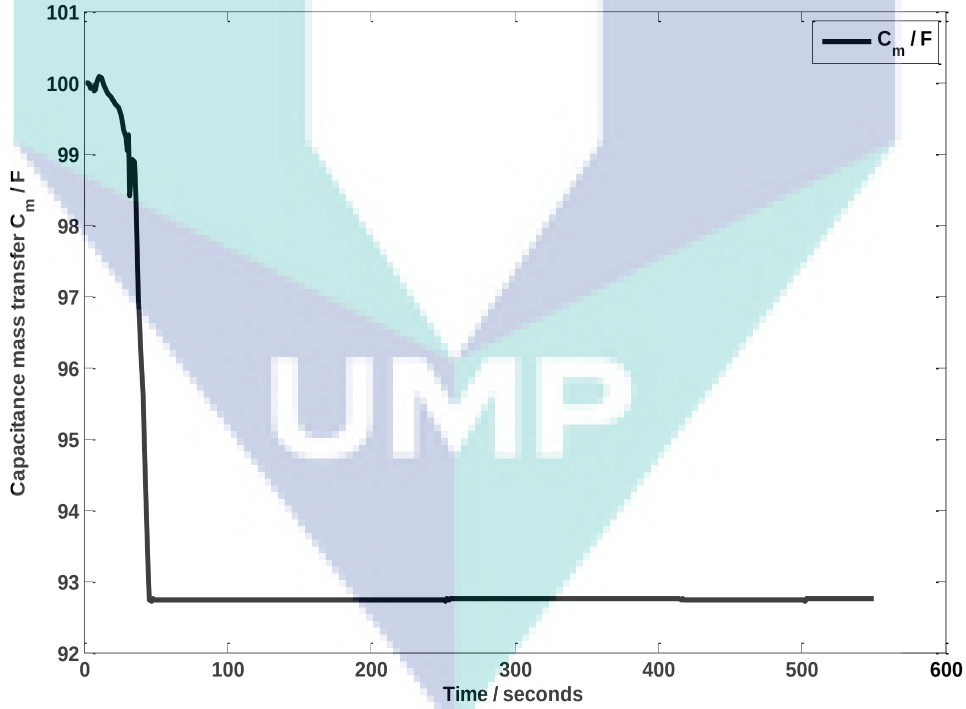

Figure 4.6 Estimation result of capacitance mass transfer polarization of equivalent electrical circuit for V-RFB

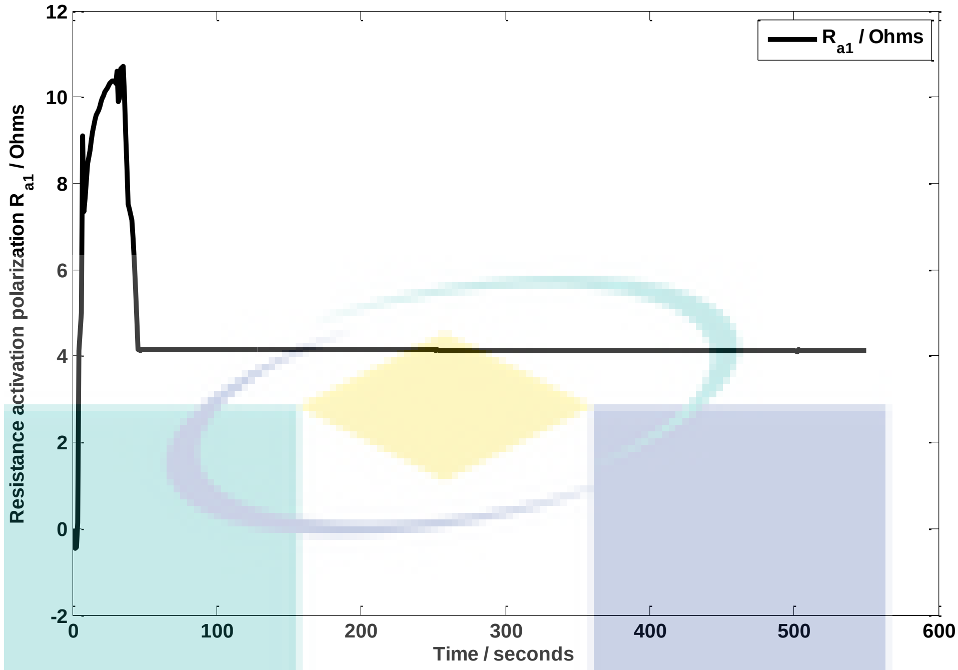

Figure 4.7 Estimation result of resistance activation polarization (1) of equivalent electrical circuit for V-RFB

