A Thesis

entitled

Modeling and Analysis of Hydraulic Energy Storage System for Hybrid Locomotives

by

Boya Zhang

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in Mechanical Engineering

Dr. Walter W. Olson, Committee Chair

Dr. Hongyan Zhang, Committee Member

Dr. Yong Gan, Committee Member

Dr. Patricia R. Komuniecki, Dean

College of Graduate Studies

The University of Toledo

Dec 2010
An Abstract of

Modeling and Analysis of Hydraulic Energy Storage System for Hybrid Locomotives

by

Boya Zhang

Submitted to the Graduate Faculty as partial fulfillment of the requirement for the Master of Science in Mechanical Engineering

The University of Toledo

Dec 2010

Hybrid locomotive have more than one power source to provide driving power. The prime power source of a hybrid locomotive can be a diesel engine or fuel cell, and the on-board energy storage system can provide a secondary power. The rechargeable energy storage system (RESS) of hybrid locomotives can temporarily store energy which is captured from braking action or redundant energy produced by the diesel engine to reduce fuel consumption and pollution.

The Electro-mechanical Battery (EMB) which is an energy storage system for hybrid locomotives, consisting of the accumulator, pump/motor, reservoir and an electric motor/generator is introduced in this thesis. The hydraulic energy storage system has the advantages of high power density and low cost compared to the other vehicle’s energy storage systems and has the potential to be an energy storage system for hybrid locomotives.

Simulation of the EMB system is implemented to verify its capability of providing burst power for short period during charging and discharging. Based on the
mathematical analysis of the EMB, the control system is designed to control the hydraulic pump/motor of the EMB to discharge and charge with the required power. The control response frequency of control system which determines how fast the system responds could be between 1 Hz and 3 Hz. A lower frequency of the control system results in smoother operational results of the EMB.

The simulation results obtained by MATLAB/SIMULINK model and Simscape/SimHydraulic model are compared to make the conclusion. Based on the simulation results, four independent and changeable parameters within the EMB system were analyzed to further understand this designed energy storage system.
Acknowledgements

Firstly, I would like to express my deepest appreciation to my advisor, Dr. Walter W. Olson. His persistence and enthusiasm to the research have motivated me during my graduate education and will influence me in my future engineering career. Without his patient painstaking and guidance, this thesis would not have been possible.

Special thanks to the distinguished faculty members who served on my committee member: Dr. Yong Gan and Dr. Hongyan Zhang. In addition, I would like to thank Dr. Matthew Witte and Dr. Mingwei Shan who shared many valuable experiences and provided continuous encouragement and support.

Thirdly, many thanks to the help and friendship of HHV group members Chao, Mohamed and Zach. Without their reviewing and corrections, my thesis writing could not be well completed.

Last but not the least, I would like to thank my family and my boy friend that love and support me, especially through the depressed days. Without their love and support, I can not achieve what I’ve got today.
Table of Contents

Abstract ........................................................................................................................... iii
Acknowledgements ........................................................................................................ v
Table of Contents ......................................................................................................... vi
List of Tables ................................................................................................................ viii
List of Figures ................................................................................................................. ix
Nomenclature ................................................................................................................ xi
Chapter 1 INTRODUCTION ....................................................................................... 1
  1.1. Diesel Electric-Battery Locomotives ................................................................. 2
  1.2. Electro-Mechanical Battery (EMB) ................................................................. 3
  1.3. Statement of Problem ....................................................................................... 5
  1.4. Approach of Problem ....................................................................................... 5
Chapter 2 LITERATURE REVIEW ............................................................................. 6
  2.1. Diesel-Electric Locomotives ............................................................................ 6
  2.2. Hybrid Locomotives ......................................................................................... 7
  2.3. Hydraulic Hybrid Locomotives ........................................................................ 16
      2.3.1 Hydraulic Accumulator ............................................................................. 16
      2.3.2 Hydraulic Pump/Motor Unit ...................................................................... 17
      2.3.3 Electric Motor/Generator Unit (EMGU) ..................................................... 20
Chapter 3 DESIGN AND ANALYSIS OF THE EMB ................................................ 25
  3.1 Introduction ....................................................................................................... 25
      3.1.1 Objective ................................................................................................ 26
      3.1.2 EMB design concept .............................................................................. 26
      3.1.3 Concept of control ................................................................................. 27
  3.2 Analysis ............................................................................................................. 28
      3.2.1 Hydraulic Accumulator ............................................................................ 28
      3.2.2 The hydraulic pump motor unit (HPMU) .................................................. 31
      3.2.3 The electric motor/generator unit (EMGU) .............................................. 35
      3.2.4 Control system ....................................................................................... 37
  3.3 Summary ........................................................................................................... 42
Chapter 4 SIMULATIONS .......................................................................................... 43
  4.1 EMB Model by MATLAB/SIMULINK ............................................................. 43
  4.2 EMB Model by Simscape/SimHydraulic ......................................................... 45
Chapter 5 RESULTS .................................................................................................. 48
List of Tables

Table 2.1 Comparison of rechargeable batteries [23] [24] ................................. 12
Table 2.2 Comparison of energy storage systems [12] [16] [39] [40] ...................... 16
Table 3.1 Related parameters of 1000 cc unit ...................................................... 34
Table 3.2 $K, \frac{1}{Ti}$ with respect to applicable control response frequency .......... 41
Table 4.1 Block parameters of the variable displacement pump/motor ............. 46
Table 4.2 Block parameters of gas-charged accumulator ................................. 47
Table 5.1 Simulation results with different control response frequencies .......... 55
List of Figures

