High Voltage DC Arc Detection Model

Bassem Farag
Abstract

High Voltage DC Arc Detection Model

Bassem Farag

High voltage (HV) battery systems are widely used in many applications nowadays. And due to the safety concerns regarding lithium-ion cells, the safety of the lithium-ion based battery systems is vital. One crucial danger for lithium-ion cells is heat. And as arcs formation can lead to heat generation within the system, it is important to detect arcs that take place frequently within HV battery systems. This thesis is done in cooperation with Northvolt AB and it focuses on assessing the ability to detect the occurrence of arcs in the system, but it does not focus on preventing arcs. The goal is to build a detection system to identify the occurrence of arcs, both within the battery system and in the connection between the battery system and the load (vehicle). The detection circuit should not affect the ability of the isolation measurement unit inside the system, and the detection system should be protected at all times.

The circuit was designed and tested using LTSPice software. This is due to the absence of a ready system to test the circuit against at Northvolt. The system was able to detect arcs both within the battery system and when connecting the battery system to the vehicle. Additionally, as required by Northvolt, the detection system is designed without affecting the isolation measurement unit and the detection system is kept safe at all times by using an isolation circuit.

Future work is recommended to generalize the detection system so it can be used in different high voltage applications. This can be done by testing the system against other HV systems and updating the filter and amplifier’s values, as well as the software thresholds. Additionally, it is recommended that the software module is calibrated against the real system during hardware testing. This calibration will optimize the software module and, thus, result in better detection.
Acknowledgements

This publication has been produced during my scholarship period at Uppsala University, thanks to a Swedish Institute Scholarship. Additionally, I would like to express my gratitude to my supervisor at Northvolt AB, Anders Mangnusson for the support of my master thesis. His help and guidance was really valuable.
Furthermore, I would like to express my deep thanks to my reviewer at Uppsala University Steffi Knorn for her patience and guidance. Her comments and notes was essential to complete this report.
Conjointly, I would like to thank Anders Markland at Northvolt AB for his extremely useful comments, suggestions and feedbacks.
My sincere thanks to Andreas Bildberg and Hicham Sadoun at Northvolt AB for their knowledge and advice concerning lithium-ion batteries.
Last but not the least, I would like to thank my family and friends for their support.
Contents

List of Figures .................................................. iv
List of Tables ................................................... v

Part I: Introduction and Background 7

1 Introduction ................................................. 9
  1.1 Problem Description ................................. 10
  1.2 Related Work ........................................... 10
  1.3 Contributions ........................................... 11
  1.4 Thesis Structure ........................................ 11

2 Background .................................................. 12
  2.1 Overview ............................................... 12
  2.2 Secondary Batteries ................................. 12
  2.3 Lithium-ion Battery ................................. 13
    2.3.1 Chemistry ........................................ 13
    2.3.2 Operation ........................................ 14
    2.3.3 Battery Model ................................... 14
    2.3.4 Hazards .......................................... 15
    2.3.5 Battery Pack ..................................... 16
  2.4 Inductor Behavior .................................... 16
  2.5 High Voltage Spark ................................. 18
  2.6 Amplifier .............................................. 18
    2.6.1 Operational Amplifier .......................... 19
    2.6.2 Ideal Non-Inverting Amplifier ................. 20
  2.7 First Order High-Pass Filter ..................... 20
  2.8 Analogue to Digital Conversion .................. 21

Part II: Simulations and Design 23

3 Simulation Setup ........................................... 25
  3.1 Overview ............................................. 25
  3.2 Simulation Software ............................... 25
3.3 Simulation Limitations ........................................ 25
  3.3.1 Sub-Pack Model ........................................ 26
  3.3.2 System Model ........................................ 26

4 Design ......................................................... 28
  4.1 Overview .................................................. 28
  4.2 Detection Circuit Objectives ................................ 28
  4.3 Detection Circuit Design ................................... 29
    4.3.1 Resistors Chain ..................................... 29
    4.3.2 Isolation Circuit ...................................... 30
    4.3.3 Instrumentation Amplifier ............................. 30
    4.3.4 First Order High-Pass Filter ......................... 32
    4.3.5 Non-Inverting Amplifier .............................. 32
    4.3.6 ADC .................................................. 32
    4.3.7 Software Analysis .................................... 35

Part III: Results and Conclusions .................................. 39

5 Simulation Results .................................................. 41
  5.1 Overview .................................................. 41
  5.2 Detection Methodology .................................... 41
  5.3 One Sub-Pack System ..................................... 43
  5.4 Two Sub-Pack System .................................... 45
  5.5 Number of sub-packs effect on the detected signal ...... 47

6 Conclusions and Future Work ..................................... 49
  6.1 Overview .................................................. 49
  6.2 Conclusions ................................................ 49
  6.3 Future Work .............................................. 49
    6.3.1 Calibration ........................................... 49
    6.3.2 Enhancement .......................................... 50