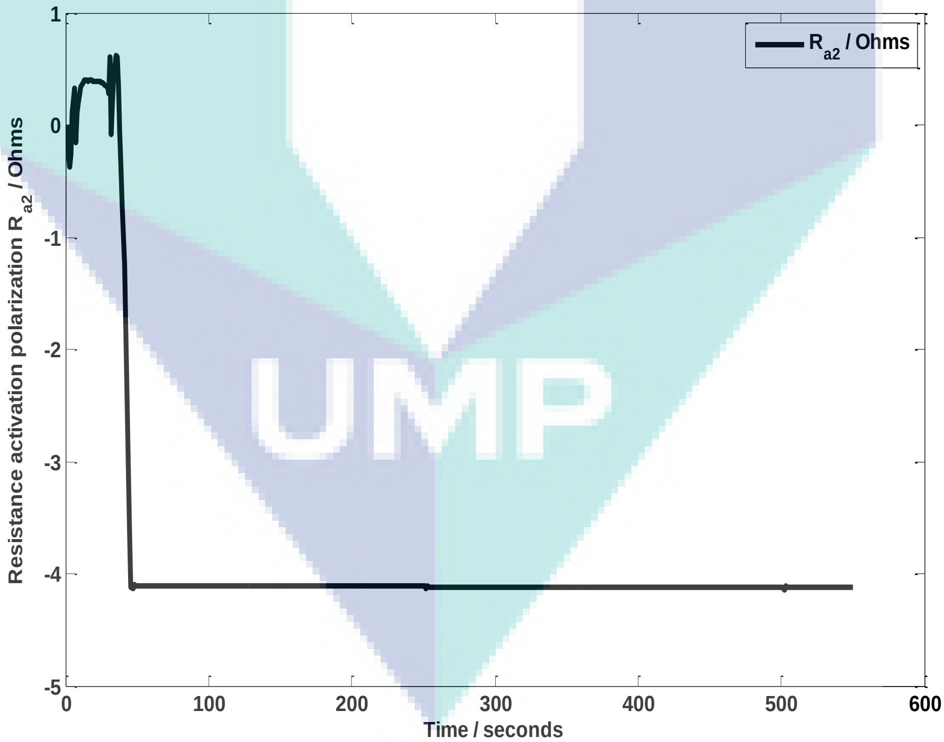

Figure 4.8 Estimation result of resistance activation polarization (2) of equivalent electrical circuit for V-RFB

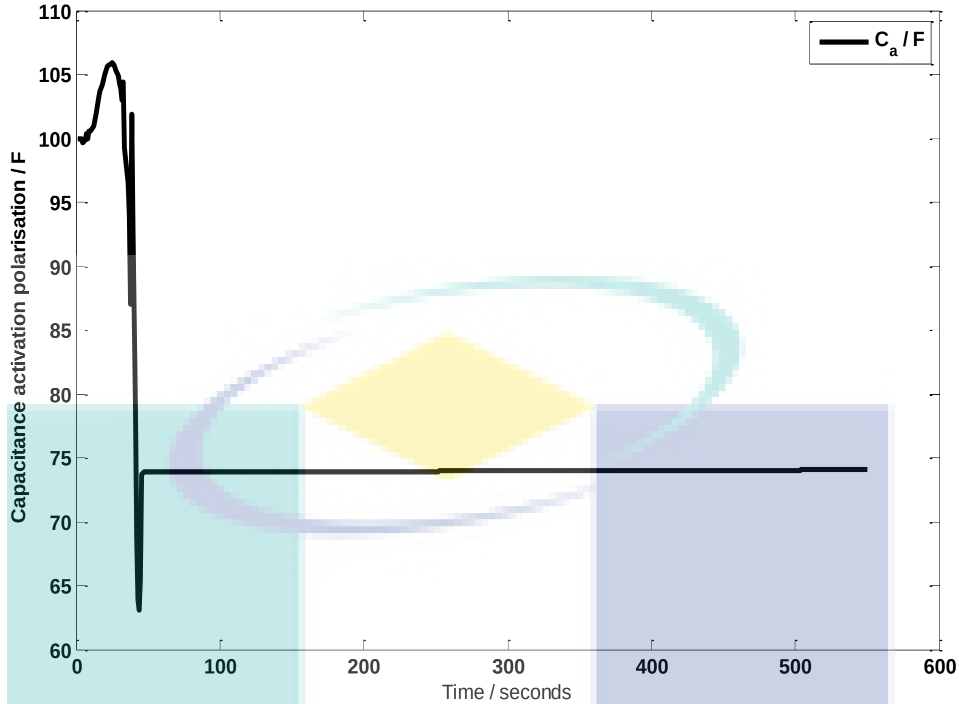

Figure 4.9 Estimation result of capacitance activation polarization of equivalent electrical circuit for V-RFB

