ENERGY MANAGEMENT AND BATTERY TESTING FOR THE ANALYSIS OF A DIESEL-ELECTRIC HYBRID LOCOMOTIVE POWERTRAIN

A Thesis in

Mechanical Engineering

by

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ABSTRACT

Development of optimized control strategies to coordinate the internal combustion (IC) engine and battery system in series hybrid locomotives allow the advantages of the hybrid system to be fully realized. This work investigates the benefits of advancing control techniques that are state-of-the-art to more computationally involved strategies. By developing models and simulations of real world locomotive drive cycles, advanced control hybrid locomotives are evaluated.

Simulation of power management control strategies allows for fine tuning of the logic involved and benchmarking against state-of-the-art control strategies used today. In this work, a hybrid locomotive powertrain plant model is developed for the purpose of analyzing the effectiveness’ of different power management strategies. The logic of each control strategy is tuned and analyzed in software-in-the-loop (SIL) simulations. These control strategies are then applied to a physical battery system for hardware-in-the-loop (HIL) simulation. HIL simulation is especially valuable in the study of the performance of proposed control techniques on full scale hardware in real time. Analysis of HIL results is also used to validate the accuracy of the proposed models used for SIL simulations. Once the SIL model is known to be accurate, rapid simulation varying all significant parameters is implemented to gain an understanding if the hybrid design makes improvement over standard locomotives in service today. Results from these simulations are used to analyze the effectiveness of a proposed hybrid powertrain in meeting goals desired in the locomotive industry.
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<tr>
<td>Ahr</td>
<td>Amp-hours</td>
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<tr>
<td>DOD</td>
<td>Depth of Discharge</td>
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<td>HIL</td>
<td>Hardware in the Loop</td>
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<td>SIL</td>
<td>Software in the Loop</td>
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<td>IC</td>
<td>Internal Combustion</td>
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<td>ESS</td>
<td>Energy Storage System</td>
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<td>SOC</td>
<td>State of Charge</td>
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<td>SOH</td>
<td>State of Health</td>
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Chapter 1

Introduction

The layout of the common diesel-electric locomotive powertrain is ideally arranged for the adaptation of a series hybrid configuration. The hybrid diesel-electric locomotive utilizes the addition of an onboard energy storage system (ESS) in the form of batteries, capacitors, flywheels, or other means of energy storage. The added complexity of having more than one source of power to the traction motors requires the implementation of a power management strategy to ensure that the ESS and diesel-electric generator work as one optimized power source to the driving motors. Control strategies are developed based on the minimization of cost functions that are deemed significant for optimal vehicle performance.

Hybridization of a diesel locomotive, where energy is recovered during braking, is an effective method for decreasing fuel consumption. In a typical diesel locomotive, braking is performed using both an air brake system and a dynamic braking system. The air brakes are controlled as the locomotive engineer manually selects the braking pressure through a control lever. Friction between the brake shoes, which receives pressure from the air brake system, to the locomotive wheels slow the train. Dynamic braking is the system in which the traction motors polarity is switched. This in turn uses the forward rotation of the motor to apply torque in the reverse direction. In a non-hybrid application this current feeding back into the locomotive drive system must be forfeited in the form of thermal displacement through a resistive grid on the roof of the locomotive. The addition of an ESS utilizes the otherwise wasted energy by allowing the traction motors to charge the onboard ESS. Allowing the traction motors to capture the kinetic energy from the locomotive greatly reduces fuel consumption and workload of the diesel-electric generator.

The addition of an ESS requires a power management strategy to control the power-split between the diesel generator and ESS. Often, a strict rule-based (RB) strategy is used to command the ESS. As
shown by Guzzella et al.[1], the rule-based algorithm controls the output of the battery when specific conditions are met. The ESS operates based on its state of charge (SOC) in relation to the driver demand. This direct relation provides a simple and robust method of control however it does not provide minimization of fuel consumption due to the static logic of the control method.

Real-time optimization algorithms provide a means to more effectively minimize fuel consumption. A common method for power management in hybrid automobiles is the equivalent consumption minimization strategy (ECMS). In the ECMS, ESS output is dictated by relating the potential power output of the ESS to an equivalent fuel consumption rate from the diesel generator. The ESS is then commanded to output a proportion of the requested power based on the cost function that is set to be minimized. In this work, ECMS will be used to minimize only fuel consumption. The ability of ECMS to optimize the power management control of the hybrid powertrain in real-time is realized. However, the tradeoff between minimizing fuel consumption and operating the battery in a health conscious manner is of concern with this control technique.

Batteries serve as the most common form of ESS for hybrid locomotives and in this work a lithium nickel-manganese-cobalt battery system is used. State-of-health (SOH), which is a measure of the degradation of the capacity of the battery over time, is important for long term viability of any hybrid application. A strategy to account for upcoming power needs is developed to operate the battery in a steady-state current output mode as often as possible. The derived forward-looking- control (FLC) takes advantage of the predetermined nature of a locomotive drive cycle. Taking into account a known incoming power demand, the FLC provides a method of control for overly aggressive battery cycling and commands the battery output in such a way that minimizes negative SOH effect upon the battery. This additional control parameter allows the operator of the locomotive to determine the level of importance of each cost function. The value of fuel consumption and battery life vary due to the economic factors that determine them.
Testing the developed power management control strategies over an actual locomotive load profile is important in determining which strategy most effectively minimizes the predetermined cost functions of fuel consumption and effect upon battery SOH. The speed and ease of parameter modification of SIL allow for a vast array of simulation to be completed for analysis. The multitude of simulation scenarios also allow for predictions to be made about the operational situations where hybridization will be most effective.

HIL testing allows for validation of the SIL model. This is accomplished by analyzing the real performance of the proposed battery hardware against the battery model used in SIL simulations. Testing on hardware requires a laboratory setup that includes a full scale battery system that is to be implemented into a hybrid locomotive. The complexity of the actual battery system makes HIL testing a valuable tool for identifying possible inadequacies in the model. Hardware testing provides further confidence that the developed control logic functions as expected on a physical system. With HIL results that closely resemble the outcomes from SIL simulation, a greater level of assurance can be placed on SIL testing.

The following chapters will highlight the steps taken to develop power management control strategies to optimize the functioning split between a diesel generator and onboard ESS. The setup of the hardware testing facility will be discussed and the interface between the battery system and various other test components will be explained. The procedure to run simulations in both SIL and HIL will be described. Results from these simulations will be analyzed and the bridge between SIL and HIL results will be explained. Last, statements about the information gathered from this work in regard to the real-world implications of running hybrid locomotives against traditional locomotives will be discussed.
Chapter 2

Literature Review

2.1 Hybrid Locomotives

As the rise in energy demand continues, so does the need for more efficient and renewable forms of energy. The aim of hybrid and electric vehicle technology is to cut back on one of the largest consumers of carbon energy, the transportation industry. In order to push the development of hybrid and electric technologies, regulations at the federal and state levels have been implemented to penalize manufacturers of carbon emitting power systems [2]. These regulations have deadlines to meet specific emissions levels and have led to the implementation of hybrid technologies in many industries as a segue way to ultimate solution of becoming completely fossil fuel independent.

The locomotive layout provides for a simple transition to a hybrid powertrain. Most line haul freight locomotives in operation use a diesel generator to traction motor propulsion system which is the basis for a series hybrid configuration from the IC engine side [3]. This configuration is used in the locomotive industry due to the simplicity of a straight mechanical drive, the lack of maintenance needed for a large electrical DC series wound motor, and the ability to use the motors as braking mechanisms (giving the possibility of regenerative braking). The interest in hybrid locomotives has grown for this reason and the reduction in fuel consumption for line haul freight locomotives is estimated to be as high as 15% when using a hybrid powertrain [4].

Battery systems have already proven to be an ideal storage method for locomotives due lower special confinement in the locomotive application, which allows for many battery modules to be connected in a series configuration. Thus, an ESS utilizing large battery systems can meet both the power and capacity requirements to meet typical locomotive demand. The Norfolk Southern NS 999 is an example of the capability of battery powered locomotives. The NS 999 was unveiled at the Juniata Locomotive
Shop in Altoona, PA in 2009. This locomotive was all-electric, therefore released zero carbon emissions. The NS 999 is a switcher locomotive which hauls trains onto different sets of tracks at locomotive yards.

![NS 999 under test at Rose Yard in Altoona PA.](image)

**Figure 1:** NS 999 under test at Rose Yard in Altoona PA.

### 2.2 Power Management Control Strategies

The added complexity of the hybrid propulsion system creates the need for supervisory control of the torque split between the diesel-electric generator and the onboard battery ESS. However, optimization of the power management control can be extended beyond just the torque split to consider the minimization of fuel consumption, and further reducing carbon emissions, which is the driver for implementing hybrid technologies [5]. A variety of power management control strategies has been proposed for hybrid systems with varying levels of optimality and robustness. Factors such as computational time, a priori knowledge of the driving pattern, and ability to optimize for the desired cost function dictate the approaches that can be considered [6]. Being that the locomotive drive cycle is extremely well known due to the confinement of tracks, the opportunity to optimize the hybrid powertrain is even more apparent when compared to other modes of transportation.
For this work, three control strategies are chosen to be developed and implemented for the purpose of a hybrid locomotive. These strategies are chosen because they lend particularly well in a hybrid locomotive application. These strategies mentioned earlier in Chapter 1 consist of both rule-based and optimization-based strategies. The variety in the complexity is desired to show the payoff of implementing optimal control techniques. Power management control strategies for hybrid platforms are classified by level of optimization. Figure 2 shows this organization and the strategies to be investigated are boxed. This chart shows how control strategies are organized by optimization type and then method of optimization.

Figure 2: The power management control strategies for hybrid platforms [6].
2.3 Hardware-in-the-Loop as a Validation Tool

HIL simulation is a process in which real components can be, individually or in combination, tested via simulations of expected operational conditions. This engineering process is becoming increasingly popular as it provides a cost effective and rapid measure of hardware performance before full product testing is performed [7]. For the testing of a battery system, HIL gives the ability to show that the battery model used in SIL simulations is valid. Running both SIL and HIL simulations over an identical simulation cycle gives a measure of the fidelity of the SIL model and highlights the shortcomings in a model [8]. Beyond this, HIL is a useful tool to validate that the proposed control strategy properly effects the hardware as expected. HIL testing of particular portions of full scale systems drastically shortens troubleshooting of complex system control issues.
Chapter 3

Development of Hybrid Locomotive Powertrain Model

In order to analyze the effectiveness of the power management control strategies, a representative hybrid locomotive powertrain model must be developed. The configuration of the components in the hybrid locomotive model are based on the Norfolk Southern Hybrid Locomotive Concept [4]. The MATLAB/Simulink environment was used as the main tool to develop the locomotive powertrain model to be used in simulation.