References ......................................................... 51
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Secondary Batteries Discharge Profiles</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>Lithium-ion Cell Operation</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Cell Module</td>
<td>15</td>
</tr>
<tr>
<td>2.4</td>
<td>Explosion of Cell Demonstration During Fire Test</td>
<td>15</td>
</tr>
<tr>
<td>2.5</td>
<td>Battery Pack Example (6S2P)</td>
<td>16</td>
</tr>
<tr>
<td>2.6</td>
<td>Series LR Circuit Example</td>
<td>17</td>
</tr>
<tr>
<td>2.7</td>
<td>Inductor Current Transient Response</td>
<td>17</td>
</tr>
<tr>
<td>2.8</td>
<td>Simplified Version of Wire Model</td>
<td>18</td>
</tr>
<tr>
<td>2.9</td>
<td>Ideal Amplifier Model</td>
<td>18</td>
</tr>
<tr>
<td>2.10</td>
<td>Ideal Operational Amplifier</td>
<td>19</td>
</tr>
<tr>
<td>2.11</td>
<td>Example of a Differential Operational Amplifier</td>
<td>19</td>
</tr>
<tr>
<td>2.12</td>
<td>Ideal Non-Inverting Amplifier Setup</td>
<td>20</td>
</tr>
<tr>
<td>2.13</td>
<td>First Order High-Pass Filter</td>
<td>21</td>
</tr>
<tr>
<td>2.14</td>
<td>Magnitude Response of the High-Pass Filter in dB Vs Frequency in Hz</td>
<td>21</td>
</tr>
<tr>
<td>2.15</td>
<td>Analogue to Digital Conversion Circuit Example</td>
<td>22</td>
</tr>
<tr>
<td>3.1</td>
<td>Sub-Pack Model Used in Simulation</td>
<td>26</td>
</tr>
<tr>
<td>3.2</td>
<td>Model for the Battery System Being Studied</td>
<td>27</td>
</tr>
<tr>
<td>3.3</td>
<td>Model of the DC/DC Converter and the Inverter</td>
<td>27</td>
</tr>
<tr>
<td>4.1</td>
<td>Proposed Detection System Model</td>
<td>29</td>
</tr>
<tr>
<td>4.2</td>
<td>Resistors Chain Model</td>
<td>29</td>
</tr>
<tr>
<td>4.3</td>
<td>Isolation Circuit Simple Model</td>
<td>30</td>
</tr>
<tr>
<td>4.4</td>
<td>Instrumentation Amplifier Circuit Model</td>
<td>31</td>
</tr>
<tr>
<td>4.5</td>
<td>Inducing a Spark Before and After the DC/DC Converter in a System with One Sub-Pack with and without Using the Non-Inverting Amplifier</td>
<td>32</td>
</tr>
<tr>
<td>4.6</td>
<td>Detection Circuit Model</td>
<td>34</td>
</tr>
<tr>
<td>4.7</td>
<td>Main Module Flow Chart</td>
<td>35</td>
</tr>
<tr>
<td>4.8</td>
<td>Detection Module Flow Chart</td>
<td>37</td>
</tr>
<tr>
<td>4.9</td>
<td>Sleep Module Flow Chart</td>
<td>38</td>
</tr>
<tr>
<td>5.1</td>
<td>The System Including the Detection Circuit</td>
<td>42</td>
</tr>
<tr>
<td>5.2</td>
<td>Inducing a Spark Before and After the DC/DC Converter in a System with One Sub-Pack</td>
<td>43</td>
</tr>
</tbody>
</table>
5.3 Inducing a Spark After the DC/DC Converter and Before the Inverter in a System with One Sub-Pack .................. 44
5.4 Inducing a Spark Before and After the Inverter in a System with One Sub-Pack ................................. 44
5.5 Inducing a Spark Before and After the DC/DC Converter in a System with Two Sub-Packs .................. 45
5.6 Inducing a Spark After the DC/DC converter and Before the Inverter in a System with Two Sub-Packs ............ 46
5.7 Inducing a Spark Before and After the Inverter in a System with Two Sub-Packs ................................. 46
5.8 Inducing a Spark Before the DC/DC Converter for Both the One Sub-Pack and the Two Sub-Packs Systems .... 47
5.9 Inducing a Spark Before the DC/DC Converter in Systems with Different Number of Sub-Packs ................. 48
List of Tables

2.1 Chemistry of Different Secondary Batteries . . . . . . . . . . . 12
2.2 Advantages and Limitations of Different Secondary Batteries . 13
Part I:
Introduction and Background
1. Introduction

A battery is a device which consists of one or more galvanic cells and can power electrical equipment. Batteries can be identified as primary or secondary batteries, depending on their ability to be recharged. While primary batteries are for single use only, secondary batteries can be recharged. This report focuses on secondary batteries, specifically the Battery Energy Storage Systems (BESSs). These BESSs are used as energy storage devices. In order to efficiently use a renewable energy source, any excess energy production should be stored in a battery energy storage system. Batteries have a critical role in our daily lives. On a daily basis, people rely on several devices which contain batteries. Batteries are not only the main power source for most of our modern wireless devices, but they, particularly secondary batteries, will soon play an important role in reducing CO₂ emissions.

A majority of CO₂ emissions created by energy production can be attributed to fossil fuels. Given the harms that such emissions have, it is crucial that we shift from such non-renewable energy sources to more renewable ones. Many countries have taken steps towards reducing their fossil fuel usage, and batteries can help with this. Renewable energy resources, such as solar or wind power, can have instable power production. Batteries can help maintain stable power production by storing excess energy for use when needed, thus ensuring a stable power line and addressing this problem. In recent years, car manufacturers have introduced hybrid cars. Hybrid cars are a good step towards fully electrified cars, with batteries as the main energy source.

Combining a renewable energy source with an efficient battery is a significant step towards successfully reducing the usage of fossil fuels. The main factor in the success of this step is building an efficient battery pack that is safe, robust, and energy dense enough to run the vehicle with the needed power for a sufficient amount of time before recharging. The entrance of many automotive companies into the hybrid car market over the past few years has increased the interest in secondary (rechargeable) batteries. This increased interest has encouraged the development and introduction of battery solutions and new battery chemistries. Several battery chemistries have been introduced during the 20th century, including nickel-iron batteries, alkaline batteries, nickel-metal-hydride and lithium-ion batteries. Each chemistry has its advantages and disadvantages, which will be discussed below. Battery quality depends on a few aspects such
as power density, energy density, memory effect, and self-discharge rate.
The optimal battery should have high power and energy density, no memory
effect, and a low self-discharge rate.

1.1 Problem Description

Lithium-ion batteries have shown favorable characteristics compared to
other chemistries, as we will discuss in Section 2.3. Hence, they are widely
used in a variety of applications, including military devices and consumer elec-
tronics, such as phones, notebooks, and digital cameras.
One main drawback of the lithium-ion battery is the need for a protection cir-
cuit against internal or external short-circuits, overheating, overcharging, or
over-discharging, as discussed in Section 2.3.
It is necessary to take extra precautions when creating battery packs that sup-
port applications with a high power demand as battery packs have the potential
to be more damaging if accidents occur. For example, a bad or loose connec-
tion can cause glitches, which lead to sparks. This will discussed further in
Section 2.5. Since the potential impacts of a spark increases as power in-
creases, it is critical to detect and measure the occurrence and severity of these
sparks.
Additionally, it is important to differentiate between a "normal" spark, which
takes place upon opening contactors, and sparks that take place due to a bad
or loose connection. In fact, mis-detection can lead to false alarms or miscat-
egorize a bad connection as a normal spark.
As a result, we need to detect the occurrence of sparks and introduce different
thresholds for risks due to the intensity of the spark.