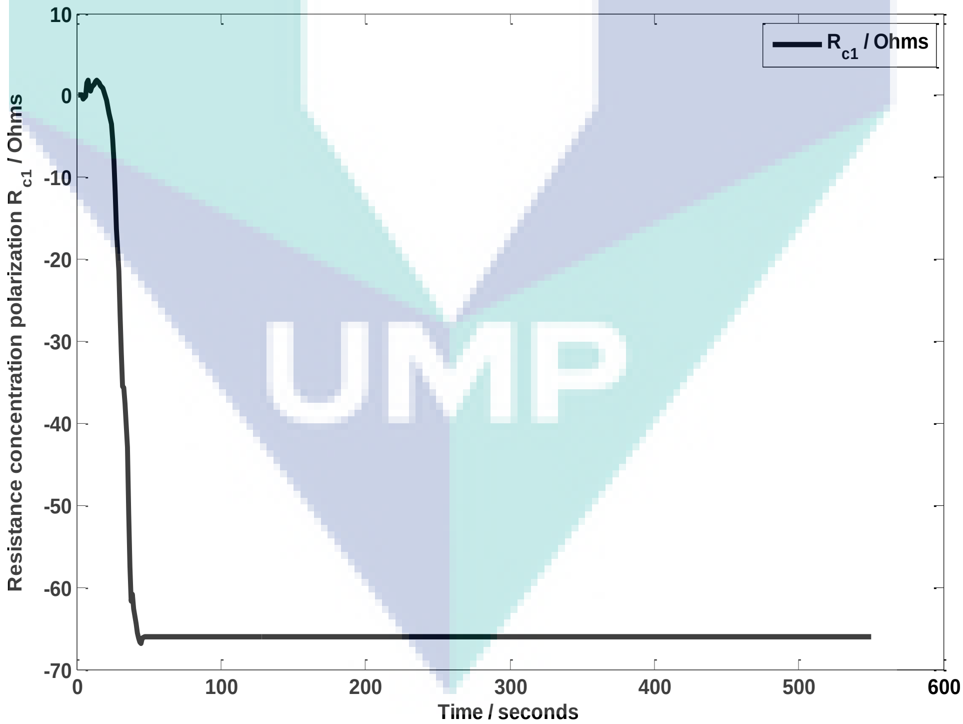

Figure 4.10 Estimation result of resistance concentration polarization (1) of equivalent electrical circuit for V-RFB

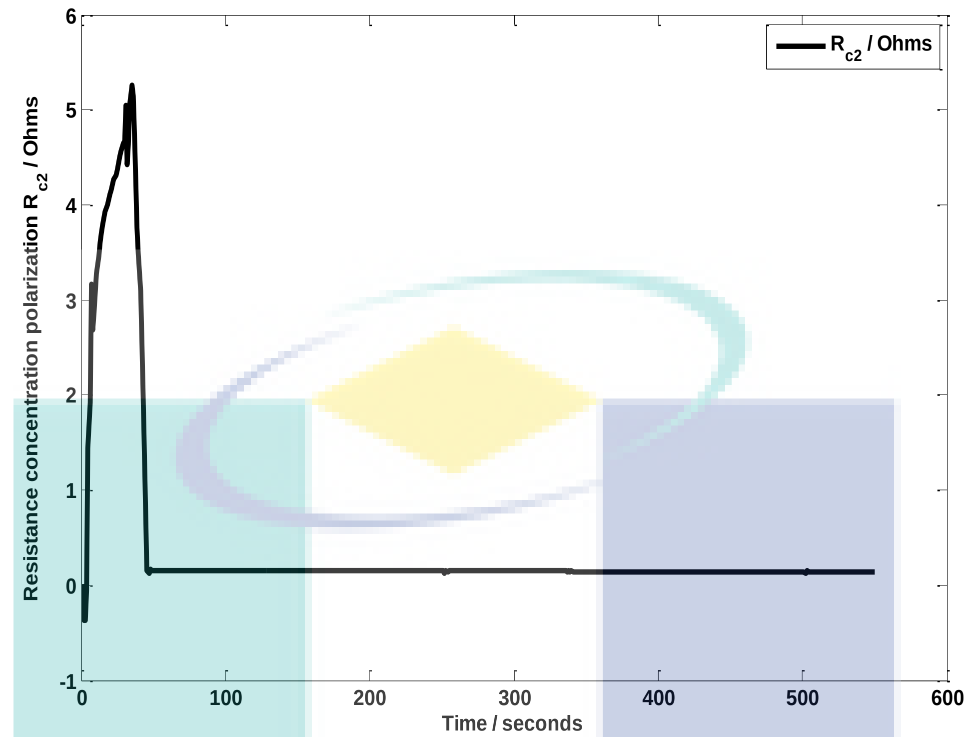

Figure 4.11 Estimation result of resistance concentration polarization (2) of equivalent electrical circuit for V-RFB