![Norfolk Southern Hybrid Locomotive Concept](image)

**Figure 3:** Norfolk Southern Hybrid Locomotive Concept [4].

3.1 Hybrid Locomotive Powertrain Configuration

The hybrid locomotive power plant consists of a turbocharged diesel engine coupled to a main generator and companion alternator. The main generator is a high voltage system which provides the power for tractive effort. Importantly, the amount of consumed fuel is directly proportional to the generator output power and this relation will be used for calculation fuel offset by the ESS. A map of fuel consumption map for a 4,000 hp generator used in typical NS freight locomotives is used for this purpose. The power generated drives DC traction motors. The traction motors can also be used for regenerative
braking, which charges the onboard ESS. The battery ESS used in this work consists of large format lithium – nickel manganese cobalt (Li-NMC) battery modules connected in series. This battery system will be discussed in more detail in sections to come. Alternatively, the traction motors can dump energy through a dynamic resistor bank on the roof of the train. This energy is dissipated to the ambient environment in the form of thermal energy. The input of the energy sources to the tractive motors is controlled by a controller unit. This controller manages the power split of the propulsion components as well as controls dynamic braking.

3.2 Component Modeling

Power demand and time are the only inputs into the powertrain model. This input of power is chosen because it is readily available data from locomotives in service and gives a simple means of controlling both the IC- generator and battery system as well as providing a direct relation from battery
output power to amount of diesel fuel offset by the battery. Typically, a full plant model of the entire locomotive would be used in industry for simulation and testing of components and systems. A full plant model would take into account many factors such as train length, weight, specific operational characteristics of each hardware component onboard the locomotive, a driver model, among other aspects of the locomotive system. For the scope of this work, creating such a system is not necessary to estimate the magnitude of the effect the addition of an ESS will have on the powertrain performance. Also, the simple powertrain model provides a rapid method to acquire informative SIL and HIL simulation results to analyze the effectiveness of powertrain management control strategies.

This power demand is the culmination of actual data obtained from locomotives in operation performing typical line-haul freight trips. The power demands over various drive cycles was provided by Norfolk Southern Corporation for the development of the power split control algorithms to perform hybrid locomotive trip simulations. Figure 5 shows the system diagram of the necessary components to model to achieve accurate simulation of a hybrid-electric locomotive.

Figure 5: Top level of hybrid locomotive model for simulation.
3.2.1 Power Split Control

As the power demand to the traction motors is input into the power split model, a control strategy, predetermined by the user, is initiated. The developed power management control strategies in this work, as described in Chapter 1, are RB, ECMS, and FLC. The algorithm logic continually determines the power split to the diesel generator, battery, and dynamic brake. The control strategies will be discussed in more detail in the following section and a basis for why each strategy would be used is established.

The controller determines the split of the power by taking into account battery characteristics at the present time, primarily battery SOC. All power requested of the battery is in kW. The power demand is sent to a control system which will use these battery characteristics and determine the battery power output. Power demand that the battery cannot meet is requested of the diesel generator or dynamic brake. In this way, each power management control strategy is used to relate the total locomotive power demand to a battery output calculation. After the battery output is determined, then the generator and dynamic brake outputs are controlled.

Before the control logic can be performed on the power demand, a safety buffer to manage battery output at the SOC extremes is used. Figure 6 shows this buffer which will place a gain upon the battery power demand in order to ramp down the demand when the battery is at SOC limits.
The power gain for the charge and discharge power is determined by a model that analyzes current battery SOC in relation to the demanded power. If the battery is inside the SOC buffer, the gain linearly grows to zero as the SOC reaches the limit extremes. This buffer can be set to any desired level; Figure 7 shows the SOC buffer control system.

The buffer is set to take effect when battery SOC comes within 10% of its set maximum and minimum SOC. The buffer sets a gain to the power demanded as follows:

Figure 6: SOC limit avoidance buffer.

Figure 7: SOC limitation avoidance control.
When battery SOC, in % of total capacity, is within 10% of SOCmax (upper SOC limit) or SOCmin (minimum SOC limit),

\[
\text{Charge Power Gain} = \frac{SOC_{\text{max}} - SOC_{\text{present}}}{0.1 \times SOC_{\text{max}}}
\]

\[
\text{Discharge Power Gain} = \frac{SOC_{\text{present}} - SOC_{\text{min}}}{0.1 \times SOC_{\text{min}}}
\]  

(1)

This method of setting a buffer on the power demand received by the battery allows for control of the rate at which the battery SOC reaches its limitations. Upon passing through the SOC buffer the power demand can then be processed by the selected power management control strategy.

### 3.2.2 Rule-Based Control

RB strategies provide a simple method of power management in hybrid applications. The strategy is also very robust and can be easily manipulated and tuned for a wide range of battery performance characteristics.

In this work, a strict RB algorithm dictates the amount of power commanded to the battery based on a predetermined charge and discharge proportion. A gain is set to the battery power demand that is directly related to the instantaneous battery SOC. This logic effectively limits the power output from the battery to be maximized as the battery reaches its full SOC. Conversely, the battery will not aid the diesel generator as it approaches its lower SOC bound. Figure 8 shows the RB model. The power output is the power that will be requested from the battery. Split percentages are tuned based on simulation performance to use the RB control most effectively.
Here, battery power out is dictated by a predetermined charge or discharge gain. The eventual power demanded from the battery equates to:

In charge,

\[ \text{Battery Power} = (1 - \text{SOC}_{\text{present}}) \times \text{RB charge gain} \]  \hspace{1cm} (2)

In discharge,

\[ \text{Battery} = \text{SOC}_{\text{present}} \times \text{RB discharge gain} \]  \hspace{1cm} (3)

The RB strategy is a robust real-time control that is often used for hybrid power management [1]. The purpose of such a control strategy is to provide a simple yet effective means of implementing a hybrid system with high level of confidence that the battery will and within desired operational
tolerances. The performance of the RB control in simulation serves as a benchmark to quantify the improvements that optimized control methods serve.

### 3.2.3 Equivalent Consumption Minimization Strategy

The ECMS is a real-time online control method derived from the Pontryagin Minimization Principle. In this work, a form of ECMS is developed for the series hybrid application, focusing only on the minimization of fuel consumption. The form of ECMS tailored for this work originates from the work of L. Serrao et al. [3].

The objective of the ECMS is to find a solution to reach a predetermined goal SOC. The algorithm references the current power demand and makes a battery output decision proportional to the difference between the current battery SOC and the desired goal SOC. The algorithm logic determines the ideal battery power output corresponding to the combined potential generator and battery power outputs. This relation gives the ideal ECMS power split, in terms of minimizing fuel consumption, between diesel generator and ESS and this split is then applied to the power demanded in the model.

The ECMS control has several parameters for tuning. Proportional and integral gains in the algorithm can be changed to more or less aggressively decrease the difference between current and goal SOC. The goal SOC itself can be manipulated. Setting a goal SOC at the lower bound of the SOC operating range commands the controller to discharge the battery completely if the battery has an energy capacity to meet that demand. The goal SOC can also be set in between the bounds of the SOC range, therefore commanding the controller to act in a charge sustaining mode and demanding less energy output from the battery.
Global optimality is equivalent to the instantaneous problem of minimizing the Hamiltonian:

\[ u^*(t) = \arg \min_u \langle H(x, u, t) \rangle \]  \hspace{1cm} (4)

where \( u^* \) is the optimal solution, \( x \) is the state vector, \( u \) the control vector, and \( t \) is time. In the simplified form of ECM for HEVs, where fuel consumption is the only cost function, the Hamiltonian is the summation of the power generated from fuel and an equivalent power from the battery:

\[ H(\xi, u, t) = P_{\text{fuel}}(u, t) + s(t) \cdot P_{\text{ech}}(\xi, u, t) \]  \hspace{1cm} (5)

where \( P_{\text{fuel}} \) is fuel power, \( P_{\text{ech}} \) is electrochemical power (discharge power), \( \xi \) is battery SOC, \( \xi_{\text{ref}} \) is SOC desired final value, and \( u \) is the control vector. The power from both fuel and battery are defined as follows:

\[ P_{\text{fuel}}(u, t) = Q_{\text{lhv}} \hat{m}_f(u, t) \]  \hspace{1cm} (6)

\[ P_{\text{ech}}(\xi, u, t) = -\dot{s}(t) \cdot \frac{1}{Q_b} I_b(\xi, u, t) \]  \hspace{1cm} (7)

where, \( Q_b \) is battery charge capacity, \( Q_{\text{lhv}} \) is the constant fuel energy density, \( I_b \) is the battery current, and \( \dot{m} \) is diesel fuel mas flow rate. \( \dot{s}(t) \) is the co-state variable defined as:

\[ \dot{s}(t) = -E_b \cdot s(t) = -V_{\text{oc,max}} Q_b s(t) \]  \hspace{1cm} (8)

where, \( V_{\text{oc,max}} \) is the maximum battery open circuit voltage, \( E_b \) is battery total energy content, \( s(t) \) is the equivalence factor which weight the battery power with respect to fuel power. In order to solve for the
equivalence factor, a feedback estimation method can be used and implemented online as the ECMS
control logic. The feedback estimation takes the form of a PI control:

\[ s(\xi, t) = s_0 + k_p (\xi_{ref} - \xi(t)) + k_i \int_0^t (\xi_{ref} - \xi(\tau)) d\tau \]  \hspace{1cm} (9)

Using this PI feedback estimation, the optimal split between generator and battery by relating the power
requested to the current battery SOC by:

\[ u^* = Q_{thv} \dot{m}(u, t) + V_{oc, max} I_b(\xi, u, t)[s_0 + k_p (\xi_{ref} - \xi(t)) + k_i \int_0^t (\xi_{ref} - \xi(\tau)) d\tau] \]  \hspace{1cm} (10)

The equivalent power from the battery is determined by the energy content per gallon of diesel: 1
gallon of diesel = 128,450 BTU/gallon = 37.64 kWh/gallon. Accounting for locomotive system
efficiency, 1 gallon of diesel = 20.80 kWhr [4].