1.2 Related Work

Volvo Car Corporation filed a patent [1] in 2014 where a loose plug de-
tector was designed for an alternating current (AC) system. The idea is to
detect any loose plug while charging the vehicle. While the current in this
case was an AC, we focus on direct current (DC).
Another patent [7] published in 2004, was concerned with arc detection in DC
systems. The system detects the existence of a series or parallel arcs by detect-
ing the drop in voltage over the load.
Finally, another patent [2] was published in 1995. The designed system detects
the contact arcing in AC systems. This is done by monitoring either line cur-
rent, line voltage, or the energy radiated from the power line for the presence
of high-frequency noise exhibiting certain distinctive patterns.
1.3 Contributions

In this project we aim to build an arc detection system for a battery system. The battery system is part of an ongoing project at Northvolt AB where the battery system components have already been decided. The battery system is modeled based on the expertise and the experience of the engineers in the field to get an accurate system model and, thus, validate the detection system correctly.

The arc detection system aims to prevent any hazardous accidents due to arcs within the system by reporting the existence of any arcs occurrence. However the project does not aim to prevent the occurrence of arcs.

The project studies the effect of the battery structure on the detected signal due to an arc and the detection ability. Moreover, the project aims to identify where in the system it is possible to detect an arc.

1.4 Thesis Structure

This thesis contains three parts, each part contains two chapters and is structured as follows:

- The first part introduces the topic and the background information as follows:
  1. The first chapter introduces the topic of this thesis, describes the problem being investigated, reviews the related work within this topic, the contribution made by project, and the report structure.
  2. The second chapter focuses on the background information within the lithium-ion batteries, wires inductance behavior, amplifiers background, high pass filters and analog to digital conversion (ADC).

- The second part focuses on the simulation of the model and the design of the detection system and is divided as follows:
  1. Chapter 3 describes the simulation software and simulation limitations.
  2. Chapter 4 proposes the detection circuit design and describes each component in the circuit in details.

- The third part is concerned with the simulation results, the conclusions drawn from the simulation, and the future work:
  1. Chapter 5 shows the simulation results achieved by the designed detection system.
  2. Chapter 6 discusses the conclusions drawn and suggests the future work needed.


2. Background

2.1 Overview

After understanding the problem tackled within this project and the contribution of this thesis work, we will now focus on the background information. The following sections introduce secondary batteries in general, and lithium-ion batteries, as they are the main component in the battery system, the inductor behavior of the wires within the battery system, which leads to the HV sparks.

Furthermore, we focus on giving information about the components used in the detection system.

2.2 Secondary Batteries

A battery consists of one or more galvanic cells. Each cell consists of a cathode (positive electrode), an anode (negative electrode), a separator, and an electrolyte.

Battery types differ in the materials used to make their electrodes and electrolyte.

Table 2.1 as deduced from [3], shows an example of some secondary battery chemistries. The difference in materials leads to advantages and disadvantages for each chemistry.

<table>
<thead>
<tr>
<th>Components</th>
<th>Lead-acid</th>
<th>Nickel-cadmium</th>
<th>Nickel-metal hydride</th>
<th>Lithium Cobalt Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>Pb</td>
<td>Cd</td>
<td>MH</td>
<td>C</td>
</tr>
<tr>
<td>Cathode</td>
<td>PbO₂</td>
<td>NiOOH</td>
<td>NiOOH</td>
<td>LiCoO₂</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>H₂SO₄</td>
<td>KOH</td>
<td>KOH</td>
<td>Organic solvent</td>
</tr>
</tbody>
</table>

It is worth mentioning that the theoretical cell voltage depends on the type of the active materials contained in the cell. For example, the theoretical voltage of a lithium cobalt oxide LiCoO₂ is 4.1 V.

The theoretical capacity of a cell depends on the amount of active materials, such as lithium and cobalt, in the cell. This capacity assumes that all ions per formula unit take part in the electrochemical reaction.

Figure 2.1 shows the discharge profiles of several secondary batteries. As shown in the figure, lithium-ion has the maximum cell voltage among the
In the next section we will briefly discuss the chemistry, operations, and hazards of lithium-ion batteries.

2.3 Lithium-ion Battery

2.3.1 Chemistry

Electricity generation takes place due to the oxidation of the anode and the reduction of the cathode as shown in Figure 2.2. The cathode is made of lithium metal oxide, such as LiCoO\(_2\), the anode is made of graphitic carbon. The electrolyte either a liquid or gel made of lithium salts in one or more organic solvents.
2.3.2 Operation

During discharge and when the cell is connected to an external load, oxidation takes place at the anode (negative electrode) and reduction takes place at the cathode (positive electrode) while electrons flow from the anode through external load to the cathode.

However, during charging, the current direction is reversed. Oxidation takes place, by default, at the anode. Hence, the anode becomes a positive pole and the cathode becomes negative pole. A LiMO$_2$ cell, as discussed in [3], can be used as an example. The operation equations for this example can be written as follows:

**Positive**: \[\text{LiMO}_2 \xrightarrow{\text{Charge}} \text{Li}_{1-x}\text{MO}_2 + x\text{Li}^+ + xe^- \quad (2.1)\]

**Negative**: \[\text{C} + y\text{Li}^+ + ye^- \xrightarrow{\text{Charge}} \text{Li}_y\text{C} \quad (2.2)\]

**Overall**: \[\text{LiMO}_2 + \frac{x}{y} \text{C} \xrightarrow{\text{Charge}} \frac{x}{y} \text{Li}_y\text{C} + \text{Li}_{1-x}\text{MO}_2 \quad (2.3)\]

2.3.3 Battery Model

Multiple battery models have been introduced to imitate the behavior of a lithium-ion battery. These models are discussed and compared in [15] and [11]. The circuit model of the battery used as the building unit of the battery system is shown in Figure 2.3. This module is based on the Randle model, which is mainly created to simulate the electrical behavior of the battery. The Randle model is a widely used equivalent circuit model. 

$R_s$ represents the battery’s terminal and cell inner connections (ohmic resistance), $R_W$ is the mass transfer resistance, $R_{ct}$ is the charge transfer resistance,
\(C_1\) is the double layer capacitance, \(L_1\) and \(L_2\) are the battery internal inductance, and \(E_1\) represents the open circuit voltage of the cell.