Figure 1-1 Top view of EMB unit.................................................................3
Figure 2-1 Configuration of a diesel electric locomotive ..............................6
Figure 2-2 A diesel electric locomotive [34]..............................................7
Figure 2-3 Configuration of a hybrid locomotive [5]..................................8
Figure 2-4 „Green Goat’ switching locomotive [19]..................................9
Figure 2-5 Drive system diagram of hybrid locomotives of KiHa E200 [11]...11
Figure 2-6 Flywheels energy storage system [13]......................................12
Figure 2-7 British rail class 139 [1]............................................................13
Figure 2-8 Ultracapacitor [16].................................................................13
Figure 2-9 Hydraulic energy storage system ............................................15
Figure 2-10 bladder and piston accumulator [25]........................................17
Figure 2-11 Swash plate piston pump/motor [25]......................................18
Figure 2-12 Bent-axis piston pump/motor [25]..........................................19
Figure 2-13 A DC electric motor [37]......................................................20
Figure 2-14 Permanent magnet, shunt wound, series wound and compound
wound DC motor/generator [38]............................................................22
Figure 2-15 rpm and torque vs. amps......................................................24
Figure 3-1 Circuit of EMB system.............................................................25
Figure 3-2 Plot of operation time vs. fluid volume during discharging .......30
Figure 3-3 Plot of operation time vs. fluid volume during charging ...........30
Figure 3-4 Characteristic of 200 hp (150 kW) motor/generator ................35
Figure 3-5 Speed during charge..............................................................37
Figure 3-6 Speed during discharge........................................................37
Figure 3-7 Layout of the control system [30]............................................38
Figure 3-8 Control system of EMB..........................................................38
Figure 3-9 Characteristic of proportional control [30]............................39
Figure 4-1 Block diagram of EMB control system....................................43
Figure 4-2 PI controller............................................................................44
Figure 4-3 EMB system...........................................................................44
Figure 4-4 Accumulator...........................................................................44
Figure 4-5 Control Valve.........................................................................45
Figure 4-6 Block of the variable displacement pump and motor [33].........45
Figure 4-7 Block of gas-charged accumulator in the SimHydraulic [33]....46
Figure 4-8 EMB system ........................................................................................................... 47
Figure 5-1 Plots of yoke angle, current, pressure and flow rate ($\omega_n = 1.5$) .......... 49
Figure 5-2 Plots of shaft speed, torques and power of HPMU ($\omega_n = 1.5$) .......... 50
Figure 5-3 Plots of yoke angle, current, pressure and flow rate ($\omega_n = 2.5$) .......... 51
Figure 5-4 Plots of shaft speed, torques and power of HPMU ($\omega_n = 2.5$) .......... 52
Figure 5-5 Plots of yoke angle, current, pressure and flow rate ($\omega_n = 3.5$) .......... 53
Figure 5-6 Plots of shaft speed, torques and power of HPMU ($\omega_n = 3.5$) .......... 54
Figure 5-7 Plots of flow rate and pressure ($\omega_n = 1.5$) ..................................................... 56
Figure 5-8 Plots of yoke angle, torque and power ($\omega_n = 1.5$) ...................................... 57
Figure 5-9 Relation of the maximum pressure and operation time (150 kW, 198 gal) ......................................................................................................................... 58
Figure 5-10 Relation of operation time and fluid volume (150 kW, 5000 psi) .......... 59
Figure 5-11 Relation of the required power and operation time (5000 psi, 198 gal) ........................................................................................................................................... 60
Figure 5-12 Relation of maximum pressure and power (198 gal, 90 sec) ............ 60
Figure 5-13 Relation of power and shaft speed (198 gal, 5000 psi) .................... 61
### Nomenclatures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_s$</td>
<td>Laminar leakage flow</td>
</tr>
<tr>
<td>$C_{st}$</td>
<td>Turbulent leakage flow</td>
</tr>
<tr>
<td>$C_v$</td>
<td>Viscous loss coefficient</td>
</tr>
<tr>
<td>$C_f$</td>
<td>Friction coefficient</td>
</tr>
<tr>
<td>$C_h$</td>
<td>Hydrodynamic loss coefficient</td>
</tr>
<tr>
<td>$D$</td>
<td>Maximum displacement of pump/motor</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid electric vehicle</td>
</tr>
<tr>
<td>HST</td>
<td>High speed train</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
</tr>
<tr>
<td>$J$</td>
<td>Moment inertia</td>
</tr>
<tr>
<td>$K$</td>
<td>Specific heat ratio</td>
</tr>
<tr>
<td>$P$</td>
<td>Inlet gauge pressure</td>
</tr>
<tr>
<td>$p_g$</td>
<td>Gas pressure</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>Pressure differential of pump/motor</td>
</tr>
<tr>
<td>$P_0$</td>
<td>Precharge pressure of accumulator</td>
</tr>
<tr>
<td>$P_1$</td>
<td>Maximum pressure of accumulator</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Minimum pressure of accumulator</td>
</tr>
<tr>
<td>$P_{\text{acc}}$</td>
<td>Power of accumulator</td>
</tr>
<tr>
<td>$P_{m,g}$</td>
<td>Power of motor/generator</td>
</tr>
<tr>
<td>$P_{p,m}$</td>
<td>Power of pump/motor</td>
</tr>
<tr>
<td>$Q$</td>
<td>Volumetric flow rate</td>
</tr>
<tr>
<td>$Q_t$</td>
<td>Theoretical volumetric flow rate</td>
</tr>
<tr>
<td>$Q_a$</td>
<td>Actual volumetric flow rate</td>
</tr>
<tr>
<td>RESS</td>
<td>Rechargeable energy storage system</td>
</tr>
<tr>
<td>S</td>
<td>Sommerfeld number</td>
</tr>
<tr>
<td>SIV</td>
<td>Static inverter</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$T$</td>
<td>Torque of pump/motor</td>
</tr>
<tr>
<td>$T_t$</td>
<td>Theoretical torque of pump/motor</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Actual torque of pump/motor</td>
</tr>
<tr>
<td>$U$</td>
<td>Voltage of motor/generator</td>
</tr>
<tr>
<td>$V$</td>
<td>Gas Volume</td>
</tr>
<tr>
<td>$V_F$</td>
<td>Fluid Volume</td>
</tr>
</tbody>
</table>
$V_A$................................. Accumulator Capacity
$V_{\text{min}}$.......................... Gas volume in accumulator at maximum pressure
$V_{\text{max}}$.......................... Gas volume in accumulator at minimum pressure
$W_{\text{EMB}}$........................ Work applied by EMB system
$W_{\text{gas}}$.......................... Work applied by gas in accumulator
$W_{\text{loss}}$.......................... Work loss
$x$................................. Percentage of maximum displacement
$B$..................................... Fluid bulk modulus
$Z$................................. Damping ratio
$\eta_t$................................. Torque efficiency (mechanical efficiency)
$\eta_v$................................. Volumetric efficiency
$\eta_o$................................. Overall efficiency
$\eta_{v,m}$.............................. Motor volumetric efficiency
$\eta_{v,p}$.............................. Pump volumetric efficiency
$\eta_{t,m}$.............................. Motor torque efficiency
$\eta_{t,p}$.............................. Pump torque efficiency
$P$..................................... Fluid density
$\Sigma$................................. Dimensionless number
$\Omega$................................. Shaft speed of pump/motor
$\omega_n$............................. Natural frequency
Chapter 1 INTRODUCTION

Hybrid locomotives consist of a prime power source, an energy storage system and a traction transmission connected to the wheels [1]. The prime power can be either a diesel engine or fuel cells, and the traction transmission can be one or more electric motors. The energy storage system can capture kinetic energy from braking action or excess energy produced by the diesel engine to reduce fuel consumption and pollution. The main criteria when choosing an energy storage system for locomotives are the power capability and the cost of the system. The power produced by the system has to be high enough to drive a train weighing up to 100 ton and also the system has to be economical.
Japan, United Kingdom, France and United States have started to investigate energy storage technologies for locomotives, and reuse the dynamic braking energy to reduce fuel consumption and pollution [1]. These investigations have included flywheels, batteries and ultracapacitors. Flywheels, as a mechanical energy storage system, can store energy in kinetic form with minimal space requirements. Ultracapacitors can store electric energy as capacitance with high power density (a power-to-weight measurement of performance) but low energy density (the amount of energy stored in a given system). Batteries store electric energy in chemical form and have high energy density but low power density. These energy storage systems can coexist due to their different characteristics favorable to different applications.

Among various energy storage systems applied to vehicles, batteries are primarily chosen for hybrid locomotives due to the higher energy density, which can help vehicles move longer distance for the same weight. They have been applied to hybrid electric vehicles (HEV), such as Toyota Prius 2007 and Honda Civic 2007 [2].

1.1. Diesel Electric-Battery Locomotives

The diesel electric-battery locomotive, categorized as a hybrid locomotive, uses a diesel engine as the primary power source to drive an electric generator which supplies power for traction motor and stores energy in a rechargeable battery.

As rechargeable battery technology has been successfully applied to HEV, researchers have considered applying this technology to the locomotives. Locomotives play an important role in public transportation in many countries, and
consume considerable fuel. It is hopeful that this technology can reduce fuel consumption. However, the low power density of batteries limits the performance of the locomotives [3].

1.2. Electro-Mechanical Battery (EMB)

The Electro-Mechanical Battery designed by AHL-Tech Company consists of hydraulic accumulators, a hydraulic pump/motor, an electric motor/generator and a reservoir. This system can capture both kinetic energy from braking and excess energy produced by the diesel engine and store it as pressurized fluid in the accumulators. The hydraulic energy is released and converted back to electricity by the EMB system when additional power is needed.

![Figure 1-1 Top view of EMB unit](image)

The accumulator is a device consisting of a gas such as nitrogen which can be compressed when a hydraulic fluid is pumped into the device. The energy stored in the compressed gas can be recovered by using the pressurized oil to drive a hydraulic motor. In the EMB system of locomotives, multiple high pressure accumulators are mounted on an accumulator manifold to increase the energy stored.
The hydraulic pump/motor is a hydraulic device that works as a pump or motor depending on the direction of oil flow. It is a pump during energy capture, pumping the hydraulic fluid from the reservoir to the high pressure accumulators. It is a motor when high pressure fluid is used to produce torque.

The electric motor/generator is an electrical device that has two modes: in motor mode, it uses electric power and converts it to mechanical energy in the form of shaft torque and rotational speed. In generator mode, the input mechanical torque and speed are transformed into electrical power.

The reservoir of the EMB system is a storage tank that supplies the circuit with hydraulic fluid. It has to be large enough to store the fluids released from accumulators when the gas pressure is the minimum or supply the fluids to pressurize the gas in the accumulators.

As shown in Fig 1-1, the components of EMB are mounted in a single locomotive unit. Since the EMB is designed for locomotives, the system must be able to withstand the shocks and vibrations associated with a moving locomotive. Locomotives are often subject to heavy forces during start. Therefore, the individual EMB components must be designed in such a way that can withstand these forces. In addition the EMB must also be mounted in the way that facilitates routine maintenance of the system and individual component replacement.

The EMB system has high power density and low initial costs compared to flywheels and ultracapacitors which may also have high power density but with high initial costs and require complex maintenance. Therefore, the EMB technology is a
potential energy storage system for railway locomotives.

1.3. **Statement of the Problem**

The objective of this research is to design, configure and simulate the charge and discharge process system and to prove its capability of providing a high burst power (150 kW) to drive locomotives for a short duration (from 70 to 90 sec). The EMB system is simulated with MATLAB/SIMULINK and Simscape/SimHydraulic.

1.4. **Approach of the Problem**

Chapter 2 is a literature review introducing diesel-electric locomotives, hydraulic hybrid locomotives and the components making up a hydraulic system.

Chapter 3 provides the underlying theory, analysis of the EMB system. The sizing and modeling of the main components in the EMB system are also given.

Chapter 4 describes the EMB models built with MATLAB/SIMULINK and Simscape/SimHydraulic.

Chapter 5 presents the results and the summary for both models.