The power demand requested by the battery can be seen in the ECMS control model in figure 9.
Here using the above ECMS equations the proportion of the power split determined for battery power is
set as the output power command to the battery. Using this logic, the battery is controlled to seek the set
goal SOC during discharge.
The ECMS algorithm can effectively reduce fuel consumption over the strict RB algorithm. This is achieved by minimizing the combined diesel generator and battery outputs to meet the desired power demanded by the locomotive drive cycle. However, the ECMS does not recognize the effect on battery life as a control parameter. The inclusion of battery SOH into the cost function that is to be optimized requires additional control.

### 3.2.4 Forward Looking Control

The FLC control algorithm takes advantage of the prior knowledge of the fixed drive cycle that locomotives typically perform. FLC offers several desirable degrees of control that the other control strategies do not provide.
One of the advantages of FLC is that the algorithm can be tuned to operate the diesel generator in a steady state manner. This ability is beneficial in decreasing fuel consumption and it also is shown to reduce emissions by reducing transient diesel ICE operation [4]. This operational mode forces the battery to “fill” the power demand that the steady-state generator does not meet.

Alternatively, this control can also be used to operate the battery with steady-state charge or discharge current. This uses the diesel generator to “fill” the excess power demand that the battery does not meet. This allows for ideal battery cycling and greatly enhances the degradation rate on the battery. This mode will be used in simulation since the effect on SOH is quantifiable by the existing battery model.

Along with this, FLC is useful in sustaining SOC so that the locomotive will never encounter a situation in which the battery is depleted. This is beneficial in the case where long cycles of positive power demand occur and the ESS would be more useful if it did not deplete midway through the cycle. Rather, FLC can identify these cycles and charge the battery in preparation for such an event. The top level of the drive cycle for FLC can is shown in figure 10. Here the power demand from previous journeys over this same trip is used to identify potential charge and discharge regions as well as the amount of energy available to output or capture over those cycles.

Figure 10: Drive Cycle Preprocessing for FLC.
Knowing the energy available for charge or discharge, the length of the event, and the battery capabilities, a constant charge or discharge current for the cycle can be calculated. This model is shown in figure 11.

**Figure 11:** FLC model to operate at steady state battery current.

This FLC model executes the following logic:

1) Reads the expected energy for charge or discharge in the current cycle from knowledge of past journeys over the same trip.

2) Calculates an average charge or discharge power for the duration of the cycle using the available energy and duration of event.

3) Reads battery SOC at the beginning of the event and calculates the amount of energy the battery can charge or discharge.

4) Sets the power target based on steps 2 and 3. In other words, the power is limited so the battery is not over charged/discharged.
Safety checks are also performed in the FLC control to ensure that the charge and discharge event length is significant to initiate a new current command. If the potential energy for charge or discharge does not exceed a value deemed useful in the control parameters, the event is neglected and the battery is controlled to operate at maximum output to minimize fuel consumption as much as possible.

Ultimately, knowing some information about upcoming loads, specifically, braking events, allows for a more efficient use of stored energy as well as a more effective preparation for upcoming charge events. With planned stops preprogrammed, even mode switching is possible. In other words, steady state battery operation can be used for a selected portion of the cycle and steady state generator operation can be used for another portion, thus ensuring that the ESS is fully charged prior to a lengthy stop to allow for a reasonable engine shut down during this event. Engine emissions are largely dependent on startup events. Often revving of the diesel engine is used to quickly start moving stationary cars. A steady state diesel operation with high ESS load can significantly reduce consumption and emissions during such phases. Note, it is not the scope of this work to measure emissions but to offer a quantifiable offset in diesel consumption, which offsets the emission otherwise released by combustion.

To quantify the benefits of this FLC algorithm, a power profile of a NS 4,000 hp road locomotive was used. Knowing the future power consumption and ESS regeneration opportunities, a FLC strategy can be created. This work aims to quantify this benefit.

Some goals of FLC include:

1) Limit discharge rates during events in which there is more opportunity to discharge than energy stored in the ESS. This will decrease negative effects on the battery system.

2) The primary objective of the battery system is to charge as much as possible from available brake energy, however, if possible this rate may also be limited if the duration of the event is reasonably long and contains more than enough energy for long enough to fully charge the ESS.
3) Prepare for long idle events. Limit discharging for tractive effort so that engine shut down is possible while maintain full locomotive functionality, even tractive effort, with in limitations. OR limited tractive effort.

3.2.5 Battery Model

The proposed battery system for use in the locomotive hybrid powertrain is a pack of high power Li-NMC battery modules. A setup of 16 Li-NMC battery modules are housed at the Penn State Test Track and are used as the energy storage platform for the proposed hybrid locomotive system. Using battery characterization testing an accurate battery model of the string of t Li-NMC battery modules in series is used for SIL simulations. Each module consists of 24 cells each cell operating at $V_{\text{max}}$ of 4.2 volts. Each module is rated for 6.7 kWhr of capacity. The battery system was limited to a 300-amp peak continues discharge for all testing. Hybrid pulse power characterization (HPPC) testing and capacity testing provide the data used for lookup tables within the battery model. In HIL testing, this model is replaced with the full scale Li-NMC battery system. The battery model is necessary to test that commanded battery output from the power management controllers are as expected before implementing battery hardware.
HPPC testing is intended to determine dynamic power capability over the device’s useable voltage range using a test profile that incorporates both discharge and regen pulses. The primary objective of this test is to establish, as a function of depth-of-discharge,

1) The voltage minimum discharge power capability at the end of a 10 second discharge current pulse.

2) The voltage maximum regeneration power capability at the end of a 10-s regen current pulse.
In Figure 13 above, the current pulsations can be seen. Pulses for charge and discharge were held at 150 amps for a duration of 10 seconds in order to determine the battery voltage response.

HPPC testing allows for equivalent series resistance (ESR) tables to be created for charge and discharge cycles over the entire SOC range of the battery system. This is the basis for creating an accurate model of the battery for SIL simulation. These power and energy capabilities are then used to derive other performance characteristics such as charge-sustaining available energy, available power, and charge-depleting available energy. Figure 13 shows the derived fixed cell resistance and cell polarization resistance as a function of SOC with sufficient resolution to reliably establish cell voltage response time constants during discharge, rest, and regenerative operating regimes.
The resistance measurements will be used to evaluate resistance degradation during subsequent life testing and to develop hybrid battery performance models for vehicle systems analysis. Using the HPPC results a battery model was developed for SIL simulations.

Multiple capacity tests on the Li-NMC battery were performed to monitor battery SOH as it degrades over cycling. The battery is estimated to be capable of 100,000 cycles at 30% depth of discharge (DOD), although an accurate cycle life needs to calculated with all factors incorporated. The battery under test has a manufacturer reported capacity of 150 Amp hours for full DOD. Testing did not yield a capacity as high as stated due to limiting the charge to around 93% SOC to prevent overcharging.
Using the battery characteristics from testing, a battery model defined by voltage drop in relation to ohmic resistance as a function of SOC is created for use in simulation. The model, as shown in Figure 16, determines the present state of battery voltage of the battery via lookup table corresponding to $V_{oc}$ and charge/discharge resistance.

**Figure 15:** Li-NMC AT-6700 module capacity testing.

**Figure 16:** Battery model formulated on characterization testing.
Here Ohm’s Law is consistently used to determine battery voltage and current outputs based on the battery characterization testing.

For battery Voltage,

\[ V_{batt} = V_{oc} - V_{ESR} \]  \hspace{1cm} (11)

where \( V_{ESR} \) in relation to battery SOC is defined from HPPC testing.

Current output is determined in the battery model again, utilizing Ohm’s Law. For SIL simulation variables are placed for manipulation of the size of the battery system that is to be used. The battery system tested during HPPC and capacity testing is deemed one string, each string being equal to 16 modules in series. By increasing the number of strings, the simulation is able to account for various battery sizes which is useful in determining the necessary system size for particular locomotive trips.

![Diagram](image)

**Figure 17:** Battery current model.

For battery current per string,

\[ I_{Bat} = \frac{P_{Request} \times V_{cell} \times \text{number of cells}}{\text{number of strings}} \]  \hspace{1cm} (12)

Using this current model, SOC can be estimated. A simple SOC model is developed using the tested battery capacity. The integration of the batter output current a relation can be drawn between the amount of energy displaced from the battery with respect to total battery capacity.
For battery SOC,

\[
SOC = \frac{\int I_{Bat} dt}{Total \ string \ capacity}
\]  

(13)

An additional important element of the battery model is the model to determine the total energy dissipated and regenerated by the battery. Energy is calculated by the integration of power discharged and power charged for energy offset and energy captured respectively.

3.2.6 Diesel Generator Model

The diesel generator model accounts for all power demanded that the battery cannot meet. This is modeled by forcing all power demand above battery capability to be sent into the generator model which converts a power demand into a fuel flow rate to the ICE. Power in kW from the generator is translated
into fuel consumption for later use in comparison of the effect on fuel consumption of each control strategy. It is important to note that this generator model does not take into account combustion emissions and transient engine operational effects on the combustion efficiency so these effects are not accounted for in the equations quantifying diesel fuel used in simulation. The generator fuel consumption is based on the data received from Norfolk Southern for a 4,000 hp freight locomotive.

![Diagram](image)

**Figure 20:** Diesel generator model.

### 3.2.7 Dynamic Brake Model

Dynamic braking provides the method of capturing kinetic energy under braking for storage in the ESS. Dynamic braking is used during normal operation as an assist to air braking systems in order to
slow down the locomotive more effectively. Dynamic braking is often used as the locomotive travels on a negative grade. The dynamic braking model simply monitors all negative power demanded from the traction motors in the power profile over the drive cycle used in simulation. Negative power corresponds to braking scenarios that, without hybridization, would be wasted in the form of thermal energy. Energy captured from dynamic braking charges the battery for later use.

![Dynamic brake model diagram]

**Figure 21**: Dynamic brake model.

### 3.2.8 Other Model Features

The locomotive power management control also includes several feedback systems to monitor voltage, current, SOC limits, and temperature limits. For SIL simulation these monitors may be redundant but when implemented for HIL testing these monitors serves as a battery management system (BMS) in backup of the existing BMS on the Li-NMC pack. This is needed to ensure the power management controller is usable for other battery systems that do not have built in BMS monitoring control.
Chapter 4

Hardware in the Loop Setup

The HIL setup allows for the full scale battery system, thermal chamber, locomotive powertrain plant model, power processing machine, and supervisory computer to interface for simulations. A CANbus network is established for the communication between all components and for data logging purposes. The Matlab Simulink Real-Time target computer contains the power management control which is the interface between the power processing machine (AeroVironment AV900) and the battery system. Figure 18 shows the full setup including thermal-chamber for the Li-NMC battery.