**Figure 2.3. Cell Module**

\(R_{ct}\) depends on the current, the temperature, the state of charge (SOC), and the state of health (SOH). In the model we will assume that \(R_{ct}\) is constant at a specific current, temperature, SOC, and SOH for simplicity. This assumption was checked against experimental data which was conducted by Northvolt in the preparation phase.

### 2.3.4 Hazards

As mentioned in Table 2.2, the main limitation in using lithium-ion batteries is the need for a battery management system to protect the cell from over-discharging, overcharging, or short-circuiting; all of which can lead to a thermal runaway. Thermal runaway is usually related to a temperature rise mainly originating from the external or internal heat generation during abnormal abuse, such as an external short-circuit, over charge voltage, or mechanical abuse, as discussed in [10].

The heat dissipated from a battery under a thermal runaway can propagate to nearby cells. This can cause the adjacent cells to face a thermal runaway as well. A group of cells can be destroyed within seconds or hours.

Figure 2.4 from [12] shows the projectile danger posed by the explosion of a lithium-ion battery, which was demonstrated through a fire test. Besides the
fire hazard discussed in [6], [10], [12], and [13], there is also a gas hazard due to the emission of multiple toxic gases during venting, including hydrogen fluoride (HF), phosphoryl fluoride ($POF_3$), and carbon monoxide (CO), as discussed in [4] and [8].

2.3.5 Battery Pack

Building energy and power dense battery packs that can support several kilo-watts (kWs) are made by connecting several cells in series and parallel to form the needed voltage and current within the power limits. Battery packs are defined according to the number of series and parallel branches. A battery pack is defined by $nSmP$, where $n$ is the number of series branches and $m$ is the number of parallel branches.

![Figure 2.5. Battery Pack Example (6S2P)](image)

Figure 2.5 is an example of a $6S2P$ battery pack. The pack consists of 6 cells connected in series to form a series branch. Then, two series branches are connected in parallel to form the battery pack.

For the battery system under inspection several terms need to be clarified:

1. **Cell:** The smallest building unit in the system.
2. **Battery module:** The module is formed by connecting the cells together in the $nSmP$ technique discussed in Section 2.3.5.
3. **Battery sub-pack:** The battery sub-pack is formed by connecting multiple modules in series to reach the needed voltage for an application.
4. **Battery pack:** The battery pack is formed by connecting multiple sub-packs together in parallel to supply the necessary power.

2.4 Inductor Behavior

An inductor is a passive electrical component that stores energy as a magnetic field. It is one of the basic elements used in most electrical circuit. Electrical wires in the project are modeled with an inductor and resistor as discussed in Section 2.5.
Therefore, it is very important to study the effects of inductors on the circuit behavior.

According to Lenz’s law\textsuperscript{[9]} an inductor opposes the change in the current passing through it.

\[
V_L = L \frac{di}{dt}
\]  \hspace{1cm} (2.4)

eq. (2.4) shows the relationship between the voltage between the inductor terminals and the current through the conductor. When a current passes in a circuit, the current \( i \) passing through an inductor builds up while the inductor is storing energy. The amount of time needed to approximately fully charge\textsuperscript{1} an inductor is \( 5\tau \) where the time constant \( \tau \) is \( \tau = \frac{L}{R} \).

Figure 2.7 shows an example of the transient response of the circuit in Figure 2.6 after the contactor is closed at \( t = 0 \) ms when assuming that the inductor was fully discharged before. As shown in the graph, the time needed for the inductor current to reach 99.3% of the steady state level is \( \approx 50 \) ms which corresponds to five \( \tau \).

\textsuperscript{1}The inductor will reach exactly 99.3% of its full theoretical charge.
2.5 High Voltage Spark

The battery pack is connected through wires, which connect cells to form the pack and connect the pack to the load. The wires affect the behavior of the pack.

![Figure 2.8. Simplified Version of Wire Model](image)

A simple standard model of the wire is shown in Figure 2.8. This model consists of an inductor and a resistor. Due to the natural behavior of the inductor, the voltage peaks during disconnection. The inductor opposes the change in current, as shown in Section 2.4, when the switch is closed and current is flowing in the circuit. This opposition occurs because the current drops and, consequently, the inductor tries to oppose this change. As expected from the dynamics in eq. (2.4), this behavior leads to a peak in voltage called the kick-back voltage.

If this voltage peak is high enough to conduct through air or the insulating material, it will produce current. This produced current can generate a significant amount of heat, which can lead to insulation breakdown.

2.6 Amplifier

An amplifier is an electronic device that is used to magnify power, either by magnifying voltage or current. Amplifiers are classified according to the methodology of processing the input signal, input signal size, and the physical structure of the signal.

![Figure 2.9. Ideal Amplifier Model](image)

Figure 2.9 shows an example of an ideal amplifier. The main features of an ideal amplifier are the amplification, or gain, input resistance $R_{in}$, and the output resistance $R_{out}$.

The amplifier gain is the output signal magnitude (voltage, current, or power) divided by the corresponding input signal magnitude.

An example of the voltage gain amplitude calculation is shown in the below
The operational amplifier (op-amp) shown in Figure 2.10 is an example of an amplifier. The output voltage amplitude is calculated according to the following equation:

\[ V_o = A(V_+ - V_-). \]  

(2.6)

An ideal op-amp has the following features:

1. It has an infinite gain (A).
2. The voltages on the input terminals are equal.
3. No current is fed into the positive or negative input terminals.

The ideal op-amp circuit is solved according to the three previous axioms and using Kirchoff’s law and ohm’s law.

2.6.1 Operational Amplifier

An operational amplifier is one of the most important and basic components of electronic circuits, and it played a crucial role in this project. An operational amplifier is mainly used in signal processing and math operations. In the ideal case, it consists of three terminals; two high impedance terminals as inputs and an output terminal.

An example of the differential operational amplifier circuit is shown in Figure 2.11, which amplifies the weighted difference of two voltages \( V_1 \) and \( V_2 \).
\[ V_{out} = -V_1 \frac{R_f}{R_1} + V_2 \frac{R_g}{R_2 + R_g} \frac{R_1 + R_f}{R_1} \] (2.7)

eq. (2.7) shows the relationship between the two high impedance inputs (\(V_1, V_2\)) and the output voltage \(V_{out}\) of the differential operation amplifier example shown in Figure 2.11, assuming that it is an ideal amplifier.