Chapter 6 gives the conclusion of the EMB system and provides an outline of the future work.
Chapter 2  LITERATURE REVIEW

2.1. Diesel-Electric Locomotives

Diesel locomotives began to replace the steam locomotives in the 1920’s because diesel engines provide more power, higher efficiency, cleaner operation and less maintenance [4]. A sole diesel locomotive is possible; however such a system requires a complex transmission and drives for multiple axles of the locomotive. The operation, cost and reliability of these designs failed to be satisfactory for the railroad system.

![Diagram of a diesel electric locomotive]

Figure 2-1 Configuration of a diesel electric locomotive
The addition of an electric generator set and using electric traction motors to drive the locomotive overcame these problems. The electric traction motors did not require a transmission since it could be operated with nearly constant torque over the locomotive wheel speed range. The diesel-electric locomotives became popular because this structure greatly simplified the way that motive power was transmitted to the wheels. Additionally, the diesel engine and electric generator are both efficient with less maintenance requirement.

![Figure 2-2 A diesel electric locomotive](image)

Dynamic braking is the primary braking methodology for diesel-electric locomotives while at speeds above 10 mph. The traction motor is operated as a generator to produce electricity. The generated electrical current flows through the resistors in a resistive grid and is converted into heat that is dissipated [6]. A fan across the grid provides forced-air cooling.

### 2.2. Hybrid Locomotives

Modern diesel-electric locomotives have a minimal energy storage capacity. Excess energy generated either from the diesel engine or from dynamic braking is wasted in a resistive power grid. In order to make diesel-electric locomotive more
efficient, methods need to be found to capture this wasted energy. This results in the hybrid locomotive.

**Figure 2-3 Configuration of a hybrid locomotive** [5]

A hybrid locomotive, as shown in Fig 2-2, consists of a prime power source (also known as prime mover), a power conversion unit, a DC voltage bus, an energy storage system, a traction motor and wheels. The prime power source can be a diesel engine, a gas turbine engine, a micro-turbine, a stirling engine, a spark ignition engine or fuel cells [5]. The prime power is converted to DC electricity through a power conversion unit such as alternator.

The energy storage system could be a battery bank, a bank of capacitors, a compressed air storage system or a flywheel energy storage system, a hydraulic accumulator system or a combination of them [5]. When the prime mover cannot satisfy the power demand, stored energy in the energy storage unit can provide the additional power. When the power produced by the prime mover is more than the power demand of the locomotive, the excess energy can be stored in the energy storage unit. The kinetic energy captured during braking process can be converted to another form of energy and stored in the energy storage unit for later use. The power
generated from and transferred to the energy storage unit is required in the form of DC electricity. The traction motor converts the DC electricity to torque and drives the wheels.

![Image of Green Goat switching locomotive](image)

**Figure 2-4 ‘Green Goat’ switching locomotive [19]**

‘Green Goat’ switching locomotive is an example of a hybrid locomotive, the diesel/battery locomotive. It was built on the frame of an EMD GP9 by Railpower Company. It was used to assemble trains for long haul or disassemble a train arrived, generally to move railroad cars around. The traction motor of ‘Green Goat’ is driven by 320 lead acid batteries which are powered by a 130 hp diesel engine. It provides a 15% to 45% reduction of fuel cost [19]. Despite early success, the ‘Green Goat’ was discontinued due to poor reliability.

This structure of hybrid locomotives has several advantages compared to
diesel-electric locomotives: reduced fuel consumption, reduced emission and noise and smaller size and better performance of engine. The generated electricity during braking in the hybrid system is stored rather than dissipated as heat in the diesel-electric locomotives. This regenerative braking system reduces the fuel consumption. If sufficient energy has been stored for operating the locomotive, the prime mover is switched off reducing the emissions and noise. Provided sufficient energy has been stored, there is no need for the hybrid locomotives to idle at interim stations [7]. The locomotive is started from stop using the storage system, at the same time avoiding the noise and emission for idling.

The diesel engine of a conventional diesel-electric locomotive is regularly oversized to meet the requirement of high-power loads, thus taking up more space on the locomotive [8]. With a rechargeable energy storage system, the diesel engine may be downsized. Additional power from energy storage system can assist the prime mover in the situation of a high power demand, such as acceleration or on a grade.

The mass production of hybrid electric vehicle (HEV) shows the advantages of batteries as the energy storage system. Batteries have high energy capacity, very low standby losses and high energy efficiency [3]. However, their big drawback of low power density limits their ability to accept the high charges rates as occurring in regenerative braking. While only 15% to 20% of kinetic energy is lost in a typical HEV, almost all the energy would be lost in a hybrid electric heavy-duty vehicle, such as a locomotive [22]. Connection of several batteries in parallel increases the power characteristic of the battery packs and reduces the power density problem but at the
same time increases the costs. Additionally, batteries have a very limited life cycle under extreme charging and discharging conditions and need to be continuously replaced throughout the lifetime of the locomotives [22]. Batteries are not environmentally friendly and thus cannot be easily discarded. The cost associated with the purchase of new batteries and the disposal of old ones is cumulative. The cold weather may significantly decrease the capacity of Ni-MH batteries. Li-ion batteries could be extremely dangerous if mistreated, and explosion may occur when overheated or charged to an excessively high voltage [10].

![Figure 2-5 Drive system diagram of hybrid locomotives of KiHa E200](image)

**Figure 2-5 Drive system diagram of hybrid locomotives of KiHa E200 [11]**

The Li-ion batteries were applied to diesel/battery locomotive KiHa E200 built in Japan 2007. Its output power is 311 kW and the maximum speed is 100 km/h [12]. In the hybrid drive system, the electricity produced by the engine generator is converted into DC electricity by a converter and the inverter changes the DC to AC electricity to power the main electric motor (traction motor). The auxiliary power supply, a static inverter (SIV), provides power to service equipment, such as air conditioning [11]. Switching between charging and discharging of battery is determined by train speed and the battery’s state of charge.
### Table 2.1 Comparison of rechargeable batteries [23] [24]

<table>
<thead>
<tr>
<th>Battery</th>
<th>Energy density</th>
<th>Power density</th>
<th>Life cycle</th>
<th>Efficiency</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-Ion</td>
<td>150</td>
<td>500</td>
<td>2500</td>
<td>80-90%</td>
<td>500</td>
</tr>
<tr>
<td>Lead-acid</td>
<td>40</td>
<td>600</td>
<td>500</td>
<td>50-92%</td>
<td>150</td>
</tr>
<tr>
<td>Na-NiCl</td>
<td>794</td>
<td>150-120</td>
<td>N/A</td>
<td>75%</td>
<td>Unavailable</td>
</tr>
<tr>
<td>Ni-Cad</td>
<td>236</td>
<td>120-150</td>
<td>1500</td>
<td>70-90%</td>
<td>Unavailable</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>65</td>
<td>400</td>
<td>500</td>
<td>66%</td>
<td>450</td>
</tr>
</tbody>
</table>

**Figure 2-6 Flywheels energy storage system** [13]

A flywheel energy storage system is shown in Fig 2-4. In this system, the kinetic energy is stored in the inertia of the rotor mass. Flywheels have high power density and are capable of delivering burst power over short periods of time, and can capture the excess power of locomotives. In addition, they are less affected by harsh working environments, such as frequent and deep discharge. They have compact
weight and size and need less maintenance requirement.

However, flywheel energy storage systems have a high initial cost. In addition, flywheels have a low energy density. Also, more energy is lost during storage compared to batteries due to the bearing friction.

**Figure 2-7 British rail class 139 [1]**

British Rail Class 139, a diesel/flywheel locomotive, was built in 2008, shown in Fig 2-5. A small diesel engine is used to power up the locomotive initially and supplies power for the flywheel [1]. The maximum speed is up to 65 km/h. This lightweight locomotive is used to be transit between cities and within cities [14].

**Figure 2-8 Ultracapacitor [16]**

An ultracapacitor, shown in Fig 2-7, also known as a double-layer capacitor,
polarizes an electrolytic solution to store energy electro-statically. The energy conversion is a highly reversible electrochemical process capable of withstanding hundreds of thousands of charge and discharge cycles without degradation [16]. Ultracapacitors are characterized by high power density. Their energy capacity is less than electrochemical batteries, but they have the ability to release and absorb energy very quickly. Also, they have less components and maintenance compared to flywheels.

The disadvantage of ultracapacitors is their low energy density. The weight of ultracapacitors is much heavier than batteries for supplying the same energy. To provide enough energy to discharge or charge the energy storage system for locomotives, the size of ultracapacitors will be very large and the additional weight added to the locomotives is much heavier compared to the battery energy storage system.