Figure 22: The HIL setup with all components.

4.1 Simulink-Real-time Target

The key component in this setup is the Simulink Real-Time target (SLRT) computer with communication to both the AV900 and battery system. This system acts as the power management controller, running the locomotive powertrain model and managing the interface between the AV900
power processing machine and the battery system. The target computer simulates the locomotive powertrain and functions as the power management control which in turn dictates the amount of power the AV900 can source/sing from the battery system.

![Diagram](image)

**Figure 23**: Interface diagram of HIL testing station.

A supervisory computer serves as the human to simulation interface. From this machine the simulation parameters, data logging instructions, power processing machine parameters, and thermal chamber parameters can be set and set and monitored. Measurements for specific CAN signals and the related data base files are also created on the supervisory computer which is used in post-test analysis.
Hardware communication is enabled following CAN protocol. First, communication must be established between the SLRT and AV-900. CAN messages are created specifically for the AV-900 that include the current command, as well as several “watch dogs” to ensure that the AV-900 and HIL simulation are in sequence.

### 4.2 CAN Setup

Controller Area Network or CAN bus is a communication bus used so that controllers can communicate with one another and to hardware components throughout a vehicle. In the HIL setup 4 CAN nodes are established to allow the SLRT, AV-900, Li-NMC battery pack, and supervisory computer to receive and send signals to one another.
All CAN signals are first created and mapped into a data base (.dbc). CAN messages are identified by their hexadecimal ID. Each CAN message can contain up to 8 bytes of information. All relevant signals to the HIL testing were created to be sent and received over the CAN bus.

![CAN Message ID]

<table>
<thead>
<tr>
<th>CAN Message ID</th>
<th>CAN Signal Name</th>
<th>CAN Signal Properties</th>
<th>Orientation in Message</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 25: CAN message setup.]

4.2.1 SLRT CAN communication

The SLRT environment has the ability to unpack and pack CAN message to be used in the powertrain model. This allows any element of the model used for simulation to be monitored and sent to the other CAN nodes. This is particularly useful in communication with the Li-NMC BMS to read cell temperatures, voltages, current, SOC, and other characteristics.
Figure 26: Battery CAN signal unpacked into SLRT.

All communication to the AV-900 is performed by reading specific signal output from the SLRT to control the machine. The AV-900 has its own software to follow the power demand from the simulation.

4.2.2 Battery CAN Setup

Battery communication must be established. In order to connect to the battery safely, CAN signals emulating an emergency brake and key switch are created. The battery cannot connect until these CAN signals are received by the battery. Placing either signal in a low state opens a corresponding relay which cuts the emergency brake or key switch signal to the SLRT controller.
Figure 27: Emergency stop and Key in CAN signals.

Once, relays are closed the battery CAN node is connected to the network and can send and receive signals. Battery status is monitored and high voltage connection to the AV-900 power processing machine is now possible.

The SLRT controller and powertrain plant model CAN messages must be established and sent to the AV-900 and Li-NMC battery. These messages include battery monitoring, current output, battery characteristics, and many safety limitations among others. The generator and dynamic brake models remain as they are for SIL simulations and the battery model is replaced with the Li-NMC Hardware. CAN messages are monitored in real time and logging the desired signals allows for post processing of the HIL simulations.

All CAN signal data is logged and processed after the simulation is completed. Specifically, battery characteristics are important to check the validity of the SIL battery model. CAN communication provides an effective means of both receiving status of hardware and modeled components as well as sending status and commands to hardware.
4.2 Thermal Chamber and Battery System

The battery system is enclosed in an ESPEC ETC-200L thermal chamber for simulation of thermal management. The Li-NMC battery system is composed of a string of 16 modules and the Li-NMC battery management system (BMS).

![Figure 28](image)

**Figure 28:** Li-NMC battery system.

The thermal chamber allows for testing of the battery in various ambient conditions. The Li-NMC BMS monitors cell temperatures and has built-in safety monitors to limit the battery performance at extreme temperatures. The battery system is liquid cooled via a chiller system that keeps the battery in a safe operating temperature in extreme ambient temperatures. Conditions for HIL testing varied from 7°C-38°C. This variety of ambient temperature also allows the chiller energy consumption to be monitored to estimate the additional power output required to run the chiller system at elevated temperatures.
4.3 Aerovironment AV-900 Power Processing Machine

The AV900 Electrical Loading Device gives the hardware simulation the capability to meet battery power output capabilities. This machine is capable of operating continuously up to 1000 Amps, at 1000 Volts, and up to 250 kW. The AV900 has the benefit of having automatic cutoff switches in the case of power outage or operation exceeds load capabilities. The AV900 allows for high power operation of the battery up to the limitations mandated by the battery management system. This machine is capable of sinking and sourcing all current that the power management controller demands. The AV900 also has its own software that includes built in safety monitoring so that the machine does not output current that could be potentially dangerous in the case of hardware or communication failures. Figure 10 shows the HIL test setup and all of the components incorporated for simulations.

![AV-900 power processing machine.](image)

**Figure 29:** AV-900 power processing machine.
The AV-900 is capable of operating up to 900 Volts, 500 Amps, or 250 kW during testing. However, these settings are changed for the operation of the Li-NMC battery due to its limitation of a 300-amp peak charge or discharge current. Scripts for operating the AV-900 for HIL testing can be found in the appendix.

### 4.4 HIL Test Procedure

The HIL test procedure implements a startup procedure to run the desired test. By following the startup procedure, HIL tests follow the same simulation constraints as SIL testing but with physical hardware in place of modeled components. The startup procedure is as follows:

1. Turn on and prepare software packages (Matlab, Vector CANoe, Aerovironment ROS) for desired test.
2. Ensure CAN communication is linked between all devices (target controller, battery, AV900, data logging and test management computer).
3. Ensure battery is conditioned to proper temperature and initial charge.
4. Set test parameters such as SOC range, controller parameters, environmental parameters, power profile, battery limits.
5. Prepare Vector CANoe software to log desired data.
6. Prepare ROS scripts to run desired test.
7. Connect all hardware and ensure communication is successful.
8. Begin data logging.
9. Begin power profile.
10. Check frequently to ensure the test is running as expected.

11. Once the test is finished, conduct shutdown procedure of all devices
Chapter 5

Initial SIL Simulation Results

Simulations show the advantages and disadvantages of each strategy over the same drive cycle. Most importantly, the fuel consumption and effect on battery SOH will discussed. After initial SIL testing is performed HIL will be used to check the validity of the SIL model. HIL gives another degree of confidence in the robustness of the power management control strategy and gives a measure of the accuracy of the SIL simulations used for further analysis of the hybrid locomotive system. This chapter discusses initial SIL simulation results of each power management control strategy only and provided the data to properly plan HIL testing.

For the simulations, Norfolk Southern provided power profile data from a locomotive running freight from Atlanta to Memphis and returning to Atlanta. This profile is used to compare all control strategies and determine the most effective method. Simulations are then performed using the most effective method of control over various drive cycles using multiple control parameter setting including battery size, SOC range, and ambient temperature to name a few.

5.1 SOH Loss Model

Having an SOH loss estimation that closely represents what can be expected from the battery system in this work is essential to ranking the most effective control strategy. Battery capacity fading varies for different battery chemistries as well as many operational factors. There has been a great deal of focus on lithium-ion battery degradation recently as they become more popular for use in the automotive and consumer electronics industries among others.
The SOH loss proposed by Wang et al. was used in this work for the estimation of the battery capacity degradation over each simulation [9].

\[ Q_{loss} = B \cdot \exp\left(\frac{-E_a}{RT}\right)Ah^z \]  

(14)

Here, \( Q_{loss} \), is the percentage of capacity lost, \( B \) is the pre-exponential factor, \( E_a \) is the activation energy in J/mol, \( R \) is the gas constant in J/mol K, \( T \) is the absolute temperature of the battery, \( Ah \) is the amp-hour throughput (number of cycles\times DOD\times cell capacity), and \( z \) is the power law factor.

5.2 Diesel Offset and Generator Diesel Use

Using the battery output over the simulation the power management control’s effectiveness in minimizing the most the cost function of diesel fuel consumed can be analyzed. 1 gallon of diesel = 20.80 kWhr will again be used to relate battery output to a diesel fuel equivalence. Other important results from simulations include power error (power deviating from power profile), diesel consumption without ESS, potential diesel offset, potential regenerative energy, and current, voltage, and power from all energy systems.

5.3 Power Management Control Comparison Simulations

Each controller is simulated over a real world drive cycle with modulated terrain. Identical simulation and battery parameters are loaded into the simulation. The following tables highlight the most important settings for the SIL controller performance comparison testing.
Table 1: SIL Comparison Simulation Parameters.

<table>
<thead>
<tr>
<th>Test Type</th>
<th>SIL Controller Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Profile</td>
<td>Atlanta Memphis Atlanta Profile 1</td>
</tr>
<tr>
<td>Control Type</td>
<td>RB Control, ECMS, FLC</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>65 Hours</td>
</tr>
<tr>
<td>Battery Used</td>
<td>Li-NMC AT-6700 Model</td>
</tr>
</tbody>
</table>

Table 2: SIL Comparison Battery Parameters.

<table>
<thead>
<tr>
<th>String Capacity</th>
<th>139.2 Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial SOC</td>
<td>80%</td>
</tr>
<tr>
<td>Max SOC</td>
<td>80%</td>
</tr>
<tr>
<td>Min SOC</td>
<td>20%</td>
</tr>
<tr>
<td>Max Charge Current</td>
<td>300 A</td>
</tr>
<tr>
<td>Max Discharge Current</td>
<td>300 A</td>
</tr>
<tr>
<td>Max Module Voltage</td>
<td>4.1 V</td>
</tr>
<tr>
<td>Min Module Voltage</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Number of Strings</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 30: Atlanta-Memphis-Atlanta power profile.

5.3.1 Rule Based SIL Results

The RB strategy shows high frequency cycling of the battery along with long periods of time spent at the lower bound of SOC range. The large amount of time at low SOC is due to the rule based logic in that, whenever positive power is demanded, the battery will discharge. With the drive cycle requiring primarily positive power, the battery commanded to meet that demand whenever possible.
Using the RB strategy, the battery performance is the least effective of the three simulated strategies. This is seen in figure 4 as the RB strategy offsets only 7.5% of the energy used in this drive cycle. At low SOC the battery cannot operate with large discharge currents like it would at a higher SOC.