### 2.6.2 Ideal Non-Inverting Amplifier

The non-inverting amplifier is a setup made using an operational amplifier (op-amp) and resistors, as shown in Figure 2.12.

\[ \frac{V_{out}}{V_{in}} = A_v = 1 + \frac{R_f}{R_g} \] (2.8)

### 2.7 First Order High-Pass Filter

Within the design of the detection system, a first order high-pass filter will be used. Filters are mainly made of capacitors, inductors and resistors. Depending on the topology, high-pass, low-pass, or band-pass filters, amongst others, can be implemented.

The filter in Figure 2.13 is an example of a first order high-pass filter. The values of resistance \(R\) and capacitance \(C\) define the pass band and the stop band.

\[ f_c = \frac{1}{2\pi RC} \] (2.9)
The cutoff frequency of the high-pass filter can be calculated as shown in eq. (2.9). Figure 2.14 depicts the magnitude response of a model high-pass filter. This filter has a cutoff frequency of 1 Hz.

A high-pass filter similar to the one shown in Figure 2.14 will be used to attenuate the DC components of the spark signal.

### 2.8 Analogue to Digital Conversion

Analog to digital conversion (ADC) is an electronic process where an analog signal is converted into a digital signal.

The two main steps in ADC are sampling and quantization, as depicted in Figure 2.15. First, an immediate snapshot of the input is taken and kept for some time through the sample and hold (S/H) circuit.

This snapshot is then quantized using the quantizer circuit to get the nearest value to the signal value. The number of quantization levels depends on the number of bits available for quantization; A typical 10-bit ADC gives 1023 different levels.
Figure 2.15. Analogue to Digital Conversion Circuit Example

Using eq. (2.10) we can convert an analog signal to its corresponding digital value.

\[
\frac{\text{Resolution of ADC}}{\text{Reference Voltage}} = \frac{\text{ADC Reading}}{\text{Analog Voltage Measured}}
\]  

(2.10)

For example, a 5 volt reference voltage and a 10-bit ADC will result in a resolution of 4.8 mV.
Part II:
Simulations and Design
3. Simulation Setup

3.1 Overview

In the following sections, the software used to simulate the battery and detection systems will be introduced. Additionally, the limitations of the simulations, as well as the resulting modifications, that occurred throughout the project will be discussed. Finally, the sub-pack and system models used for the system simulation will be introduced.

3.2 Simulation Software

Multiple simulation softwares were considered at the start of the project. The main focus was on Matlab, Multisim and LTSpice. LTSpice was chosen for the following reasons:

1. The limitation on the number of nodes in the Multisim student version.
2. The model was more complicated to simulate in Matlab.
3. LTSPice is used as a simulation software at Northvolt.

LTSpice is a high performance SPICE simulator, schematic capturer, and waveform viewer with enhancements and models for easing the simulation of switching regulators\(^1\).

The main benefit of using LTSpice for simulation and design purposes instead of other software solutions is the ability to simulate a massive number of nodes as, theoretically, it can simulate unlimited number of nodes. However, when attempting to simulate a large number of nodes, the simulation crashes.

3.3 Simulation Limitations

Despite this important feature mentioned above, LTSpice was not able to simulate the whole system (the battery pack and detection circuit) in one simulation due to the numerous calculations needed at each step. This limitation led to using a simple model of the sub-pack to prove the concept. With this simplification in the simulation, some measures will be taken into consideration when testing the system.

\(^1\)http://www.linear.com/designtools/software/#LTspice
3.3.1 Sub-Pack Model

Due to simulation limitations discussed above, the cell model discussed in Section 2.3.3 was not suitable to be used to simulate the battery sub-pack. This is due to the numerous number of cells used in each battery sub-pack (more than 5300 cells).

![Sub-Pack Model Used in Simulation](image.png)

When calculating the inductance component because of the battery sub-pack, it is found that \( \approx 2\% \) of the inductance component is due to the wires within the battery sub-pack.

Due to this fact, the sub-pack model shown in Figure 3.1 is used to simulate the battery sub-pack instead of using a model with the batteries models.

It is important to mention two facts regarding the sub-pack model:
1. It is important to notice the connection to ground through a 10 M\( \Omega \) resistor. This connection is meant to shift the system from an 800 V system to a 400 V system, which helps the wire harnessing within the system.\(^2\)
2. The source type used to model the battery sub-pack is also important to consider. The battery sub-pack is modeled as a voltage source with an internal resistance. The value of this resistance is estimated to be \( \approx 386 \text{ m}\Omega \) at 50 % SOC and this resistance is used to increase the precision of the sub-pack model.

3.3.2 System Model

The system model considered, shown in Figure 3.2, consists of the following elements:
1. The battery sub-pack model
2. The wires inside the sub-pack
3. Whitening capacitors
4. DC/DC converter model
5. The wires to the vehicle
6. The inverter model
7. Motor resistive model

\(^2\)Instead of having an 800 V terminal and system ground terminal we have a 400 V and \(-400\) V terminals
The system model is based on a systems in one of Northvolt’s projects. The system model uses only one sub-pack and simplified models for the DC/DC converter, the inverter, and the motor. The model for the DC/DC converter and the inverter can be seen in Figure 3.3. The main difference between these models is the value of the resistor, inductor, and the capacitor. These values are manufacturer dependent. The motor is modeled as a $10 \, \Omega$ resistor.

The real values for the components within the model are beyond the scope of the project and differ according to the setup and the components used.
4. Design

4.1 Overview

The previous chapter focused on simulation, this chapter focuses on the design of the detection system. This detection system will be assessed using the simulation software and the system model discussed in the previous chapter. The following sections and subsections focus on the details and benefits of each component of the detection circuit.