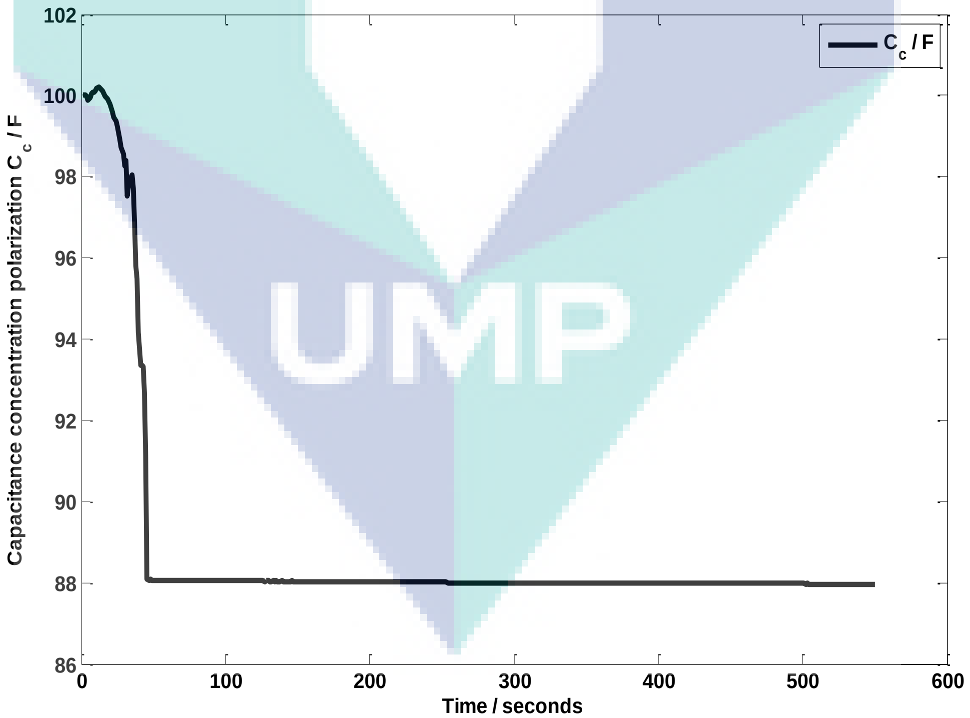

Figure 4.12 Estimation result of capacitance concentration polarization of equivalent electrical circuit for V-RFB