Interestingly, the energy regenerated is also the lowest of the three strategies. Again, the RB algorithm is conservative in the sense that the battery is not commanded to perform at its operational limits unless it is at an ideal SOC. With so much time spent near the lower SOC bound the RB algorithm is conservative when it does have the opportunity to charge.
Table 3: RB strategy results.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Discharge Energy</td>
<td>34.04 MWhr</td>
</tr>
<tr>
<td></td>
<td>= 1636.6 gallons</td>
</tr>
<tr>
<td>Potential Regenerative Energy</td>
<td>8.107 MWhr</td>
</tr>
<tr>
<td>Energy Offset by Battery</td>
<td>2.67 MWhr</td>
</tr>
<tr>
<td></td>
<td>= 128.62 gallons = 7.85% of possible</td>
</tr>
<tr>
<td>Energy Captured</td>
<td>2.266 MWhr</td>
</tr>
<tr>
<td></td>
<td>= 31.48% of possible</td>
</tr>
<tr>
<td>Generator Diesel Consumption</td>
<td>1508.7 gallons</td>
</tr>
<tr>
<td>SOH Loss</td>
<td>0.2601%</td>
</tr>
</tbody>
</table>

5.3.2 Equivalent Consumption Minimization

The goal SOC for the ECMS is tuned to 35% as it provides the best results in simulation. ECMS is much more effective in utilizing the ESS in simulation. It is observed in figure 5 that the ECMS strategy utilizes the SOC range more than the RB strategy in that the battery cycles from full charge to full discharge.

Figure 32: ECMS SOC vs time.
Using the ECMS, all performance metrics are improved over the RB strategy. This is seen in figure 6 as the energy offset improves 3.9% of the energy required by the drive cycle. The effect upon battery life is also improved over the RB strategy.

The functionality of the charge sustaining attribute of ECMS can be seen as the SOC oscillates around 40% SOC. This setting was selected as it allows a high level of diesel offset while not being as harmful to battery life by spending large amounts of the drive cycle at the minimum SOC.

Also to be noted, is the predictable charge and discharge cycling pattern that is seen with ECMS. The battery output is mainly a function of the difference between goal SOC and current SOC. This allows for the control method to not pulse from maximum charge to maximum discharge levels rapidly which is the main reason this control method is better for battery health than RB control.

<table>
<thead>
<tr>
<th>Table 4: ECMS SIL results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Discharge Energy</td>
</tr>
<tr>
<td>Potential Regenerative Energy</td>
</tr>
<tr>
<td>Energy Offset by Battery</td>
</tr>
<tr>
<td>Energy Captured</td>
</tr>
<tr>
<td>Generator Diesel Consumption</td>
</tr>
<tr>
<td>SOH Loss</td>
</tr>
</tbody>
</table>
5.3.3 Forward Looking Control

The forward looking control method applied here is to operate the battery in a steady state manner. This means the control method should command the battery to output a constant current as often as possible. The logic here is to recognize discharge and charge cycles, then apply a constant current over that cycle to reach either a discharge or charge respectively. This FLC is used to operate the battery in a fashion that is more decreases negative SOH effects that occur in aggressive control strategies while also resulting in minimal fuel consumption.

![FLC SIL SOC vs time.](image)

**Figure 33:** FLC SIL SOC vs time.

In observing the SOC over the simulation, FLC effectively discharges the battery completely just as each discharge cycle ends, rather than quickly discharging and sitting at a minimum SOC which is an issue with the other control methods. Charge cycles are also more effective as often the power profile allows for charging at a maximum rate. This allows all possible available regenerative energy to be captured by the ESS.
The proper functionality of the steady state battery operation is more easily seen in figure 29. This is a visual of the current command over a small time window.

![Figure 34: FLC SIL Current vs time.](image)

FLC recognizes charge and discharge events and commands an average current over the cycle to operate the battery in a steady state manner. The benefit of this can be seen in the much lower negative effect on battery SOH. This is achieved by eliminating rapid charge and discharge cycling as well as commanding constant current levels during these cycles.
Table 5: FLC SIL results.

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Discharge Energy</td>
<td>34.04 MWhr = 1636.6 gallons</td>
</tr>
<tr>
<td>Potential Regenerative Energy</td>
<td>8.107 MWhr</td>
</tr>
<tr>
<td>Energy Offset by Battery</td>
<td>3.922 MWhr = 188.57 gallons = 11.52% of possible</td>
</tr>
<tr>
<td>Energy Captured</td>
<td>3.526 MWhr = 43.5% of possible</td>
</tr>
<tr>
<td>Generator Diesel Consumption</td>
<td>1448.1 gallons</td>
</tr>
<tr>
<td>SOH Loss</td>
<td>0.173%</td>
</tr>
</tbody>
</table>

It can be seen that FLC performs better than other control strategies in SIL simulation in terms of the two cost functions that are of most importance (diesel fuel consumption, SOH degradation). These results are consistent over various drive cycles. While FLC slightly outperforms ECMS when it comes to diesel offset, it is controls the battery in such a way that is much more beneficial for battery life.

**Figure 35**: SIL comparison of diesel offset.
In looking more closely at the current output of both the ECM and FLC methods we can see the reason for discrepancy in effect upon battery life. Figure 37 shows this comparison. The targeted charge and discharge regions are clear and FLC controls battery output at a constant current output during these cycles. The average lower C rate and minimal cycling of the battery is clearly different from the ECM control and gives reason for the differing SOH effect with respect to the battery degradation model.

Figure 36: Current vs Time of FLC and ECM simulations.

<table>
<thead>
<tr>
<th>SOH Effect</th>
<th>RB</th>
<th>ECMS</th>
<th>FLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOH Effect</td>
<td>0.2601%</td>
<td>0.3176%</td>
<td>0.173%</td>
</tr>
</tbody>
</table>

Table 6: SIL SOH effect comparison.

FLC is used for HIL simulations as it is best suited to meet the desired performance goals. Further SIL simulations are also performed to analyze the feasibility of hybrid locomotives.
Chapter 6

HIL Simulation and Analysis

FLC is used in all HIL simulations since it proves to be the power management control strategy with the best level of performance. To compare the HIL and SIL simulations a series of tests were run varying battery and control factors. The factors included were: initial SOC, battery DOD, input load profile and ambient temperature.

6.1 HIL Test Plan

The test plan derived for the HIL simulation of the Li-NMC battery system ensures a thorough variation of conditions so to check the validity of the SIL model. Among SOC and temperature variation, three separate Atlanta to Memphis to Atlanta power profile data sets were used. The following table shows the test plan for HIL.

Table 7: HIL test plan.

<table>
<thead>
<tr>
<th>Run Order</th>
<th>Load Profile</th>
<th>SOC_Range</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>±30</td>
<td>7°</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>±15</td>
<td>7°</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>±30</td>
<td>38°</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>±15</td>
<td>38°</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>±15</td>
<td>38°</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>±30</td>
<td>-7°</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>±15</td>
<td>7°</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>±30</td>
<td>38°</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>±30</td>
<td>38°</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>±30</td>
<td>-7°</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>±15</td>
<td>38°</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>±15</td>
<td>7°</td>
</tr>
</tbody>
</table>
6.2 HIL Results

Analysis of results from HIL show that the power management control and battery performance match closely with that produced in initial SIL simulations. Importantly, comparing battery characteristic between HIL and SIL simulations confirm an accurate battery model.

Figure 37: HIL and SIL SOC comparison.

In taking a closer look at the discrepancies in SOC, we can see that the source of error stems from the fact that the battery hardware does not charge as quickly as the battery model and also discharges more rapidly under the same power command. Figure 38 shows this graphically.

Figure 38: A closer look at SOC differences.
Results from both HIL and SIL testing of the HIL test plan show that the SIL overestimates the battery input by about 8%. These differences stem from unaccounted for battery dynamics in which the Li-NMC BMS corrects SOC estimation when the battery reaches resting voltage over periods where the simulation commands little battery input. However, the differences are acceptable considering the length that the length of simulations last up to 65 hours. The SIL model is deemed useful for more in depth analysis of the potential of the hybrid locomotive powertrain. The following tables show the outcome of the HIL tests.

Table 8: HIL-SIL Energy offset

<table>
<thead>
<tr>
<th>Test</th>
<th>SIL (MWhr)</th>
<th>HIL (MWhr)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.85</td>
<td>3.28</td>
<td>14.96</td>
</tr>
<tr>
<td>2</td>
<td>2.97</td>
<td>3.19</td>
<td>-7.41</td>
</tr>
<tr>
<td>3</td>
<td>3.85</td>
<td>3.66</td>
<td>4.94</td>
</tr>
<tr>
<td>4</td>
<td>2.97</td>
<td>2.89</td>
<td>2.69</td>
</tr>
<tr>
<td>5</td>
<td>2.76</td>
<td>3.04</td>
<td>-10.14</td>
</tr>
<tr>
<td>6</td>
<td>3.58</td>
<td>3.28</td>
<td>8.38</td>
</tr>
<tr>
<td>7</td>
<td>2.76</td>
<td>3.05</td>
<td>-10.51</td>
</tr>
<tr>
<td>8</td>
<td>3.58</td>
<td>3.05</td>
<td>14.90</td>
</tr>
<tr>
<td></td>
<td><strong>3.21</strong></td>
<td><strong>3.18</strong></td>
<td><strong>3.34</strong></td>
</tr>
</tbody>
</table>

The resulting energy offset from simulations is used to determine how much fuel is potentially displacing by the battery system. It will be shown in the following chapter how this metric is important to determine the value of an added ESS and the potential benefits of using a larger sized ESS.

Energy offset results prove to be very accurate between HIL and SIL simulation. However, the precision of individual simulations varies more greatly. These results give confidence that the SIL model can be used for large batch simulations to evaluate energy offset levels for locomotives over drive cycles of various length and power demand magnitude.
Energy captured under regenerative dynamic braking is overestimated by the SIL model. It is important to note that this discrepancy is in part due to BMS SOC correction during HIL simulation which causes SOC estimations in HIL is more conservative.

The overestimation for energy captured is consist and is built in to future SIL data processing to show both the expected result from HIL simulation and that which is recorded from SIL simulation.