Researchers from Swiss Federal Institute of Technology Lausanne designed an onboard ultracapacitors storage system. Their simulation results show a 44% fuel reduction with 8200 ultracapacitors as a storage bank. The system has a high initial cost compared to a diesel-electric locomotive with a payback period of 10 years [17].
A hydraulic energy storage system consists of a hydraulic accumulator, a hydraulic pump/motor and a reservoir, as shown in Fig 2-8. In the hydraulic energy storage system, the energy is stored in the form of pressurized fluid. This energy storage system has the advantage of high power density and low costs. It can either release or absorb energy very quickly depending on the load, therefore is preferable to capture the excess power of locomotives. In addition, the system is environmentally friendly. Similar to flywheels, hydraulic energy storage systems have low energy density.
### Table 2.2 Comparison of energy storage systems [12] [16] [39] [40]

<table>
<thead>
<tr>
<th>Storage system</th>
<th>Energy density</th>
<th>Power density</th>
<th>Efficiency</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead-Acid Battery</td>
<td>40</td>
<td>300</td>
<td>50-92%</td>
<td>150</td>
</tr>
<tr>
<td>Li-ion Battery</td>
<td>150–200</td>
<td>500</td>
<td>80-90%</td>
<td>500</td>
</tr>
<tr>
<td>Flywheel</td>
<td>~50</td>
<td>1000~</td>
<td>85-90%</td>
<td>690-800</td>
</tr>
<tr>
<td>Hydraulic Accumulator</td>
<td>140</td>
<td>Depending on the pump/motor</td>
<td>~70%</td>
<td>220</td>
</tr>
<tr>
<td>Ultra-capacitor</td>
<td>6</td>
<td>500</td>
<td>80-90%</td>
<td>5000</td>
</tr>
</tbody>
</table>

#### 2.3. Hydraulic Hybrid Locomotives

Hydraulic energy storage systems have been applied to automobiles for the high power capability and low costs. U.S Environmental Protection Agency (EPA) developed a hydraulic hybrid UPS truck with a series configuration. The hydraulic hybrid energy storage system are able to capture and reuse 70-80% of the otherwise wasted braking energy. The reduced fuel consumption was verified and CO$_2$ emission was demonstrated by the truck [35].

##### 2.3.1 Hydraulic Accumulator

The accumulator is an energy storage device based on the reversibility of gas, typically nitrogen. There are two major types of accumulators, bladder and piston, shown in Fig 2-13. In a bladder type accumulator, the gas is contained in a deformable bladder. Hydraulic fluid squeezes the bladder to compress the gas. The advantage of
this bladder accumulator is that it may be used in any orientation provided care was taken in design to insure that the bladder does not rub against the accumulator walls. A drawback of bladder accumulator is that the gas permeates through the bladder over time. This may reduce the bulk modulus of the fluid. In this research, bladder accumulators will be used in the EMB system. In a piston accumulator, a piston separates the gas and fluid. With adequate sealing, the piston accumulator is inexpensive and almost maintenance free. However, piston accumulators should only be used in a vertical position to avoid building up debris that could destroy the seal.

![Bladder and piston accumulator](image)

**Figure 2-10  bladder and piston accumulator [25]**

In an energy storage application, a bladder accumulator typically is precharged to 90% of the minimum hydraulic system pressure [25]. The precharge pressure determines how much fluid will remain in the accumulator at the minimum system pressure.

### 2.3.2 Hydraulic Pump/Motor Unit

The hydraulic pump/motor unit (HPMU) used in this thesis is axial piston design. These include the swash plate as shown in Fig 2-14, and the bent axis designs as shown in Fig 2-15. Both of these designs have very high efficiencies nearing 95%. There are a great number of commonalities between the designs. The principal
The difference between the designs is how the angle that causes the pistons to reciprocate is created.

In the swash plate design, the rotating group includes the drive shaft, the pistons, and the cylinder block or barrel. The swash plate is not connected to the drive shaft. The piston bases, usually through connecting rods, sit in slippers that ride in a pitch circle on the fixed swash plate. The swash plate is at an angle to the perpendicular to the drive shaft. This angle is variable in variable displacement HPMU. As a result, the rotation of the drive shaft causes the pistons to move up and down with respect to the cylinder block. In the pump mode, torque on the drive shaft forces the pistons to push the fluid out of the piston barrel into the discharge valve plate opening for one half of the rotation. On the other half of the rotation, the retraction of the piston sucks in fluid from the suction side of the pump through the suction valve plate opening. In the motor mode, that action is opposite: the fluid pushes against the piston to produce torque on the drive shaft. Spent fluid is

---

**Figure 2-11 Swash plate piston pump/motor [25]**

In the swash plate design, the rotating group includes the drive shaft, the pistons, and the cylinder block or barrel. The swash plate is not connected to the drive shaft. The piston bases, usually through connecting rods, sit in slippers that ride in a pitch circle on the fixed swash plate. The swash plate is at an angle to the perpendicular to the drive shaft. This angle is variable in variable displacement HPMU. As a result, the rotation of the drive shaft causes the pistons to move up and down with respect to the cylinder block. In the pump mode, torque on the drive shaft forces the pistons to push the fluid out of the piston barrel into the discharge valve plate opening for one half of the rotation. On the other half of the rotation, the retraction of the piston sucks in fluid from the suction side of the pump through the suction valve plate opening. In the motor mode, that action is opposite: the fluid pushes against the piston to produce torque on the drive shaft. Spent fluid is
discharged into the low pressure port.

![Diagram of a bent-axis piston pump/motor](image)

**Figure 2-12 Bent-axis piston pump/motor** [25]

In the bent axis design, the axis of the rotating cylinder block and the non-rotating valve plate are at an angle to the drive shaft. This angle is adjustable in variable displacement HPMU. The plate at the base of the pistons is now fixed to the drive shaft at a perpendicular angle. As the drive shaft rotates, the articulating universals between the drive shaft and the cylinder block cause the cylinder block to rotate on its axis. This rotation then causes the pistons between the base plate and the barrel to reciprocate with respect to the barrel. In the pump mode, torque on the drive shaft results in fluid being pumped into the high pressure port. In the motor mode, the high pressure fluid creates torque on the drive shaft.

Compared to a bent-axis piston HPMU, a swash plate piston HPMU has the advantage of compact size but is more sensitive to oil contamination. The bent axis HPMU has the best efficiency of all hydraulic pump/motors but with less reliability than the swash plate HPMU.

In the EMB system, the bent-axis HPMU was chosen to be used since high
efficiency was essential for the energy storage system. As a component of energy storage system, its efficiency has significant impact on the efficiency of the whole EMB system.

2.3.3 Electric Motor/Generator (EMGU)

A DC electric motor/generator unit (EMGU) is used in the EMB system since the control system of DC EMGU is simple and the electrical power released by the EMB can be directly stored in batteries if needed.

![Figure 2-13 A DC electric motor](image)

The theory of a DC motor is based on the Lorentz Force Law: current is supplied to a conductor in a changing magnetic field, a force will be produced. As shown in Fig 2-13, the electrical current is supplied through a commutator to the armature (rotor) which is a set of wound wire coils. The magnetic field of the rotor is then created by the current flow in the coils. The other magnetic field produced by the permanent magnet stator acts on the former one, and these magnetic forces produce a torque to make the armature rotate; therefore the shaft connected to the rotor is driven to rotate and converts the electrical power to torque and speed in the shaft. The
commutator causes the current through the coils to be switched, keeping the magnetic poles of the rotor from ever fully aligning with the magnetic poles of the stator field, so that the rotor never stops but rather keeps rotating as long as electric power is applied.

The theory of a DC generator is based on the Faraday’s Law; when a conductor is moved or cutting across a magnetic field, then current is induced in the conductor. In contrast to motor mode, the rotor of DC generator is driven to rotate by the shaft and the coils wound on the armature turn and cut across the magnetic field; the electromotive force (voltage) in the coils is then generated. The generated alternating voltage is undirected by the commutator and brushes.
Generally, the magnetic field in the DC motor/generator is provided by excitation rather than permanent magnets which are applied in smaller DC motor/generator, shown in Fig 2-14 (a). The windings of field coils can be either shunt windings (in parallel with armature windings) or series windings (in series with the armature windings) or a combination of both; they determine the characteristic of the DC EMGU [38]. The shunt wound EMGU offers relatively flat speed-torque
characteristics, and it provides a good speed regulation over wide load ranges, however, the starting load is lower than the other winding types, shown in Fig 2-14 (b) [38]. Series wound type has the armature connected in series with the field, it offers very high starting torque but with poor speed regulation, as shown in Fig 2-14 (c). Compound wound design utilizes a field winding in series in addition to the shunt field to obtain a compromise in performance between a series and shunt type design. It offers a combination of good starting torque and speed stability and assures a speed drop with overload, shown in Fig 2-14 (d).

A 200 hp (150 kW) unit stabilized shunt windings DC motor, categorized as compound windings DC motor, is chosen to be the EMGU. The performance curves are shown in Fig 2-15. As can be seen, the current of EMGU is proportional to the torque; the shaft speed is relatively constant due to a certain voltage. The efficiency is about 90% within the speed range.
Figure 2-15 rpm and torque vs. amps
Chapter 3 DESIGN AND ANALYSIS OF THE EMB

3.1 Introduction

The EMB system consists of hydraulic accumulators, a hydraulic pump/motor, an electric motor/generator and a reservoir. The circuit of EMB system is shown in Fig 3-1. The load side can be either an electric motor/generator or batteries.