4.2 Detection Circuit Objectives

The detection circuit is designed to prove the detection concept. The system model used for testing the circuit is a real system in one of Northvolt’s projects. However, the detection system is meant to be as general and modular as possible. Some minor modifications may be needed before using the system with any other application but the main components should not be changed. It is also important to mention that there is a slight difference between the system model used for simulation using LTSpice and the real system that is suggested for use. The model in LTSpice is simplified for ease of implementation but this is taken into consideration to ensure the validity of the results for the real system. The main objectives of the detection circuit can be summarized in the following points:

1. Detect the occurrence of arcs in different places, whether it is inside the battery system or in the connection between the battery system and the vehicle.
2. Protect the detection circuit itself against high voltages and currents.
3. Prevent the detection circuit from affecting the system’s performance.
4.3 Detection Circuit Design

Figure 4.1. Proposed Detection System Model

Figure 4.1 is a model for the proposed detection system. The system consists of the following modules:
1. Resistors chain
2. Isolation circuit
3. Instrumentation amplifier
4. High-Pass filter
5. Non-inverting amplifier
6. Analog to digital conversion (ADC)
7. Software module

The components of this model will be discussed briefly in the next subsections. In each subsection, we will discuss the components, their benefits, and the reasoning behind some of the chosen components, if applicable.

4.3.1 Resistors Chain

The chain of resistors used is shown in Figure 4.2. This model is based on Kirchhoff’s voltage divider rule as shown in [14].

Figure 4.2. Resistors Chain Model
The main purpose of the resistor’s divider circuit is to reduce the input voltage to the detection section from 800 V between $V_i^+$ and $V_i^-$ to $\approx 4.25$ V between $V_O^+$ and $V_O^-$. Additionally, the values for the resistors are chosen to result in a low current rating to the detection circuit. The value of the resistors is chosen to reduce the input current to the detection circuit from 80 A to $\approx 0.2$ mA.

### 4.3.2 Isolation Circuit

The isolation circuit (also known as the isolation barrier) is used to separate the battery system from the detection circuit. The isolation is meant to prevent the detection circuit from affecting the isolation measurement unit in the battery system. Another reason the isolation circuit is used is to protect the detection circuit itself in case of unexpected high voltages or currents.

![Isolation Circuit Simple Model](image)

**Figure 4.3.** Isolation Circuit Simple Model

The isolation circuit used in this project is an optical isolation amplifier. The optical isolation amplifier is based on an optocoupler. The optocoupler is meant to transform electrical signals into light over a dielectric isolation barrier between two isolated circuits. It is worth mentioning that adding an optocoupler leads to bandwidth limitation, but the scope of the project will not be impacted as there are optocouplers that have a bandwidth large enough for our application. Figure 4.3 is a simple example for the isolation circuit concept. For the current design, an off-the-shelf circuit is used for this purpose. Multiple circuits are available in the market including the **HCPL-7510** family, the **ACPL-C79B**, the **ACPL-C79A**, and the **ACPL-C790** circuit, manufactured by **Broadcom**. For simplicity, the system is simulated without the isolation circuit.

### 4.3.3 Instrumentation Amplifier

The instrumentation amplifier is built by connecting multiple operational amplifiers together through resistors. The values of the resistors defines the gain magnitude ($A$).
The instrumentation amplifier used in the project as shown in Figure 4.4. It is used to amplify the voltage difference between $V_+$ and $V_-$. An instrumentation amplifier is used instead of using a regular differential amplifier setup due to the following reasons:

1. The system is expected to detect low voltage differences between the two terminals, this difference needs to be amplified. In order to achieve the needed voltage for detection, a high gain is needed. This high gain can cause problems when using the differential amplifier setup due to the resistors mismatch, which will led to common mode voltage at the output. This issue does not exist in the instrumentation amplifier setup as most of gain is due to $R_{gain}$.

2. It is always preferred to have a very high input impedance. This high impedance will limit the current drawn by our circuit (in this case the amplifier circuit). Drawing this current will cause a voltage drop over the resistance inside the input source, which will disturb the input voltage at $V_+$ and $V_-$. For the instrumentation amplifier, this is achieved by having two non-inverting op-amps (voltage buffers) before the input to the amplifier. These two op-amps have a very high input impedance, which will limit the drawn current.

3. The instrumentation amplifier has a very high common mode rejection ratio (CMRR) compared to the differential amplifier.

4. The instrumentation amplifier is more stable than normal differential amplifier.

5. It is easy to achieve a specific gain value as concluded from eq. (4.1)

The relationship between the differential input voltage and the output voltage is shown in the following equation:

\[
\frac{V_{out}}{V_+ - V_-} = \left(1 + \frac{2R_1}{R_{gain}}\right) \frac{R_3}{R_2} \quad (4.1)
\]
4.3.4 First Order High-Pass Filter

The high-pass filter type used in the circuit is discussed in Section 2.7. It has a cutoff frequency of 16.6 kHz. The reason for using the high-pass filter is to attenuate the direct current (DC) component and the low frequency components in the detected signal.

4.3.5 Non-Inverting Amplifier

The non-inverting amplifier arrangement used in the circuit is discussed in Section 2.6.2. The non-inverting amplifier is used to:
1. Attenuate the negative values in the output signal of the high-pass filter.
2. Act as a second amplification stage, where it amplifies the second signal after removing the unneeded components.

![Figure 4.5. Inducing a Spark Before and After the DC/DC Converter in a System with One Sub-Pack with and without Using the Non-Inverting Amplifier](image)

4.3.6 ADC

The output of the non-inverting amplifier is then fed into the analogue pin of the microcontroller. This pin is pulled down using a pull down resistor. This is done to have defined state when no arcs take place.

The specifications of the analog to digital conversion (ADC) that will be used within the real system are not determined yet as the ADC will be part of the battery management unit within the battery system. The minimum requirements proposed is as follows:
1. A resolution of 10-bits.
Figure 4.6. Detection Circuit Model
4.3.7 Software Analysis

After we measure the signal using the analog input, the signal is fed through an ADC. The value of the signal needs to be analyzed so that we can decide the severity of the arc that took place within the system. This severity is checked by comparing the number of arcs that took place within a certain time frame to a certain predefined threshold. Figure 4.7 shows the flow chart of the main module proposed to analyze the signal and, thus, determine the right decision, accordingly. The main module contains two more modules: the detection module and the sleep module.

![Main Module Flow Chart](image)

**Figure 4.7. Main Module Flow Chart**

**Main Module**

The main module represents the main loop in the detection software. The aim of this loop is to keep tracking the voltage value. This is done through an interrupt over the analogue pin used for detection. By default, the system is always in the idle state. Every 10 seconds the system checks for the value of the `Check_Trigger` to decide if we need to reset the voltage buffer.