SIL simulation are used for emission and financial analysis of a perspective hybrid locomotive in the next chapter. Significant assessments of the hybrid locomotive feasibility are able to be made due to the validation of SIL simulation from these HIL tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>SIL(MWhr)</th>
<th>HIL(MWhr)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.50</td>
<td>2.82</td>
<td>19.32</td>
</tr>
<tr>
<td>2</td>
<td>2.77</td>
<td>2.29</td>
<td>17.27</td>
</tr>
<tr>
<td>3</td>
<td>3.50</td>
<td>2.82</td>
<td>14.54</td>
</tr>
<tr>
<td>4</td>
<td>2.77</td>
<td>2.14</td>
<td>16.86</td>
</tr>
<tr>
<td>5</td>
<td>2.53</td>
<td>2.24</td>
<td>11.13</td>
</tr>
<tr>
<td>6</td>
<td>3.08</td>
<td>2.32</td>
<td>11.46</td>
</tr>
<tr>
<td>7</td>
<td>2.53</td>
<td>2.24</td>
<td>11.41</td>
</tr>
<tr>
<td>8</td>
<td>3.08</td>
<td>2.29</td>
<td>25.65</td>
</tr>
</tbody>
</table>

**2.92**  **2.40**  **17.97**
Chapter 7
SIL Simulation for Hybrid Feasibility

Confidence established through HIL testing of the SIL model is utilized to perform a more thorough analysis of the feasibility of the hybrid locomotive design for real world application. Of course, when relating the environmental effect carbon emission cause, any fuel that can be offset through non-toxic emission is obviously beneficial. However, at the time of this work, fuel prices have been notoriously unstable and has led to speculation that fuel prices may not rise to levels that induce the locomotive industry to be driven to adopt the hybrid platform. This chapter will focus on where the prospect of implementing hybrid locomotives into service stands in present economic conditions.

7.1 SIL Factorial Batch Simulation

A large batch of simulations is used to gather the necessary data to engage in economic analysis. A full factorial design of experiment is conducted to investigate the effects of multiple battery pack and control system parameters. The factorial parameter consist of the following:

1) Power factor (number of battery strings)
2) Battery DOD
3) SOC range
4) Load profile input (3 Atlanta-Memphis-Atlanta profiles and 3 Chicago-Conway-Chicago)

In total 72 simulations were conducted to approximate typical North American freight train trips over varying topography and ambient conditions.
### 7.2 Emission Reduction

By decreasing the amount of energy demanded from the diesel generator over, the ESS in turn reduces overall emissions over each load profile. The emissions for the hybrid powertrain application were calculated for a typical Tier 0 emissions 4,000hp road locomotive. A figure displaying the simulation factors and total emissions (CO2 in lbs/year) is shown in figure 36.

![Multi-Vari Chart for Poll Offset by SoC Range - Power Factor](image)

**Figure 39:** Emission offset for SIL factorial [4].

It is shown that emission reduction is highly dependent upon battery system size and the amount of elevation change throughout the load profile. Undulating terrain gives the opportunity to use regenerative braking to recharge the ESS so emissions are more greatly reduced in such scenarios. By increasing the ESS size and allowable DOD emissions continue to be reduced. The above figure is useful in identifying that particular geographic trips, those with large and frequent elevation changes, may be ideal for the implementation of the hybrid platform with respect to emission reduction.
7.3 Financial Analysis

In determining the financial benefits of the hybridized locomotive, the annual cost savings of the Li-NMC battery system were analyzed with respect to its proposed lifetime of 100,000 hours at full DOD. The cost of upgrading existing locomotives to a hybrid platform along with the accompanying additional electronics that would be needed are not included in this analysis. These annualized costs were offset with savings from reduced fuel use as calculated from simulations. Fuel consumption in these simulations are a reflection of what can be expected from the proposed hybrid electric powertrain. The annualized cost figure below was calculated with a battery cost of $1250/kW-hr and a fuel cost of $3.00/gallon of diesel fuel. The $1250/kW-hr cost estimate of the battery pack is a reference to the proposed battery system used in HIL testing.

Figure 40: SIL factorial battery cost.

![Multi-Vari Chart for Total Cost by SoC Range - Power Factor](chart)

Panel variable: Power Factor
The cost benefit figure shows that fuel offset alone cannot cover the cost of implementation of any sizing or operation of the proposed battery system. It is shown that smaller battery systems, leading to lower initial cost, along with operation over less demanding terrain is the most economically feasible scenario for the hybrid powertrain at the current moment. However, Lithium battery prices continue to drop while the performance from these systems increase, leading to further interest for the hybrid electric powertrain design in the near future.

An analysis of the best case simulation of the proposed hybrid electric powertrain with respect to annual cost savings gives a picture of the economic conditions necessary for feasible implementation. The figure below shows the annual savings that can be expected with respect to varying battery and fuel costs.

![Hybrid Locomotive Annual Savings](image)

**Figure 41**: Annual savings for proposed hybrid locomotive.
With projections for Li ion battery prices to drop to around $250/kWh by year 2020, the hybrid application has great potential to become desirable for widespread use. Fuel prices are the obvious driver to induce the financial benefits that would lead to further rapid development of the hybrid locomotive platform.
Chapter 8
Conclusions and Future Work

The overarching goal of this work was to investigate the viability of the hybrid locomotive through HIL and SIL simulation. A hybrid locomotive powertrain model was developed to share the load typically experienced in common freight locomotive journeys. SIL simulations of various proposed power management control strategies were used to determine the most effective means of splitting load between the main diesel generator driver and the onboard ESS. FLC utilizing the well-known nature of previous duty cycles from locomotives performing the same trip proved to be an effective means of hybrid power management. HIL simulations demonstrated satisfactory model fidelity to give motivation for further SIL simulations to be conducted. Economic viability and emissions performance were assessed to give a clarify the prospect benefits of the hybrid locomotive solution. CO2 Emission reduction from hybridization range from 3,000lbs to 12,000lbs annually and cost savings vary from -$50,000 to -$300,000 depending geographical operation and ESS sizing. Although fuel cost savings alone cannot offset the cost of converting existing locomotive to the hybrid platform, a strong case is presented that hybridization may be economically beneficial in the near future.

The creation of a full locomotive plant model would be valuable for both precision and depth of SIL simulation. The existing powertrain model relies on past locomotive duty cycle data and does not allow for simulation of locomotives that use hardware that differs from those that provided the load profiles. This model is also limited to specific geographical trips for this same reason. A thorough plant model would include modeling of specific hardware components especially the diesel generator, traction motors, dynamic braking system components, and air brake systems. The ability to vary train length, driver tendencies, and environmental factors would also be of great value for simulation analysis.

The developed FLC was shown to be ideal for power management of this hybrid locomotive model. Extensions could be made to further optimize this control strategy with a more developed
locomotive plant model. Enhancing the model to make real-time decisions based on the disturbance from the predicted data would allow for the battery charge and discharge cycling to become more accurate. Also, a mode to transition the locomotive into full EV mode could greatly enhance fuel savings. Even at idle, the 4,000 hp diesel generator consumes a considerable amount of fuel. This EV mode could be used when the battery is at high SOC and the upcoming demand is well within battery capability.
References


Appendix A: Simulink Models

This is only an illustration of high level models. More detail can be found by accessing the digital file.

Figure 42: SIL Model

Figure 43: Power Split Top Level
Figure 44: Feedback Controls

Figure 45: SOC Buffer and Control Selector
Figure 46: RB Control

Figure 47: ECMS Control
Figure 48: SOC Limitation Management

Figure 49: FLC Top Level
Figure 50: Battery Model Top Level
Appendix B: AV-900 Scripts

CAN Control
/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 % Pennsylvania State University %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/

FILENAME: CAN_Controlled

DESCRIPTION: This script will allow CAN control of the AV900

REFERENCES: Include any references used for your script if applicable.
  1. AV-900 Manual 06503-03E
  2. ROS Scripting Manual 06633-03_A
  3. AeroVironment CAN Programming Insert
  4. AV900_extended_frame_11_2_15.dbc

DATE AUTHOR REVISION
2-November-2015 Timothy Cleary New Version

/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 % Variable Initialization %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/
/* CAN watchdog variables */

#global float current_time_stamp = 0;
#global float delta_time = 0;
#global int CAN_Watchdog = 0;
#global float CAN0_delta_time = 0; /* init delta time can message */
#global int CAN0_CAN_Watchdog = 0; /* init watchdog can message */

/* Miscellaneous Variables */

#global int TimerID_High = 0;
#global int TimerID_Medium = 0;
#global int TimerID_Low = 0;

/* %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/

% CAN Communication Setup %

/* %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/

/*NOTE - #Custom:LSBFirst only defines input CAN messages. All output are always Motorola (MSB)*/

/* CAN Messaging Setup */

#request name=CAN0 /* requesting name for CAN port */
#Custom:LSBFirst /* MSBFirst = Motorola type of CAN message for Intel its LSBFirst */

/* No timestamp variables */

/* #NoTimestamps */

/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/

/* The following messages are received by ROS */
/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/

/* BUG - must add 0x2 to all extended fram id’s. So 0x18FF212D is 0x38FF212D. */

#CANSetupLink _Min_Cell_Voltage, 0x38FF212D, 4, u16, 0.001
#CANSetupLink _Max_Cell_Voltage, 0x38FF212D, 0, u16, 0.001

#CANSetupLink _Allowed_Current, 0x1F6, 0, i16, 0.1
#CANSetupLink _Current_Enable, 0x1F6, 2, u8, 1,

/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/

/* The following messages are sent by ROS    */

/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/

/* AV900 Status_1 Message */
#CANSetupEncoding *ABCCurrent,i32,0.01, 0.0
#CANSetupEncoding *ABCVoltage,i32, 0.01, 0.0
#CANSetupMsg 0x27000000,8,*ABCCurrent,0,*ABCVoltage,4

/* AV900 Status_2 Message */
#CANSetupEncoding *ABCPower,i32, 0.1, 0.0
#CANSetupEncoding *ABCCommandMode,u8, 1.0, 0.0
#CANSetupEncoding *ABCStatus,u8, 1.0, 0.0
#CANSetupMsg 0x27000001,6,*ABCPower,0,*ABCCommandMode,4,*ABCStatus,5

/* AV900 Ah_1 Message */
#CANSetupEncoding *ABCAh,i32,0.01, 0.0
#CANSetupMsg 0x27000002,4,*ABCAh,0

/* AV900 Ah_2 Message */
#CANSetupEncoding *ABCAhIn,i32, 0.01, 0.0
#CANSetupEncoding *ABCAhOut,i32, 0.01, 0.0
#CANSetupMsg 0x27000003,8,*ABCAhIn,0,*ABCAhOut,4

/* AV900 kWh_1 Message */
#CANSetupEncoding *ABCkWh,i32,0.01,0.0
#CANSetupMsg 0x27000004,*ABCkWh,0