Figure 3-1 Circuit of EMB system
3.1.1 Objective

The objective of this thesis is to analyze the EMB system, build a simulation model to demonstrate the discharge and charge process and to prove its capability of providing a burst power for short period based on the model. The requirements for the burst power and short period are 150 kW and 90 sec.

3.1.2 EMB design concept

The EMB allows energy to be transferred with high efficiency and stored for future use, either to assist in powering the locomotive or to charge the battery system. The battery system can not handle high power transfers because the batteries cannot tolerate high rates of charging and discharging. Essentially, the EMB system takes a high power transfer of energy and either makes it available for a high power transfer into motive force or converts the energy transfer into a lower power transfer as needed. The advantage of the EMB is that energy transfer can be performed at very high efficiency.

Under a high power transfer situation, the EMGU is activated. If the excess power exists on the load side, the EMGU is placed into motor mode. The torque produced is put on the HPMU in pump mode. The hydraulic fluid is transferred to the accumulators; the fluid pressure increases resulting in energy storage.

If power is needed by the locomotive which exceeds the power transfer rate from the batteries, power is drawn from the energy stored in the accumulators. High pressure hydraulic fluid powers the HPMU in motor mode producing torque. This torque is applied to the EMGU in generator mode to produce the electricity needed by
the load side.

The design problem for the EMB is to size both the EMGU and the HPMU to allow the power transfer and to size the accumulator bank to accept the power produced. Several assumptions need to be made. The system needs to be operational under full power for at least 90 seconds. The torques and speeds of the HPMU and EGMU need to be compatible. For safety reasons, the HPMU must have a smaller power rating than the EMGU to prevent damage to the main locomotive circuits.

3.1.3 Concept of control

In a charging or power capture event, the EMGU will initially spin near its no load speed under the voltage and amperage impressed on the EMGU. The HPMU will be under a zero displacement condition. The initial torque will be the system loses under these conditions. Immediately the displacement of the HPMU will be increased. This will increase the torque between the EGMU. If the displacement is too high, the HPMU demanding torque will be too high and the speed of the system will drop and potentially stall. If the displacement is too low, the system will race in response to the excess power. The goal of the control system is to operate at the speed where the power transfer is most efficient.

In a discharge event, the EMGU and the HPMU are initially at zero speed. As displacement is increased on the HPMU, the torque on the inter-shaft between the HPMU and EGMU will increase until the EGMU is able to meet the voltage and amperage requirements of the load. Conversely to the charging mode, if the displacement is too low, the system speed will drop and potentially stall. If the
displacement is too high, the system will race. The control strategy is to produce the demand power at the highest efficiency of the system.

3.2 Analysis

Before building the mathematical model, the size of the components within EMB has to be determined according to the analysis of the whole system and the requirements.

3.2.1 Hydraulic Accumulator

In the EMB system, the state of inert gas in the accumulator is considered to be adiabatic, so the following equation of state is used,

$$pV^{1.4} = const$$  \hspace{1cm} (3.1)

The actual flow rate through the HPMU is related to the gas volume in the accumulator through the continuous process. The flow rate of the hydraulic fluid entering the HPMU is equal to the rate of expansion of the accumulator gas:

$$Q = -\frac{dV}{dt}$$  \hspace{1cm} (3.2)

The energy losses of the accumulator are mainly thermodynamic heat losses, which are caused by flow entrance effects, viscous shear, conduction and piston seal friction or bladder hysteresis. These losses cause a pressure difference between the accumulator inlet and gas [31]. To simplify the modeling of an accumulator, we assume that the difference between gas pressure $p_g$ and oil pressure at accumulator inlet $p$ is 4%, which means the efficiency of the accumulator is 96%.

The volume of the fluid in the accumulator can be roughly determined based on the required power, the designed minimum and maximum pressure and the
required operation time. Then, the size and number of accumulator will be
determined.

For discharge process, the work applied to the HPMU comes from the gas
expending in the accumulator. The output work of the HPMU is less than the input
work due to the work loss through discharging. The whole process can be expressed
by,

\[ W_{EMB} + W_{loss} = W_{gas} \]  (3.3)

\( W_{EMB} \) is the output work of EMB; \( W_{gas} \) is the applied work by gas in the accumulator;
\( W_{loss} \) is the work loss through discharging, which is the product of loss at the
accumulator and the loss at the HPMU. 4% and 15% are assumed to be the
accumulator loss and HPMU loss respectively. Knowing the work loss, the relation
between \( W_{EMB} \) and \( W_{loss} \) can be rewrite as Equation 3.3,

\[ 1.2255 W_{EMB} = W_{gas} \]  (3.4)

And \( W_{max} \) and \( W_{gas} \) can be rewrite as,

\[ W_{EMB} = P \ t \]  (3.5)

\[ W_{gas} = p_1 \ V_{min} - p_2 \ V_{max} \]  (3.6)

\( p_1 \) and \( V_{min} \) are the pressure and volume of the accumulator gas at maximum pressure.
\( p_2 \) and \( V_{max} \) are the pressure and volume of the accumulator gas at the minimum
pressure. \( V_{min} \) and \( V_{max} \) can be expressed with respect to the volume of the discharging
fluid. Therefore, the relation of the operation time and fluid volume can be roughly
determined based on Equation 3.4, shown in Fig 3-2.
Based on the relation of operation time via capacity of accumulator during discharging, releasing 297 gallon fluid can produce the energy with a power of 150 kW for around 90 seconds.

The relation of fluid volume and operation time for charging can be obtained by the similar method except the 1.2255 is on the right side of Equation 3.4.

According to the relation of operation time via capacity of accumulator
during charging, 198 gallon fluid is needed to capture energy with a power of 150 kW for the duration of 90 seconds.

As shown in Fig 3-2 and Fig 3-3, much more fluid is needed during discharging than charging for the same operating duration. This is because the work applied by the gas loss partly when it is applied to the HPMU during discharging. While the work loss very little (can be considered to be zero) when it is applied to the HPMU from the EMGU during charging.

### 3.2.2 The hydraulic pump motor unit (HPMU)

The theoretical volumetric flow rate through the HPMU and theoretical torque provided by HPMU are given by,

\[ Q_t = \omega x D \]  \hspace{1cm} (3.7) [31]

\[ T_t = px D \]  \hspace{1cm} (3.8) [31]

Where, \( x \) is the percentage of maximum displacement. For a bent axis type, \( x \) is related to the yoke angle, which is defined to be positive in pump mode and negative in motor mode, thus the range of \( x \) is from -1 to 1.

Because of the inlet cavitations, leakage, and fluid compressibility, actual flow rate at the outlet is less than the theoretical flow rate at the inlet of the HPMU. The volumetric efficiency is the ratio of the actual to the theoretical flow rate,

\[ \eta_v = \frac{Q_a}{Q_t} \]  \hspace{1cm} (3.9) [31]

By neglecting the inlet cavitations loss, which is small for most modern pumps, it can be shown as,

\[ \eta_{v,p} = 1 - \frac{C_s}{xS} - \frac{p}{x} - \frac{C_{st}}{x\sigma} \]  \hspace{1cm} (3.10) [31]

Where \( C_s \) and \( C_{st} \) are the laminar and turbulent leakage coefficients, respectively,
and $\beta$ is the fluid bulk modulus of elasticity. The dimensionless numbers, $S$ and $\sigma$ are given by,

$$S = \frac{\mu \omega}{\rho} \quad (3.11) \quad [32]$$

$$\sigma = \frac{\omega D^{\frac{1}{2}}}{(2 \frac{p}{\rho})^{\frac{1}{2}}} \quad (3.12) \quad [32]$$

A torque provided to the pump is needed to overcome the frictional forces which are always present. The pump torque efficiency is the ratio of the ideal torque requirement to the actual one.

$$\eta_i = \frac{T_t}{T_a} \quad (3.13) \quad [31]$$

By accounting for the viscous torque, the Coulomb torque, the hydrodynamic torque loss of a pump can be shown as,

$$\eta_{t,p} = \frac{1}{1 + \frac{C_v S}{x} + \frac{C_f}{x} + C_h x^2 \sigma^2} \quad (3.14) \quad [31]$$

Where $C_v$, $C_f$, and $C_h$ are the viscous, frictional, and the hydrodynamic loss coefficients, respectively.