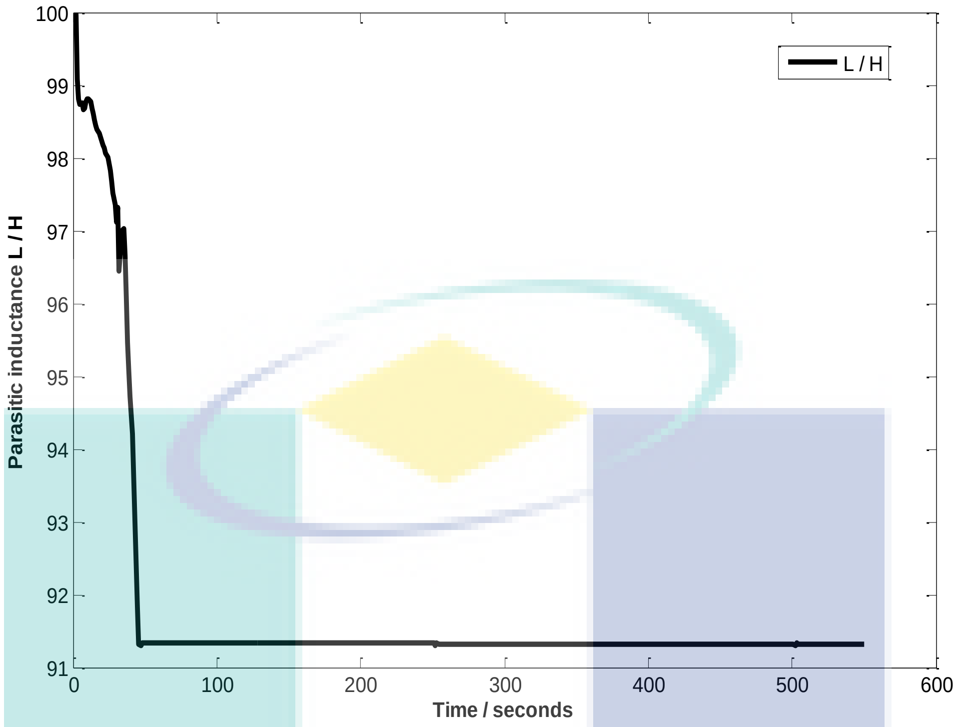

Figure 4.13 Estimation result of parasitic inductance of equivalent electrical circuit for V-RFB

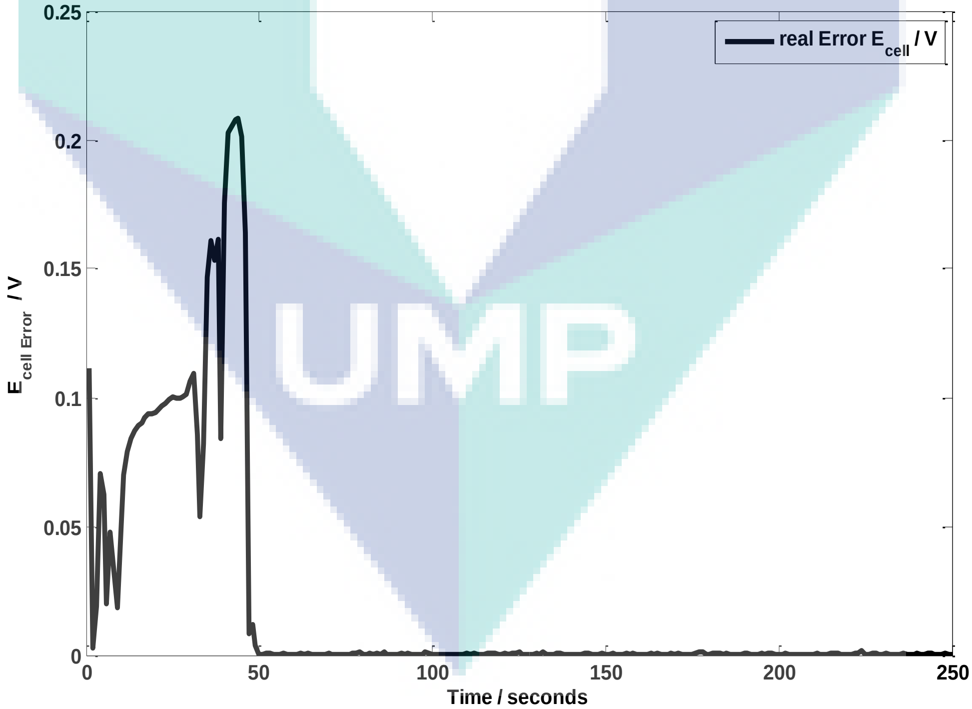

Figure 4.14 Estimation result of E_{cell} error of equivalent electrical circuit for V-RFB

The mass transfer, activation and concentration polarization of resistance and capacitance along with parasitic inductance illustrated in Figure 4.5 until Figure 4.13 at 80% SOC, as observed within the first 40s at each estimated parameters prior to approaching a steady state. Hence, the stability of the circuit by implementing EKF as a parameter estimation is evident as the graph for each parameter approaches a steady state. The small value of error indicates the accuracy of the system's result; as shown in Figure 4.14 the error for equivalent electrical circuit is 0.6%.

4.3.2 Approximate circuit

The estimation of parameters of the V-RFB based on the implemented EKF model against time and all the data recorded at discharging mode at 80% of SOC are illustrated as impedance of activation polarization(Z_a), concentration polarisation(Z_c), mass transfer(Z_m) and parasitic inductance(Z_L), and also estimation error($E_{cell}\ error$) respectively in Figure 4.15 until Figure 4.19.