/* AV900 kWh_2 Message */
#CANSetupEncoding *ABCkWhIn,i32,0.01,0.0
#CANSetupEncoding *ABCkWhOut,i32,0.01,0.0
#CANSetupMsg 0x27000005,*ABCkWhIn,0,*ABCkWhOut,4

/* AV900 Limits_1 Message */
#CANSetupEncoding *ABCVmax,i16,0.1,0.0
#CANSetupEncoding *ABCVmin,i16,0.1,0.0
#CANSetupEncoding *ABCImax,i16,0.1,0.0
#CANSetupEncoding *ABCImin,i16,0.1,0.0
#CANSetupMsg 0x27000006,*ABCVmax,0,*ABCVmin,2,*ABCImax,4,*ABCImin,6

/* AV900 Limits_2 Message */
#CANSetupEncoding *ABCPmax,i16,0.1,0.0
#CANSetupEncoding *ABCPmin,i16,0.1,0.0
#CANSetupEncoding *ABCCommandValue,i32,0.01,0.0
#CANSetupMsg 0x27000007,*ABCPmax,0,*ABCPmin,2,*ABCCommandValue,4

/* AV900 Time Message */
#CANSetupEncoding *TestTime,u32,0.1,0.0
#CANSetupEncoding *CommandTime,u32,0.1,0.0
#CANSetupMsg 0x27000008,*TestTime,0,*CommandTime,4

/* Script Status Message */
#CANSetupEncoding _CAN_Watchdog,u8,1.0,0.0
#CANSetupEncoding _delta_time,u16,1.0,0.0
#CANSetupMsg 0x27000009,_CAN_Watchdog,0,_delta_time,1

/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/
/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/
void CAN_Watchdog_Function() {
    current_time_stamp = CAN0_Max_Cell_Voltage_t;
    delta_time = (TestTime - current_time_stamp);
    CAN0_delta_time = delta_time;

    if(delta_time < 10) { CAN_Watchdog = 5; }
    if(delta_time >= 10) { CAN_Watchdog = 10; }

    CAN0_delta_time = delta_time * 1000; /* Scaled to 0.001s resolution */
    CAN0_CAN_Watchdog = CAN_Watchdog;
}

/* High frequency updates */

void Timed_Functions_High() {
    CAN_Watchdog_Function();
    CAN0PostMsg(0x27000000);
    CAN0PostMsg(0x27000001);
    CAN0PostMsg(0x27000008);
    CAN0PostMsg(0x27000009);
}

/* Medium frequency updates */

void Timed_Functions_Medium() {
    CAN0PostMsg(0x27000002);
    CAN0PostMsg(0x27000003);
}
void main()
{
    /* Setup and Start Timers to send CAN Messages */
    TimerID_High = StartTimer(100, Timed_Functions_High());
    TimerID_Medium = StartTimer(1000, Timed_Functions_Medium());
    TimerID_Low = StartTimer(60000, Timed_Functions_Low());

    /* Set AV900 Limits */
    ABCVmin = 614; ABCVmax = 806; ABCImin = -400; ABCImax = 400; ABCPmin = -220; ABCPmax = 220;
    ChangeLimits();

    /* Battery testing starts here */
    Standby(0, CommandTime>10);
    Current(CAN0_Allowed_Current, CAN0_CAN_Watchdog == 10 || CAN0_Current_Enable == 0 || CAN0_Max_Cell_Voltage > 4.2 || CAN0_Min_Cell_Voltage < 3.2);
/* Battery Testing Complete */

Standby(0, CommandTime>5);

/* Stop Timers */

StopTimer(TimerID_High);
StopTimer(TimerID_Medium);
StopTimer(TimerID_Low);
}

/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                     Pennsylvania State University
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%/n
Full Charge

/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                     Pennsylvania State University
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%/n
COPYRIGHT 2015
Pennsylvania State University
Pennsylvania Transportation Institute
201 Transportation Research Building
University Park, PA 16802

75
FILENAME: Corvus_80SOC_Charge_v2

DESCRIPTION: This script will charge the Corvus pack to 80% SOC

REFERENCES: Include any references used for your script if applicable.

1. AV-900 Manual 06503-03E
2. ROS Scripting Manual 06633-03_A
3. AeroVironment CAN Programming Insert
4. NS_HIL_Controller.slx
5. SPC12127_1 Technical Specification, Pack Controller(PC120) Interface
6. C - Charging
   - Pack Maximum Charge Current message (PGN 65314 in SPC12113)
     - Do not exceed 4.18VDC (max cell)
     - 100% SOC defined as 4.18v and < C/20 current
6.8 Alarm Conditions
   - Charge, warning/error 4.210V/4.225V for 5 seconds
   - Discharge, warning/error 3.300V/3.200V for 5 seconds
7. Av900_Extended_Frame_11_2_15.dbc

DATE AUTHOR REVISION
07-May-2015 Timothy Cleary New Version
13-May-2015 Timothy Cleary Modified to generate power trace
                   and listen to current command
21-May-2015 Timothy Cleary Modified to run Corvus
22-July-2015 Timothy Cleary Revised to run Corvus HPPC based on SOC
28-July-2015 Timothy Cleary Modified to run various load capacity test
10-August-2015 Timothy Cleary Modified to cycle between 100 and 0% SOC
10-August-2015 Timothy Cleary Modified to run HPPC
11-August-2015 Timothy Cleary Modified to only charge
27-October-2015 Timothy Cleary Modified to run at 150 amps
11-November-2015 Timothy Cleary Updated CAN messages

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/
/** Variable Initialization */

/* CAN watchdog variables */
#global float current_time_stamp = 0;
#global float delta_time = 0;
#global int CAN_Watchdog = 0;
#global float CAN0_delta_time = 0; /* init delta time can message */
#global int CAN0_CAN_Watchdog = 0; /* init watchdog can message */

/* Miscellaneous Variables */
#global int TimerID_High = 0;
#global int TimerID_Medium = 0;
#global int TimerID_Low = 0;

/* CAN Communication Setup */

/* NOTE - #Custom:LSBFirst only defines input CAN messages. All output are always Motorola (MSB) */
/* CAN Messaging Setup */
#request name=CAN0 /* requesting name for CAN port */
#Custom:LSBFirst /* MSBFirst = Motorola type of CAN message for Intel its LSBFirst */

/* No timestamp variables */
/* #NoTimestamps */

/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/
/* The following messages are received by ROS  */
/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/

/* BUG - must add 0x2 to all extended fram id's. So 0x18FF212D is 0x38FF212D. */

#CANSetupLink _Min_Cell_Voltage, 0x38FF212D, 4, u16, 0.001
#CANSetupLink _Max_Cell_Voltage, 0x38FF212D, 0, u16, 0.001
#CANSetupLink _Max_Charge_Current, 0x38FF222D, 4, u16, 1.0
#CANSetupLink _SOC, 0x38FF202D, 3, u8, 1.0

#CANSetupLink _Allowed_Current, 0x1F6, 0, i16, 0.1
#CANSetupLink _Current_Enable, 0x1F6, 2, u8, 1,

/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/
/* The following messages are sent by ROS         */
/* ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~*/

/* AV900 Status_1 Message */
#CANSetupEncoding *ABCCurrent,i32,0.01, 0.0
#CANSetupEncoding *ABCVoltage,i32, 0.01, 0.0
#CANSetupMsg 0x27000000,8,*ABCCurrent,0,*ABCVoltage,4

/* AV900 Status_2 Message */
#CANSetupEncoding *ABCPower,i32, 0.1, 0.0
#CANSetupEncoding *ABCCommandMode,u8, 1.0, 0.0
#CANSetupEncoding *ABCStatus,u8, 1.0, 0.0
#CANSetupMsg 0x27000001,6,*ABCPower,0,*ABCCommandMode,4,*ABCStatus,5

/* AV900 Ah_1 Message */
#CANSetupEncoding *ABCAh,i32,0.01, 0.0
#CANSetupMsg 0x27000002,4,*ABCAh,0

/* AV900 Ah_2 Message */
#CANSetupEncoding *ABCAhIn,i32, 0.01, 0.0
# CAN Setup Encoding

* ABCAhOut, i32, 0.01, 0.0

# CAN Setup Msg

0x27000003, 8,* ABCAhIn, 0,* ABCAhOut, 4

/* AV900 kWh_1 Message */

# CAN Setup Encoding

* ABCkWh, i32, 0.01, 0.0

# CAN Setup Msg

0x27000004, 4,* ABCkWh, 0

/* AV900 kWh_2 Message */

# CAN Setup Encoding

* ABCkWhIn, i32, 0.01, 0.0

# CAN Setup Encoding

* ABCkWhOut, i32, 0.01, 0.0

# CAN Setup Msg

0x27000005, 8,* ABCkWhIn, 0,* ABCkWhOut, 4

/* AV900 Limits_1 Message */

# CAN Setup Encoding

* ABCVmax, i16, 0.1, 0.0

# CAN Setup Encoding

* ABCVmin, i16, 0.1, 0.0

# CAN Setup Encoding

* ABCImax, i16, 0.1, 0.0

# CAN Setup Encoding

* ABCImin, i16, 0.1, 0.0

# CAN Setup Msg

0x27000006, 8,* ABCVmax, 0,* ABCVmin, 2,* ABCImax, 4,* ABCImin, 6

/* AV900 Limits_2 Message */

# CAN Setup Encoding

* ABCPmax, i16, 0.1, 0.0

# CAN Setup Encoding

* ABCPmin, i16, 0.1, 0.0

# CAN Setup Encoding

* ABCCommandValue, i32, 0.01, 0.0

# CAN Setup Msg

0x27000007, 8,* ABCPmax, 0,* ABCPmin, 2,* ABCCommandValue, 4

/* AV900 Time Message */

# CAN Setup Encoding

* TestTime, u32, 0.1, 0.0

# CAN Setup Encoding

* CommandTime, u32, 0.1, 0.0

# CAN Setup Msg

0x27000008, 8,* TestTime, 0,* CommandTime, 4

/* Script Status Message */

# CAN Setup Encoding

_CAN_Watchdog, u8, 1.0, 0.0

# CAN Setup Encoding

_delta_time, u16, 1.0, 0.0

# CAN Setup Msg

0x27000009, 3,*_CAN_Watchdog, 0,*_delta_time, 1
void CAN_Watchdog_Function() {
    current_time_stamp=CAN0_Max_Cell_Voltage_t;
    delta_time=(TestTime - current_time_stamp);
    CAN0_delta_time = delta_time;

    if(delta_time < 10) { CAN_Watchdog=5; }
    if(delta_time >= 10) { CAN_Watchdog=10; }