The equivalent equations for motors are:

$$\eta_{t,m} = \frac{1}{1 + \frac{C_v S}{x} + \frac{p}{\beta} + \frac{C_f}{x} + \frac{C_h}{x} x^2 \sigma^2} \quad (3.15) \quad [31]$$

$$\eta_{t,s} = 1 - \frac{C_v S}{x} - \frac{C_f}{x} - C_h x^2 \sigma^2 \quad (3.16) \quad [31]$$

The overall efficiency is given by,

$$\eta_o = \eta_i \eta_t \quad (3.17)$$

The A6VM bent-axis variable displacement pump/motor manufactured by Bosch Rexroth is chosen to be the HPMU of EMB, the technical data of theoretical
model is shown in Table 3.1.

**Table 3.1 Size of A6VM pump/motor [30]**

<table>
<thead>
<tr>
<th>Size</th>
<th>Displacement</th>
<th>V&lt;sub&gt;2max&lt;/sub&gt;</th>
<th>cm³</th>
<th>V&lt;sub&gt;2L&lt;/sub&gt;</th>
<th>cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>55</td>
<td>80</td>
<td>107</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>200</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>500</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mar. speed (within adhering to max. permissible flow)

<table>
<thead>
<tr>
<th>rpm</th>
<th>rpm</th>
<th>rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5500</td>
<td>4500</td>
<td>3550</td>
</tr>
<tr>
<td>5000</td>
<td>3550</td>
<td>2550</td>
</tr>
<tr>
<td>4500</td>
<td>2550</td>
<td>1950</td>
</tr>
</tbody>
</table>

Max. flow

<table>
<thead>
<tr>
<th>Q&lt;sub&gt;2max&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;2L&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>120</td>
</tr>
<tr>
<td>244</td>
<td>120</td>
</tr>
<tr>
<td>195</td>
<td>120</td>
</tr>
</tbody>
</table>

Max. torque

<table>
<thead>
<tr>
<th>T&lt;sub&gt;2max&lt;/sub&gt;</th>
<th>T&lt;sub&gt;2L&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>195</td>
<td>120</td>
</tr>
<tr>
<td>244</td>
<td>120</td>
</tr>
</tbody>
</table>

Rotation stiffness

<table>
<thead>
<tr>
<th>V&lt;sub&gt;2max&lt;/sub&gt;</th>
<th>V&lt;sub&gt;2L&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>47000</td>
<td>20000</td>
</tr>
<tr>
<td>35000</td>
<td>20000</td>
</tr>
<tr>
<td>24000</td>
<td>20000</td>
</tr>
</tbody>
</table>

Moment of inertia of the rotary group

<table>
<thead>
<tr>
<th>J&lt;sub&gt;W&lt;/sub&gt;</th>
<th>kgm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0014</td>
<td>0.012</td>
</tr>
<tr>
<td>0.0017</td>
<td>0.015</td>
</tr>
<tr>
<td>0.0020</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Angular acceleration

<table>
<thead>
<tr>
<th>V&lt;sub&gt;max&lt;/sub&gt;</th>
<th>V&lt;sub&gt;L&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>5.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Mass (approx.)

<table>
<thead>
<tr>
<th>m kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
</tr>
<tr>
<td>52</td>
</tr>
<tr>
<td>100</td>
</tr>
</tbody>
</table>

To make the HPMU operate within the high efficient area, the shaft speed has to be within the range of 1500 to 1800 rpm. The torque range for the 150 kW EMB system can be determined according to the power expression of the HPMU,

\[ P_{p,m} = T \omega \] (3.18)

The maximum theoretical torque is 955 Nm, 160 cc unit has the ability to provide this amount of torque. From the other point, the power is the product of flow rate and pressure through the HPMU,

\[ P_{p,m} = pQ \] (3.19)

The maximum and minimum pressure of EMB is 5000 psi and 1000 psi. The maximum theoretical flow rate can therefore be obtained, which is 1300 L/min. The 1000 cc unit can accommodate to this amount of flow rate. Considering these two points, the displacement of HPMU has to be a 1000 cc unit.

Since the power requirement of the EMB is 150 kW,

\[ T \omega = pQ \eta_o = 150000 \] (3.20)

The pressure in the accumulator can be obtained based on the equation 3.1, 3.2 and
3.20, and the fluid volume in the accumulator. The results show that the pressure through the HPMU is only related to the operation time, and the pressure during discharge and charge are respectively expressed by,

\[ p = (142.4 - 0.84t)^{3.5} \]  \hspace{1cm} (3.21)

\[ p = (89.9 + 0.61t)^{3.5} \]  \hspace{1cm} (3.22)

Table 3.1 Related parameters of 1000 cc unit

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Shaft speed</td>
<td>2100</td>
<td>rpm</td>
</tr>
<tr>
<td>Maximum displacement</td>
<td>1000</td>
<td>cm³/rev</td>
</tr>
<tr>
<td>Torque</td>
<td>5571</td>
<td>Nm</td>
</tr>
<tr>
<td>Flow rate</td>
<td>1600</td>
<td>L/min</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>0.55</td>
<td>kgm²</td>
</tr>
</tbody>
</table>
3.2.3 The electric motor/generator unit (EMGU)

A 200 hp (150 kW) stabilized shunt DC EMGU is used in the EMB system, and the speed range with high efficiency is from 1750 rpm to 2000 rpm. The speed-torque relationship can be built on the basis of characteristic performance curves, and this relationship can be linearly regressed to be Equation 3.23.

\[ T = -44.7 \omega + 8722.7 \]  
\( R^2 = 0.91 \)

The power of EMGU is expressed by,

\[ P_{m,g} = \omega T_{m,g} \]  
(3.24)

and can also be expressed by,

\[ P_{m,g} = I U \]  
(3.25)

where \( I \) is the current and \( U \) is the voltage of the EMGU, and the \( \omega \) is the shaft speed and \( T_{m,g} \) is the torque of EMGU. The shaft speed of EMGU equals to the shaft speed of HPMU since the two shafts are connected through a coupler.

The speed of EMGU can be adjusted by changing the voltage since they have a proportional relationship. A constant voltage can produce a constant speed of EMGU according to Faraday’s Law, given as:

![Torque-speed curve](image-url)
\[ U = -N \frac{\Delta \Phi}{\Delta t} \] (3.26)

where \( U \) is the generated voltage, \( N \) is the number of turns, \( \Delta \Phi \) is the change of magnetic flux, and \( \Delta t \) is the change of time. \( N \) is constant in a motor/generator and \( \frac{\Delta \Phi}{\Delta t} \) is the change of magnetic flux per unit time, which proportional to the shaft speed of EMGU.

To simplify the simulation, the driving torque provided by the EMGU during charging is assumed to be constant. The model of EMGU is neglected within the EMB model due to the assumption that the power of EMGU equals to the power of the HPMU. As long as the power of HPMU satisfies the power requirement, the designed EMB system is proved to be able to discharge or charge with the required power.

According to Newton’s Second Law,

\[ T - T_{load} = J \frac{d\omega}{dt} \] (3.27)

\( T \) is driving torque, which is provided by HPMU during discharge and produced by EMGU during charge; \( T_{load} \) is created by EMGU during discharge and by HPMU during charge; \( J \) is moment of inertia of HPMU. The speed of the HPMU and EMGU during operation can be determined from Equation 3.20, 3.23 and 3.27.

The numerical solution is obtained to show the speed curve with respect to the operation time. The shaft speed during charge and discharge are given in Fig 3-5, Fig 3-6 respectively.
The speed during charge is technically constant and the 1680 rpm (176.06 rad/sec) falls within the range of 1500 rpm to 1800 rpm but lower than 1750 rpm, meaning that the efficiency of EMGU will be slightly lower than 90%. The speed during discharge is about 200 rpm (19 rad/sec), which is too low to efficiently operate the HPMU and EMGU.

3.2.4 Control system

The control system of EMB is designed to create a signal to control the yoke angle of the HPMU. Adjusting the yoke angle is completed by the control device.
A6VM pump/motor has hydraulic and electric control methods. The proportional solenoid control is chosen since it is applicable for continuous displacement controlling. The control device consists of a proportional valve and a hydraulic piston with spring, which is built with the pump/motor.

![Figure 3-7 Layout of the control system](image)

**Figure 3-7 Layout of the control system [30]**

Considering the EMB system as a single-input-single-output system, PI controller can be adopted to build the close-loop automatic control system of the EMB. The control system is shown in Fig 3-8.

![Figure 3-8 Control system of EMB](image)

**Figure 3-8 Control system of EMB**

In the control system, the EMB system is the plant which needs to be controlled. The desired torque is the reference to be compared with the HPMU torque. The torque difference is the input of the PI controller, and the output is the current signal to the proportional solenoid, then the yoke angle is determined.