The tuning of covariance of P (initial state), Q (process noise), and R (measurement noise) are expressed as follows:

$$P = \begin{bmatrix} 6e^{-2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1e^{-2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6e^{-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 7e^{-6} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$Q = \begin{bmatrix} 1e^{-4} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1e^{-4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1e^{-4} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$R = 1e^{-5}$$

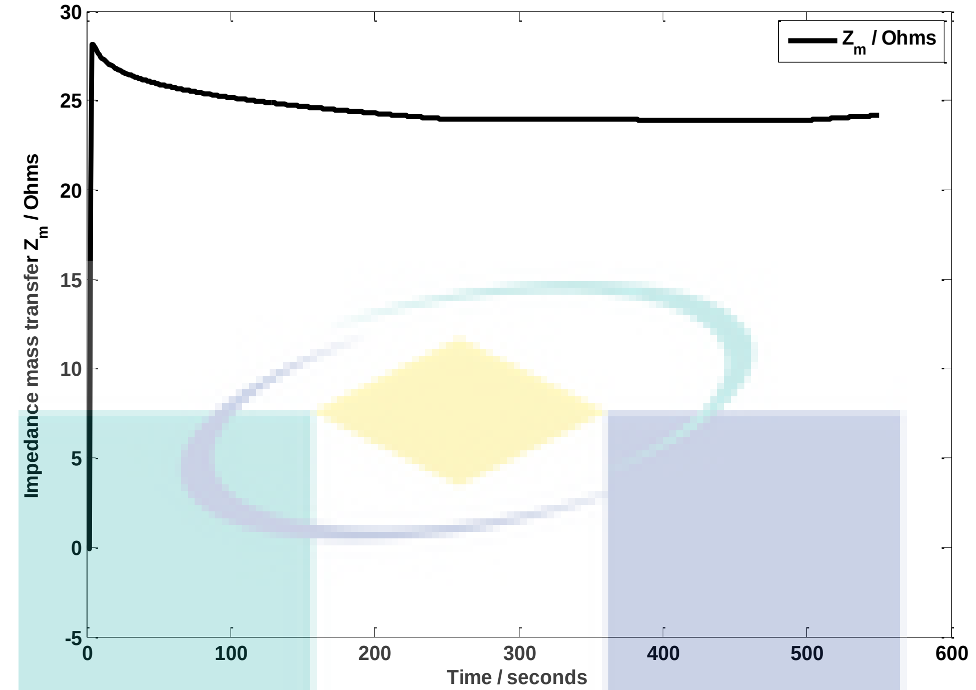

Figure 4.15 Estimation result of impedance mass transfer of approximate circuit for V-RFB

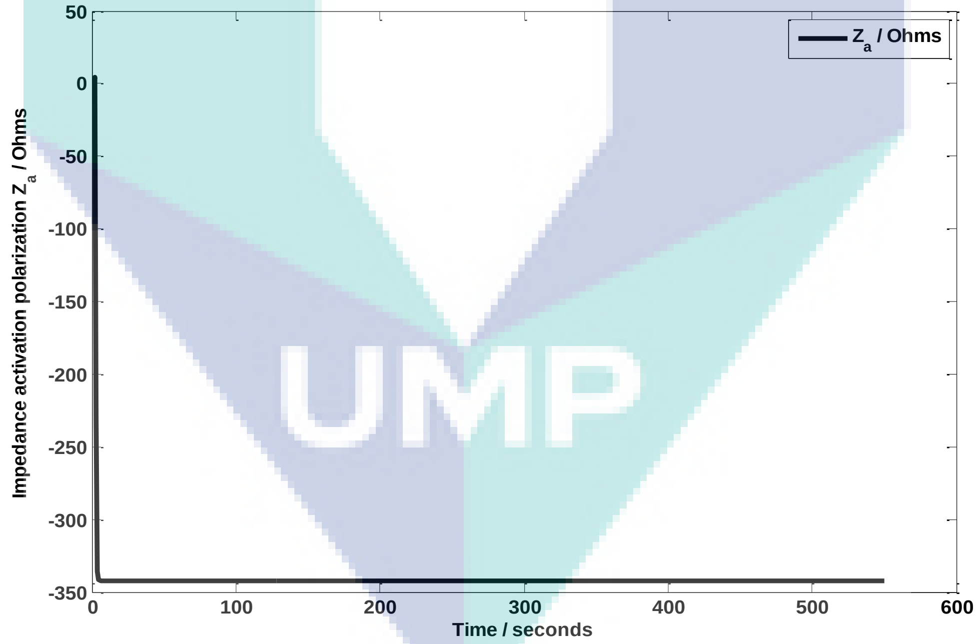

Figure 4.16 Estimation result of impedance activation polarization of approximate circuit for V-RFB