The interrupt is used to save energy, since events like arcs are not too frequent. In case of an active interrupt, the voltage over the pin is measured and compared to a predefined voltage threshold\(^1\). If the voltage is higher than the threshold the control is passed to the detection module. Otherwise, the control is passed to the sleep module.

\(^1\)The voltage threshold is \(\approx 100 \text{ mV}\)
Detection Module

The detection module analyzes the values in case of an arc. It detects whether this arc is induced because of a normal operation or an error in the system.

The detection module shown in Figure 4.8 can be summarized in the following steps:

1. The module checks the values of the contactors’ signals:
   a) If the contactor’s status did not change, the detection module continues to investigate the arc.
   b) If the contactor’s status changed, then the arc is ignored and the module exits (the next steps will be ignored).

2. The voltage and its timestamp are saved in a buffer.

3. Set the Check_Trigger variable. This variable is used to ensure that any data gathered about the arc is saved.

4. Check how much time has passed since the last occurrence of an arc.
   a) If this time is longer than the time threshold,\(^2\) then we set a warning flag and exit the module (the next steps will be ignored).
   b) If this time is shorter than the time threshold, the module continues to investigate.

5. Calculate the number of arcs that occurred in the previous second.
   a) If the number of arcs are less than the defined threshold \(^3\), then the warning flag is set and the module exits.
   b) If the number of arcs are more than the defined threshold, the error flag is set and the module exits.

---

\(^2\)Time threshold is estimated to be \(\approx 100\text{ ms}\)

\(^3\)Number of arcs threshold is around 10 arc/s
Sleep Module

This sleep module shown in Figure 4.9 is responsible for saving and resetting the buffer used to keep the last occurrences of arcs in the system. Whenever the sleep module is active, it checks the number of arcs that have occurred in the last 10 seconds.

1. If the number of arcs is more than one, then the sleep module will exit and the system will go back to the idle state.
2. If the number of arcs is one or less:
   a) The data in the buffer is saved.
   b) Reset the `Check_Trigger` variable.
c) Reset the buffer.
d) Module exits.

Figure 4.9. Sleep Module Flow Chart
Part III:  
Results and Conclusions
5. Simulation Results

5.1 Overview

The following sections and subsections discuss the detection circuit assessment methodology and the simulation results of the detection circuit introduced in the previous chapter. We will consider one sub-pack and two sub-pack systems as well as investigate the effect of the number of sub-packs.

5.2 Detection Methodology

As mentioned in Section 4.2, the main objective of the detection circuit is to detect the occurrence of arcs in different places in the system. These arcs can take place inside the battery system or in the connection between the battery system and the vehicle.

Since simulations are the main tool to verify the ability of the system, an arc is induced in multiple places within the system. Each time an arc is induced, the capabilities of detection system are assessed.

The detection circuit is always connected between the battery sub-pack and DC/DC converter. The arc is induced in the following positions:

1. Before the DC/DC converter
2. After the DC/DC converter
3. Before the inverter
4. After the inverter

These places are the most interesting places to be studied. This is because the DC/DC converter and the inverter can affect the arc signal significantly and arcs occur more frequently around these areas.

We will also examine the effect of adding more sub-packs on the detection mechanism and the arc signal. This concept is tested by introducing the same type of verification tests on a one sub-pack and a two sub-pack system.
Figure 5.1. The System Including the Detection Circuit
5.3 One Sub-Pack System

In this section we will discuss the results of the one sub-pack system. We will examine the effects of the position of the induced arc on the arc signal detected by the detection circuit.

![Graph comparing arc signal before and after DC/DC converter](image)

*Figure 5.2. Inducing a Spark Before and After the DC/DC Converter in a System with One Sub-Pack*

Figure 5.2 compares the arc signal detected due to an arc before and after the DC/DC converter, respectively. As indicated by the graph, the circuit is able to detect an arc, regardless of whether it was before or after the DC/DC converter.

Also it can be concluded that the signal detected due to an arc before the DC/DC converter has a higher voltage amplitude than the signal detected due to an arc after the DC/DC converter.

It’s likely that this is the effect of the DC/DC converter on the arc signal. As depicted in Figure 3.3, the DC/DC converter can cause the arc signal to be damped due its RLC component.

Moreover, the arc signal due to an arc after the DC/DC converter takes a longer time to decay. While the arc signal due to an arc before the DC/DC converter decays directly after the end of the induced arc, the other signal decays after 0.2 ms from the end of the arc.

Further, Figure 5.3 shows the difference between the arc signal due to an arc after the DC/DC converter and the arc signal due to an arc before the inverter. As highlighted by the graph, the circuit can detect an arc that takes place between the the DC/DC converter and the inverter. This means that the detection circuit is able to detect the occurrence of arcs in the connection between the battery system and the vehicle.

This is crucial as this connection is one of the places with a higher incidence of arcs.
Figure 5.3. Inducing a Spark After the DC/DC Converter and Before the Inverter in a System with One Sub-Pack

Additionally, it’s important to note that the two arc signals seem to be nearly identical. This is can be explained by Figure 3.2 as the only component between the two arcs is the wire model. This means that the wire between the DC/DC converter and the inverter does not effect the detected arc signal. Figure 5.4 compares the arc signal due to an arc before and after the inverter, respectively. As depicted in the figure, the arc signal due to an arc after the inverter is minuscule 1.

Figure 5.4. Inducing a Spark Before and After the Inverter in a System with One Sub-Pack

This signal value means that if an arc will occur after the inverter on the vehicle’s side, it will not be detected by the proposed system. This is not an issue as the main purpose of this circuit is to detect the existence of an arc within the battery system or in the connection between the battery and the vehicle.

1The maximum detected arc signal value is around 101 mV
If the vehicle needs such a system, another circuit can be installed on the vehicle’s side. The vehicle detection circuit will have some redundancy with the battery detection circuit. This redundancy can be used to prevent false detection.

5.4 Two Sub-Pack System

This section will focus on showing the effect of adding one more sub-pack to the system shown in Figure 3.2.

To test the effect of adding one more sub-pack, the tests conducted on the one-sub pack system (in the previous section) will be repeated on the two-sub pack system.