The transfer function of PI controller is expressed by,
The characteristic of proportional solenoid is given in Fig 3-9. The 24V proportional solenoid was used, thus the relationship between the yoke angle and current can be obtained:

\[ i = -0.3125x + 0.7625 \]  

(3.29)

To make it convenient to obtain the transfer function, Equation 3.28 is modified as,

\[ i_1 = 0.3125 \alpha \]  

(3.30)

Therefore, the actual current signal has the following relationship to the modified current signal,

\[ i = -i_1 + 0.7625 \]  

(3.31)

Assuming a 500 ms delay with the solenoid, the transfer function of the control valve is given by,

\[ \frac{3.2}{0.5S+1} \]  

(3.32)

The transfer function of EMB system is
\[ D \ p \eta_r = \text{constant} = G \]  
(3.33)

where \( p \) is pressure through HPMU, which is determined by the operation time, and \( D \) is the maximum displacement of pump/motor, \( \eta_r \) is the mechanical efficiency of pump/motor.

The characteristic equation of close-loop transfer function for this system is

\[ 1 + G(s) = 0 \]  
(3.34)

Therefore we have

\[ \frac{6.4Kp}{S(S+2)} + 1 = 0 \]  
(3.35)

Let \( K = 6.4 \ G \), the open-loop transfer function is expressed by,

\[ G(s) \ H(s) = G(s) = \frac{K(S + \frac{1}{T_i})}{S(S+2)} \]  
(3.36)

Root Locus theory is applied to limit \( K \) and determine \( Kp \) and \( T_i \), the process is discussed following.

According to the zero and two poles of \( G(s) \), the root loci relying on the real axis are \((-2, 0)\) which is between two poles and \((-\infty, -\frac{1}{T_i})\), \( 0 < T_i < 0.5 \), which is between two zeros. According to root locus analysis theory, there exist at least one breakaway point within \((-2, 0)\) and at least one break-in point within \((-\infty, -\frac{1}{T_i})\). The \( s_1 \) and \( s_2 \) can be found based on the equation \( \frac{dK}{ds} = 0 \), and they are given by,

\[ s_1 = -\frac{1}{T_i} + \frac{\sqrt{4-8T_i}}{2T_i} \]  
(3.37)

\[ s_2 = -\frac{1}{T_i} - \frac{\sqrt{4-8T_i}}{2T_i} \]  
(3.38)
Obviously, s1 is within the root locus (-2, 0) and s2 is within the root locus \((-\infty, -\frac{1}{Ti})\), therefore the range of K can be determined according to the expression of K with respect to s,

\[
K = -\frac{s(s + 2)}{s + \frac{1}{Ti}}
\]  
(3.39)

Substituting s1 and s2 into Equation 3.37, the range of K is \((0, \infty)\).

The damping ratio \(\zeta = 1\) since overshoot is not expected in the results, and the control response frequency \(\omega_n\) is related to how fast the control operates. The obtained results of the control system limit a range to choose \(\omega_n\), shown in Table 3.3.

<table>
<thead>
<tr>
<th>(\frac{1}{Ti})</th>
<th>(\omega_n)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\infty)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.250</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>2.000</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2.083</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>2.250</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>2.450</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td>2.667</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

As the control response frequency \(\omega_n\) increases, more noise appears in the results and unstable at 4, meaning that too fast operation of EMB may bring failure of the control system. The \(\omega_n\) can be chosen from \((1, 4)\), then \(K, \frac{1}{Ti}\) and \(K_p\) could be determined.
3.3 Summary

In this Chapter, mathematical analysis for each component of EMB is presented, and the size for each component is determined based on the analysis.

The calculation results show that the speed of HPMU and EMGU will be too low during discharge. This very low speed will dramatically reduce the efficiency of the EMB system, which goes against the expectation of high efficient energy transfer.

The speed during charge is within the high efficient operating area of the HPMU.
Chapter 4 SIMULATIONS

The simulation of charging the EMB is shown in this Chapter. The block diagrams of EMB and components are given. The charge process of EMB is also simulated with SimHydraulic to verify the results obtained by Simulink.

4.1 EMB Model by MATLAB/SIMULINK

The EMB control system is shown in Fig 4-1, actual current signal can be obtained based on the current result.

Figure 4-1 Block diagram of EMB control system
As shown in Equation 3.19, 3.20 in Section 3.2.2, the pressure through the HPMU depends on the operation time of EMB system. It is assumed that there is a 500 ms delay within the control valve.
4.2 EMB Model by Simscape/SimHydraulic

SimHydraulic blocks represent physical components or relationships directly to build the model [33]. Simhydraulic model is used to verify that yoke angle created in the Simulink model can produce the required power in physical test.

The assumption about the physical blocks of variable displacement pump is presented below, and parameters within the block are shown in Table 4.1.

i. Fluid compressibility is negligible [33].

ii. No inertia, friction on the shaft [33].

iii. Leakage of the pump and motor are proportional to the pressure differential [33].
Table 4.1 Block parameters of the variable displacement pump/motor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum displacement</td>
<td>1000</td>
<td>Cm³/rev</td>
</tr>
<tr>
<td>Volumetric efficiency</td>
<td>0.92</td>
<td>/</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>0.85</td>
<td>/</td>
</tr>
<tr>
<td>Nominal pressure</td>
<td>5000</td>
<td>Psi</td>
</tr>
<tr>
<td>Nominal angular velocity</td>
<td>2100</td>
<td>Rpm</td>
</tr>
<tr>
<td>Moment Inertia</td>
<td>0.55</td>
<td>Kg m²</td>
</tr>
</tbody>
</table>

The block of gas-charged accumulator is built based on the assumptions are listed below. The block parameters are shown in Table 4.2.

i. The gas in the accumulator is ideal gases [33].

ii. No inertia, friction and any load on the separator or the bladder [33].

iii. Fluid is incompressible [33].

Figure 4-7 Block of gas-charged accumulator in the SimHydraulic [33]

Capacity of the accumulator is the summation of gas volume and fluid volume. The initial volume is the volume of fluid in the accumulator before charging.
Table 4.2 Block parameters of gas-charged accumulator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value (Charge)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>198</td>
<td>gal</td>
</tr>
<tr>
<td>Preload pressure</td>
<td>1000</td>
<td>Psi</td>
</tr>
<tr>
<td>Specific heat ratio</td>
<td>1.4</td>
<td>/</td>
</tr>
<tr>
<td>Initial volume</td>
<td>0</td>
<td>gal</td>
</tr>
</tbody>
</table>

The simulation model of charging the EMB is shown in Fig 4-8. The ideal speed source represents the speed which is providing by the EMGU in motor mode.

Figure 4-8 EMB system
Chapter 5 RESULTS

The evaluation of the storage system for the locomotive must include the stability range of the control system, the duration of power available from the storage system and the effect of accumulator pressure on the power available. If the system is unstable, damage to the pump/motor and the electric motor could happen. The duration of power needs to be sufficient to cover the period when the power demand would result in damage to the electric battery system. And lastly the hydraulic system must be able to produce sufficient power regarding the accumulator pressure.

In many control systems and this one herein with no exception, as one increases the control response frequency (i.e. shortens the time response) of the control system, the system is unable to settle to an operation point and therefore unstable. For this system, stable response is needed to 2 Hz. Therefore, the system was tested to insure this response could be met.

5.1 Stability Results

Choosing a control response frequency of 1.5 Hz, the obtained results of yoke angle, the current of control valve, pressure and flow rate are shown in Fig 5-1, and the results of shaft speed, torques and power are shown in Fig 5-2.
Figure 5-1 Plots of yoke angle, current, pressure and flow rate ($\omega_n = 1.5$)
As shown in Fig 5-1 and 5-2, the tuned yoke angle of HPMU is quite low initially for allowing the EMGU to speed up and reach to the designed speed. The yoke angle increase immediately as the shaft speed rises to the designed value; the load of EMGU (torque of HPMU) is not zero any more but increased, the toque of EMGU is produced to operate the HPMU to charge the accumulators. The great change occurs to yoke angle at the beginning is obvious since the control process is operated relatively slow.
The pressure, flow rate are both within the operating range. The power of EMB increases to the required value after a few seconds due to the low frequency control system. The noise occurring as the beginning of speed is due to the great change of yoke angle.

Choosing the control response frequency of 2.5 Hz, the obtained results of yoke angle, the current of control valve, pressure and flow rate are shown in Fig 5-3, and the results of shaft speed, torques and power are shown in Fig 5-4.

Figure 5-3 Plots of yoke angle, current, pressure and flow rate ($\omega_n =2.5$)
Figure 5-4 Plots of shaft speed, torques and power of HPMU ($\omega_n = 2.5$)

As shown, it takes less time for the results to reach to the static state value. However, the noise occurs to the transient results with the frequency increasing. It shows that the control system cannot respond as accurate as it does with a lower frequency even though the responding period is shorter. These vibrations are not expected to occur in the results since the overshoot of flow rate through HPMU may cause damage and the overshoot power may do harm to the EMGU.

Choosing the control response frequency to be 3.5 Hz, the obtained results
of yoke angle, the current of control valve, pressure and flow rate are shown in Fig 5-5, and the results of shaft speed, torques and power are shown in Fig 5-6.