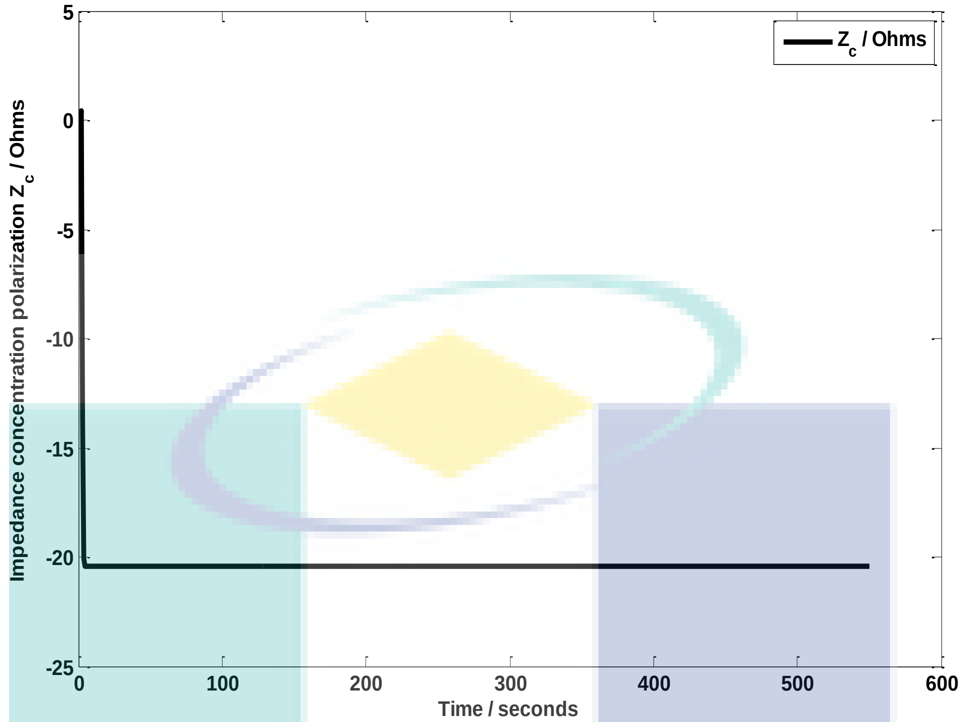

Figure 4.17 Estimation result of impedance concentration of approximate circuit for V-RFB

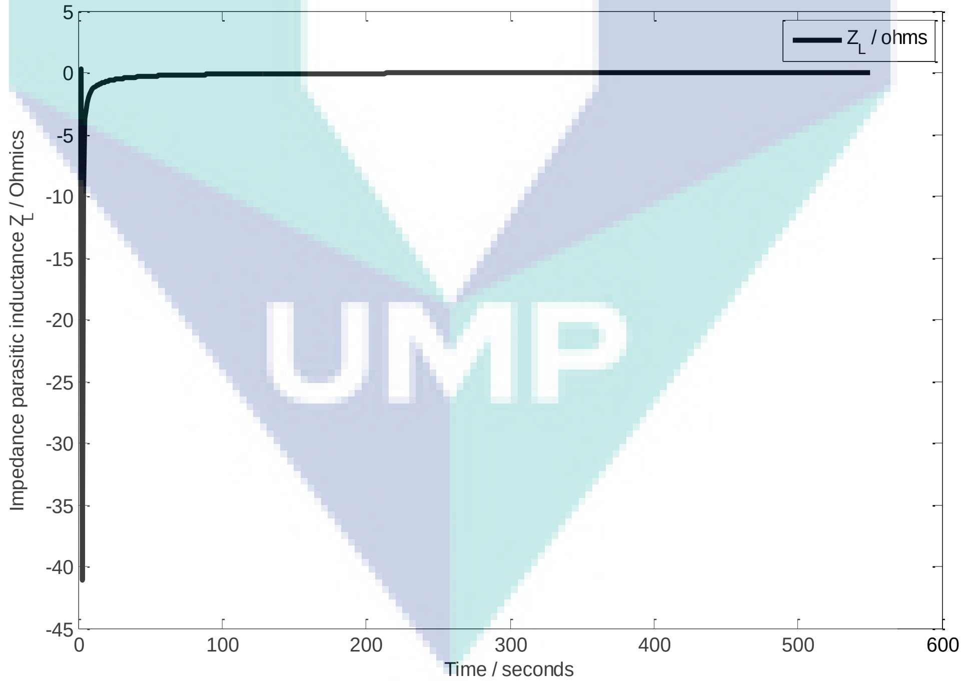

Figure 4.18 Estimation result of impedance parasitic inductanceof approximate circuit for V-RFB