Figure 5.5 compares the detected arc signal due to an arc before and after the DC/DC converter. As observable, the detection circuit can detect the occurrence of arcs before and after the DC/DC converter.

As illustrated in the figure, the detected signal due to an arc before the DC/DC converter has a higher amplitude than the detected signal for the arc after the DC/DC converter. This feature did not change between the one sub-pack and the two sub-pack systems.

Figure 5.6 compares the detected arc signal due to an arc after the DC/DC converter and the arc signal due to an arc before the inverter. As shown in the figure, the system is able to detect arcs that take place before the inverter. This means that the detection circuit can detect the occurrence of arcs in the connection between the battery system and the vehicle.

Figure 5.5. Inducing a Spark Before and After the DC/DC Converter in a System with Two Sub-Packs

DC/DC converter. As observable, the detection circuit can detect the occurrence of arcs before and after the DC/DC converter.

As illustrated in the figure, the detected signal due to an arc before the DC/DC converter has a higher amplitude than the detected signal for the arc after the DC/DC converter. This feature did not change between the one sub-pack and the two sub-pack systems.

Figure 5.6 compares the detected arc signal due to an arc after the DC/DC converter and the arc signal due to an arc before the inverter. As shown in the figure, the system is able to detect arcs that take place before the inverter. This means that the detection circuit can detect the occurrence of arcs in the connection between the battery system and the vehicle.
Additionally, as demonstrated from the figure, the signal detected due to an arc after the DC/DC converter and the signal due to an arc before the inverter are almost identical. This feature was also present in the one sub-pack system. Figure 5.7 compares the detected arc signal due to an arc before and after the inverter, respectively. As presented in the figure, the detected arc signal due to an arc after the inverter is small.\(^2\)

---

\(^2\)The maximum detected arc signal value is around 916 µV
5.5 Number of sub-packs effect on the detected signal

In this section, we will examine the effects of increasing the number of sub-packs on the detection ability of the detection circuit. This is assessed by comparing the detected arc signal due to an arc before the DC/DC converter in systems with different number of sub-packs.

Figure 5.8 compares the detected arc signal due to an arc before the DC/DC converter in a one sub-pack and two sub-pack system. As shown in the figure, the amplitude of the arc signal in the two sub-pack system is smaller than the corresponding amplitude in the one sub-pack system.

To further investigate, the simulation was repeated several times with a different number of sub-packs each time. As illustrated in Figure 5.9, the amplitude of the detected arc signal decreases as the number of sub-packs increases. This can be explained by eq. (5.1). As shown in the equation, the energy stored in an inductor is proportional to the square of the current passing by the inductor.

\[ E = \frac{1}{2}LI^2. \]  

(5.1)

By applying the concept concluded from eq. (5.1) and considering the fact that the current drawn by the load (motor) is constant, we can conclude that the current drawn from each sub-pack is reduced by adding another sub-pack in parallel. This reduction in the current will lead to less energy storage in the sub-pack wires, which will lead to a smaller arc signal.
Figure 5.9. Inducing a Spark Before the DC/DC Converter in Systems with Different Number of Sub-Packs
6. Conclusions and Future Work

6.1 Overview

The following sections and subsections discuss observations and conclusions drawn from the thesis work. Additionally, this chapter introduces the proposed future work.

6.2 Conclusions

1. The system is able to detect the occurrence of arcs within the battery system and in the connection to the load (vehicle).
2. The detection of arcs within the vehicle is not possible with the proposed system.
3. The number of connected sub-packs affects the amplitude of the detected signal.
4. The previous conclusions are based on simulations and not on an actual physical system.

6.3 Future Work

The future work is divided into two sections: the work that should be done to calibrate the system before using it on a physical system and the work that is proposed to enhance the system capabilities.

6.3.1 Calibration

As the results were based on simulation results, it is important to test the detection system with the physical sub-pack system and arcs should be induced at the positions we simulated previously. In this calibration, the focus should be on the time threshold, voltage threshold, and the threshold for the number of arcs. By calibrating these values, the software module will perform more accurately.
6.3.2 Enhancement

The system can be enhanced as follows:

1. The detection system should be tested on different physical systems to both check its abilities on these systems and to reveal any modifications needed for a generic system.

2. The software algorithm should be enhanced to link the occurrence of an arc to any unusual values or actions within the system which does not exist in the current software. This can be used for debugging purposes.

3. Signal analysis can be introduced for better detection as it is not implemented in the current system. Analyzing the frequency response of the detected signal may lead to determining the exact place where the arc took place within the system.
References


[4] Jinghui); Gao F (Gao Fei); Li XM (Li Xiangmei); Yang K (Yang Kai); Wang SC (Wang Songcen); Yang RJ (Yang Rongjie) Chen, JH (Chen. The study of the toxicity of the gas released on lithium ion battery during combustion. In AER-Advances in Engineering Research, volume 87. AMEE, September 2017.


Glossary

**charge transfer resistance** The resistance that the electron faces to transfer to the molecule.

**energy density** The energy that can be derived per unit volume of the weight of the cell[5].

**hybrid cars** A car which combines a petrol or diesel engine with an electric motor.

**Lenz’s law** States that an induced electric current flows in a direction such that the current opposes the change that induced it\(^1\).

**mass transfer resistance** The resistance that the electron suffers to travel to the electrode surface.

**memory effect** The effect found in some battery chemisteries where the battery loses part of its capacity if it is recharged after being discharged partially.

**pass band** The range of frequencies that are allowed to pass a filter without being attenuated.

**power density** The power that can be derived per unit weight of the cell[5].

**self-discharge rate** An event that takes place in batteries where the stored charge is reduced without any external connection to the battery.

**stop band** A band of frequencies, between specified limits, that a circuit, such as a filter or telephone circuit, does not transmit\(^2\).

---

\(^1\)https://www.britannica.com/science/Lenzs-law
\(^2\)https://www.its.bldrdoc.gov/fs-1037/dir-035/_5133.htm
Acronyms

AC alternating current.
ADC analog to digital conversion.
BESSs Battery Energy Storage Systems.
CMRR common mode rejection ratio.
DC direct current.
HV high voltage.
kWs kilo-watts.

op-amp operational amplifier.
SOC state of charge.
SOH state of health.