**Figure 5-5 Plots of yoke angle, current, pressure and flow rate ($\omega_n = 3.5$)**
As the frequency increases to 3.5 Hz, there are few differences of the static state value of the results compared to previous ones. However, the noise and overshoot in the results become more severe in aspects of magnitude and duration. It is quite difficult for the control system to handle this frequent vibration of the yoke angle. Also, the overshoot of flow rate and power will cause severe damage to the HPMU and EMGU. For this system, it appears that the system becomes unstable for operation near 3.5 Hz. Therefore, this system does meet the response time needed.
According to the results, the applicable natural frequency is from 1 Hz to 4 Hz, and the whole system will be unstable when it is higher than 4, shown in Table 5.1. As the natural frequency of the control system increases within the applicable range, the noise in the results become more severe and may cause damage to the components of the EMB.

<table>
<thead>
<tr>
<th>$\omega_n$</th>
<th>$\frac{1}{T_i}$</th>
<th>$K$</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\infty$</td>
<td>0</td>
<td>/</td>
</tr>
<tr>
<td>1.5</td>
<td>2.250</td>
<td>1</td>
<td>Stable</td>
</tr>
<tr>
<td>2</td>
<td>2.000</td>
<td>2</td>
<td>Stable</td>
</tr>
<tr>
<td>2.5</td>
<td>2.083</td>
<td>3</td>
<td>Stable</td>
</tr>
<tr>
<td>3</td>
<td>2.250</td>
<td>4</td>
<td>Stable</td>
</tr>
<tr>
<td>3.5</td>
<td>2.450</td>
<td>5</td>
<td>Stable</td>
</tr>
<tr>
<td>4</td>
<td>2.667</td>
<td>6</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

Table 5.1 Simulation results with different control response frequencies
5.2 Results of SimHydraulic Model

Based on the yoke angle ($\omega_n = 1.5$) obtained previously with Simulink, the results of flow rate and pressure are shown in Fig 5-7, and the results of yoke angle, torque and power are shown in Fig 5-8.

![Output1](Image)

**Figure 5-7 Plots of flow rate and pressure ($\omega_n = 1.5$)**

As the yoke angle controls the displacement of HPMU, the load (torque of HPMU) increases immediately and reaches the designed value. However, it cannot remain till the operation completed since the pressure through the HPMU rises up not as quick as designed in the Simulink model. This may because different equations about the accumulator are used. Therefore, the power of HPMU which is the product of speed and torque is not constant.
Figure 5-8 Plots of yoke angle, torque and power ($\omega_n = 1.5$)

The results obtained by SimHydraulic model verified the yoke angle created by Simulink model could produce the required power. The discrepancy of the results of SimHydraulic and Simulink are within the reasonable range since the equations within the SimHydraulic are not the same as the designed mathematical model with Simulink.

5.3 Results Analysis

The above results show that the designed EMB system has the capability of capturing energy with a power of 150 kW for around 90 sec. To further verify that the designed PI controller could also be used under other conditions, some parameters within the model will be changed. Additionally, the relations of these parameters are
obtained to help further discovering the characteristic of the designed EMB system.

For the designed EMB system, there are four parameters independent and changeable, the power, shaft speed, maximum pressure of the accumulator and fluid volume for the accumulators. When any three of them are given, the rest parameter is determined.

The operation time and the required power can be changed based on the need. The maximum pressure can be designed from 5000 psi to 1000 psi. Then, the fluid volume will be determined.

![Figure 5-9 Relation of the maximum pressure and operation time (150 kW, 198 gal)](image)

To charge 198 gal of fluid to the accumulators with a power of 150 kW, the duration of operation time will be known for a given maximum pressure of the accumulator, shown in Fig 5-9. As the maximum pressure is reduced, the duration of operation time decreases. This means that it takes less time to charge the EMB for the accumulator to reach to a lower maximum pressure.
The operation time of EMB and the fluid volume of the accumulators have a linear relation, shown in Fig 5-10. To charge the accumulator to 5000 psi with a power of 150 kW, the volume of the fluid to charge the accumulators can be determined based on the operation time. In addition, more fluid is needed to keep the energy capturing for a longer duration.

![Figure 5-10 Relation of operation time and fluid volume (150 kW, 5000 psi)](image)

**Figure 5-10 Relation of operation time and fluid volume (150 kW, 5000 psi)**

Fig 5-11 shows the relation of required power and operation time for a given maximum pressure and fluid volume. As the required power increases, the duration of the operation time is shortened. This is because it takes less time to charge the same volume of fluid to the accumulator with a higher power.
The relation of power and maximum pressure cannot be directly obtained based on the model due to the operation time cannot be initiated to the model. However, we could make roughly estimation based on Equation 3.6; we are using to determine the fluid volume. The relation is given in Fig 5-12. For a given fluid volume and operation time, the power can be determined for any maximum pressure of the accumulator. And the power capability increases with an increasing maximum pressure.

The shaft speed is determined by the power, shown in Fig 5-13. As the required power increases, the constant shaft speed decreases. There exists a minimum power for each operation since the HPMU is required to be operated within the range
of 1500 rpm to 1800 rpm for keeping a high efficiency. In this case, the required power cannot be lower than 58 kW allowing the shaft speed less than 1800 rpm.

![Figure 5-13 Relation of power and shaft speed (198 gal, 5000 psi)](image)

5.4 Summary

The designed EMB system has the capability of capturing energy with a burst power (150 kW) for short duration (90 sec). The power capability of the designed EMB system is 150 kW, and the duration time can be shorten or extended as needed. While no validation has been presented herein, confidential pump/motor test data reviewed from a manufacturer support the results found from this simulation. Confidentiality must be maintained as the manufacturer considers the data just of these competitive advantage over other manufacturers.

There are four independent and changeable parameters within the designed EMB system, the power, shaft speed, maximum pressure of the accumulator and fluid volume for the accumulators. When any three of them are given, the remaining parameters can be determined.
Chapter 6 CONCLUSION AND FUTURE WORK

6.1 Conclusions

In this research, investigation into energy storage system for hybrid locomotives was presented and a hydraulic energy storage system, EMB, was given and analyzed to compare with other energy storage systems. To verify the capability of providing a burst power for a short period of time, the EMB system was simulated with MATLAB/SIMULINK and Simscape/SimHydraulic.

The control system of EMB was designed to create an appropriate signal to control the yoke angle of the HPMU. The created yoke angle was verified by the SimHydraulic model to obtain the results of required power and operation time.

In addition, four independent and changeable parameters within the EMB system were analyzed to further understand this designed energy storage system. The analysis showed the characteristic of the designed EMB system.

According to the analysis and simulations, the following conclusions were achieved:

(1) The designed control system cannot provide an efficient discharge process due to HPMU and EMGU operating at a very low speed.
(2) The designed control system can capture energy (charge) with high efficiency. The ability of capturing burst power for a short period of time was verified by those simulation models.

(3) To make the charge control system stable, the control response frequency of control system has to be higher than 1 Hz and less than 4 Hz. When lower frequency of the control system is chosen, smoother and better results of EMB can be produced.

6.2 Future Work

This research proves charge process can satisfy the power requirement and disprove discharge process can meet the requirement. However, it doesn’t mean there is no way to do so since the control system designed in this thesis is based on a transfer function control method. There might be another more complex control methodology that can produce a required power during discharge.

In the future, an experiment can be operated in the lab, and the practical efficiency of the HPMU and accumulator can be collected and added into the model to obtain more accurate results.
References


11. “Kiha E200 Hybrid Drive System for East Japan Railway Company Trains”,
    HITACHI Technology 2008-2009, P.24

12. Taketo Fujii, Nobutsugu Teraya, Mitsuyuki Osawa, “Development of an NE train”,
    special edition paper, By JR EAST technical Review- No.4, Japan, 2005


    propulsion system (ALPS) Project”, The University of Texas at Austin, Center
    for Electromechanics, p1-p4


17. Philippe Barrade, Blaize Destraz, Alfred Rufer, “Hybrid vehicle in railways
    applications: supercapacitive energy storage for diesel-electric locomotives”,
    Laboratory of Industrial Electronics, STI-ISELEI, Switzerland.


23. Arnold R. Miller, John Peters, Brian E. Smith, Omourtag A. Velev, “Analysis of
    fuel cell hybrid locomotives”, Journal of power sources, paper number


27. 

28. 
http://www.roymech.co.uk/Related/Pumps/Rotary%20Positive%20Displacement.html


30. “Axial Piston Variable Motor A6VM” data sheet, RE 91604/07.09, Rexroth Bosch Group


32. Mingwei Shan, “Modeling and control strategy for series hydraulic hybrid vehicles”, Electric Engineering and Computer Science Department, 2009, The
33. SimHydraulics® 1 Reference, by the MathWorks Inc

34. http://www.uprr.com/aboutup/history/loco/locohs03.shtml


37. http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/motdc.html