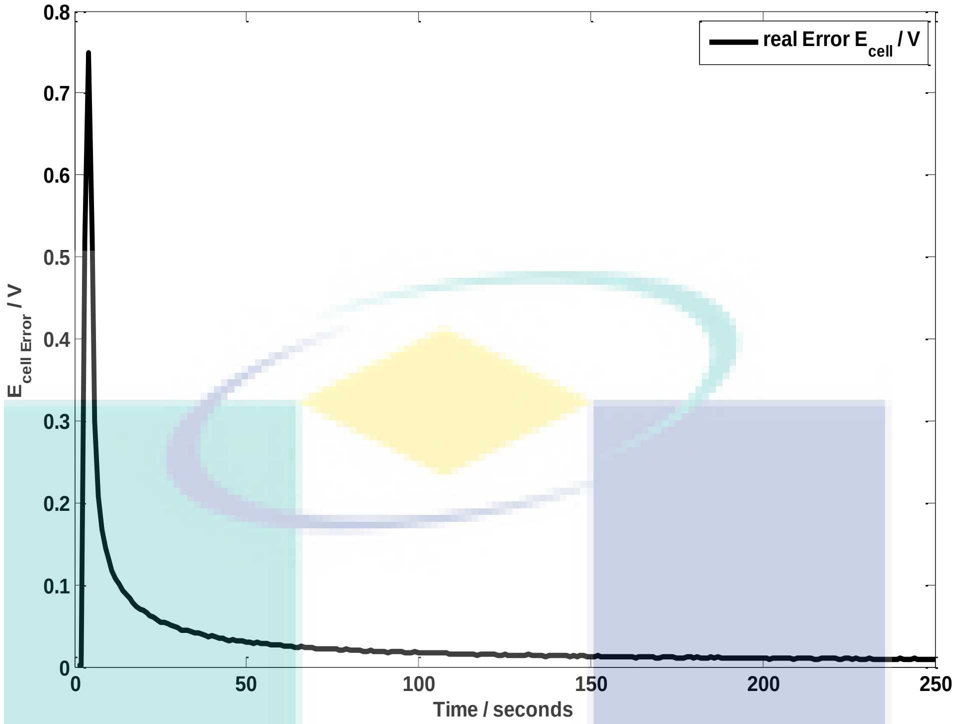

Figure 4.19 Estimation result of cell voltage error of approximate circuit for V-RFB

The impedance of mass transfer, activation and concentration polarization and also parasitic inductance are illustrated in Figure 4.15 until Figure 4.19 at 80% SOC, as observed within less than 10s the estimated parameter reached a steady state within the first few seconds. The small value of error indicates the accuracy of the system's result, as shown in Figure 4.19 in which the error for the approximate circuit is 2.0%.

It is vital to be consistent when evaluating the filter performance because the estimation vector can be affected. Based on both actual and approximate circuits, for each parameter of the circuit, the behaviour of the estimation approaches a steady state with 0.6% and 2.0% errors, respectively. As the error shows closer to zero it can be proven that both circuits are adaptable in any V-RFB systems. Both circuits approach a steady state at less than 10s and 40s, respectively, as reported in the previous work (M. R. Mohamed et al., 2013) that the proposed circuit achieved a steady state after 150s. This demonstrated that the circuit in this project is compatible for V-RFB.

4.4 Chapter conclusion

In this chapter, the result for each parameter of actual and approximate circuit for V-RFB shows that the state estimation smoothly approaches a steady state at the end with 0.6% and 2.0% errors, respectively. Hence, it proves the stability of the circuits as the error is closer to zero. As shown in Figure 4.1 and 4.2, both circuits shows adaptability to represent V-RFB as estimation EKF-based and experiment cell voltage are overlapped with minor differences. Furthermore, the estimation result of all states for actual and approximate circuit shows approaching steady state. Based on the result, EKF is proven as the suitable method for parameter estimation due to both circuit shows the adaptiveness for V-RFB. So, it is also depicts that the approximate circuit can be an alternative of actual circuit for V-RFB.

CHAPTER 5

CONCLUSION

5.1 Conclusion

Vanadium Redox Flow Battery is promising as an energy storage technology and in the future it would be widely used. Based on the research, equivalent circuit for V-RFB is presented, which can be categorised into actual and approximate circuit. Both circuit was derived accordingly and then estimated using EKF algorithm. Approximate circuit is formed as an alternative for actual circuit by lumped some of the parameters. This is to reduce the complexity in represent the simulation result and also time.

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.

5.2 Recommendation

Based on the presented result of parameters high value of noises can affect the estimation of the system. Continuous research on the equivalent circuit for Vanadium Redox Flow Battery (V-RFB) can be take place by authenticate using Kalman Filter at different SOC and circuit to validate the system.

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