    CAN0_delta_time = delta_time*1000; /* Scaled to 0.001s resolution */
    CAN0_CAN_Watchdog = CAN_Watchdog;
} /* High frequency updates */

void Timed_Functions_High() {
    CAN_Watchdog_Function(); CAN0PostMsg(0x27000000);
} /* High frequency updates */
/* Medium frequency updates */
void Timed_Functions_Medium() {
    CAN0PostMsg(0x27000002); CAN0PostMsg(0x27000003);
    CAN0PostMsg(0x27000004); CAN0PostMsg(0x27000005);}

/* Low frequency updates */
void Timed_Functions_Low() {
    CAN0PostMsg(0x27000006); CAN0PostMsg(0x27000007);
ChangeLimits();

Standby(0, CommandTime>10);

/* Battery testing starts here */

/* Charge to 80% SOC -----------------------------------------------*/

while (CAN0_SOC <= 80)
{
    WaitForABC();

    if(CAN0_Max_Charge_Current < 250){
        Current(CAN0_Max_Charge_Current,CommandTime > 1 || CAN0_Max_Cell_Voltage > 4.2);
    }

    if(CAN0_Max_Charge_Current >= 250){
        Current(250,CommandTime > 1 || CAN0_Max_Cell_Voltage > 4.2);
    }
}

Current(0,CommandTime > 60);

/* Battery Testing Complete */

Standby(0, CommandTime>5);

/* Stop Timers */

StopTimer(TimerID_High);
StopTimer(TimerID_Medium);
StopTimer(TimerID_Low);
}

/*%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Pennsylvania State University %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%*/
Appendix C: Matlab Initialization Simulation and Analysis Script

Init SIL

%% Simulation Setup
% sample_time = 0.1; Now defined in the load_run_plot.m file

%% Battery
% Units: %, Volts, Ohms, Ah, Amperes, Celsius, W

%% Corvus Pack Characterization Data
load('Supporting Information/Corvus_Pack_Characterization');
SOC_Index       = OCV_Map(:,1);
OCV_Map         = OCV_Map(:,2);
ESR_Charge      = interp1(ESR_Charge(:,1),ESR_Charge(:,2),SOC_Index);
ESR_Discharge   = interp1(ESR_Discharge(:,1),ESR_Discharge(:,2),SOC_Index);
% string_capacity = 140; %[Ah]
string_capacity = capacity_ah; %[Ah]

%% Axion Pack Characterization Data

% SOC_Index      = [0:10:100];
% OCV_Map        = [332.2000 353.7000 384.1000 414.0000 442.6000 470.4000 495.9000 521.1000 544.8000 569.7000 650.0000];
% ESR_Charge     = [0.3447 0.3060 0.2624 0.2321 0.2148 0.2090 0.2132 0.2263 0.2467 0.2766 0.4322];
% ESR_Discharge  = [0.2812 0.2741 0.2673 0.2642 0.2646 0.2681 0.2740 0.2824 0.2927 0.3058 0.3652];
% string_capacity = 51.25;

%% Model Parameters
nP_strings       = 3;
initial_SOC = 80;
initial_SOH = 1;
battery_life = 10000*string_capacity;
initial_voltage = interp1(SOC_Index,OCV_Map,initial_SOC);
pack_capacity = string_capacity * nP_strings;
ambient_temperature = 38;

% Control Parameters
min_SOC = 20;
max_SOC = 80;

min_module_voltage = 3.3;
max_module_voltage = 4.1;

min_current = -300; % discharge
max_current = 300; % charge

min_temperature = -40;
max_temperature = 50;

% Current Limiter
Min_Voltage_Limit = min_module_voltage;
Voltage_Limit_DischARGE = 2.8;

Max_Voltage_Limit = max_module_voltage;
Voltage_Limit_Charge = 3.8;

GainD = 1;
GainC = 1;
Peak_Rating_Discharge = -500;
Peak_Rating_Charge = 300;

Error_Latch_Time = 10;
%% Origional Controller (used in other controllers)
split_percentage_discharge = 30/100;
split_percentage_charge = 70/100;

%% Decay Controller
SOC_High = 65; [%]
SOC_Low = 35; [%]

%% EC Minimization ./ MCP

goal_SOC = 40; [%]
Kp = .5; [% We need to determine the best setting for this, It only slightly affects result
Ki = 0.1; [% Controls how aggressive (# of cycles) and how far overshoot will be

%Fuel consumption lookup data
fuel_rate = [0, 0.00293575, 0.00991603, 0.02110465, 0.05433029, 0.07448995, 0.10750139, 0.13275137, 0.15166365, 0.18042897];

%% Forward Looking

number_of_strings = nP_strings;

Ah_Capacity = capacity_ah; [% [Ah]

Max_SOC = max_SOC; [%]
Min_SOC = min_SOC; [%]

nominal_battery_voltage = 192 * 3.6; [% Volts]
Load and Run SIL

% Pennsylvania State University
% COPYRIGHT 2015
% Pennsylvania State University
% Pennsylvania Transportation Institute
% 201 Transportation Research Building
% University Park, PA 16802

% FILENAME: load_run_pot

% DESCRIPTION: load input and constants, run the HIL_Simulation model and
% plot results

% REFERENCES: Include any references used for your script if applicable.
% 1.
% 2.

% DATE          AUTHOR       REVISION
% 28-Jan-2015   Timothy Cleary    New Version
% 12/15/15      Andrew Wilson   New Model/Processed profile

% INPUTS: Provide description of script inputs if applicable.
% e.g. 1. Mass : System Mass (kg)
% 2. Acceleration : System acceleration

% OUTPUTS: Provide description of script outputs if applicable.
% e.g. 1. Force : Resultant Force (Newtons)
%% CLEAR ALL CLOSE ALL CLC
%
clear all; close all; clc;

%% INITILIZE CONSTANTS

init_12_8_15;

%% INITLIZE MODEL INPUT

load('Power Traces\Atlanta_Memphis_Atlanta_1 processed');
power_trace = kW;

%% Controller Select

% 1 = Fixed Power Split (Original Controller)
% 2 = Decay Controller to adjust gain on power split
% 3 = ECM
% 4 = MPC
% 5 = ECM on both charge and discharge

Controller_Selection = 6;

%% RUN SIMULATION

time = kW(:,1);
sim_time = time(end);
% sim_time = 5000;
step_size = 1;
sim('HIL_Simulation_ECM_MPC');

SOH_effect = (1-((capacity_wh*nP_strings/1000)-Battery_kWh_Out(end))/initial_SOH);

%% PLOT RESULTS
```matlab
plot_results_12_8_15;

 Plot SIL Result

%% Post Process

power_error = (((Battery_Power_kW... +Dynamic_Brake_Power_kW... +Generator_Power_kW)... -Power_Trace))./Power_Trace)*100;

gallons_diesel_offset = (abs(Battery_kWh_Out(end))) / 20.80;
gallons_diesel_locomotive = Total_Locomotive_Energy(end)/20.80;
gallons_diesel_generator = Generator_Energy(end)/20.8;
gallons_diesel_potential_regen = Potential_Regen_Energy(end)/20.8;
gallons_diesel_potential_offset = Potential_Discharge_Energy(end)/20.8;

Percent_Potential_Regen = (abs(Battery_kWh_In(end)/Potential_Regen_Energy(end)))*100;
Percent_Potential_Offset = (abs(Battery_kWh_Out(end)/Potential_Discharge_Energy(end)))*100;

%% SOH Calculator

Av_Battery_Current=mean(Battery_Current(Battery_Current<0));

C_Rate=abs(Av_Battery_Current)/capacity_ah;

SOH_Factor_Map=[41000;31630;21681;12934;15512];

C_Rate_Map=[1/10; 5; 2; 6; 10];

SOH_Factor=interp1(C_Rate_Map,SOH_Factor_Map,C_Rate);
```
count=0;
for k = 1:length(Battery_SOC)-1;
    if Battery_SOC(k)>= 50 && Battery_SOC(k+1) < 50;
        count=count+1;
    end
end

Ah_Factor=(0.8*count)^0.55;

%2369 is R (gas constant) times absolute temp (285K)
percent_loss_SOH=(SOH_Factor*exp(((31700+370.3*C_Rate)/2369))*Ah_Factor;

%% Energy content per gallon of diesel = 128,450 BTU/gallon = 37.64 kWh/gallon [US DoE, Alternative Fuels & Advanced Vehicles]
% Brent supplied number to also take in to account the locomotive system efficiency ... kWh/Gallon Diesel = 20.80

%% Plot Battery Results

p0=figure('Name','Control Parameters','NumberTitle','Off');

Parameters=[sim_time/3600;Controller_Selection;string_capacity;nP_strings;initial_SOC;max_SOC;min_SOC;max_current;min_current;max_module_voltage;min_module_voltage;ambient_temperature;Kp;Ki];

rnames={'Simulation Time (hr)', 'Controller Selection', 'String Capacity (Ah)', 'Number of Strings', 'Initial SOC', 'Max SOC', 'Min SOC', 'Max Current', 'Min Current', 'Max Voltage', 'Min Voltage', 'Ambient Temperature (C)', 'Proportional Gain', 'Integral Gain'};

cnames={'Value'};
table=uitable(p0,'Data',Parameters,...
    'ColumnName',cnames,...
    'RowName',rnames);
table.Position(3) = table.Extent(3);
table.Position(4) = table.Extent(4);

p02=figure('Name','Control Parameters','NumberTitle','Off');
Results=[Total_Locomotive_Energy(end);abs(Battery_kWh_Out(end));Battery_kWh_In(end);gallons_diesel_offset;abs(Potential_Regen_Energy(end));gallons_diesel_potential_offset;gallons_diesel_locomotive;gallons_diesel_generator;Percent_Potential_Regen;Percent_Potential_Offset;percent_loss_SOH];

r2names={'Energy Required For Cycle','Energy Offset (kWh)','Energy Captured (kWh)','Diesel Offset (gal)','Potential Regen Energy (kWh)','Potential Diesel Offset (gal)','Unaided Locomotive Diesel Use (gal)','Generator Diesel Use(gal)','% of Potential Energy Captured','% of Potential Energy Offset','SOH Loss (%)'};

c2names={'Value'};

table2=uitable(p02,'Data',Results,...
    'ColumnName',c2names,...
    'RowName',r2names);

table2.Position(3) = table2.Extent(3);
table2.Position(4) = table2.Extent(4);

p1=figure('Name','Battery','NumberTitle','Off');

subplot(4,1,1);
    plot(simulation_time/3600,Battery_Power_kW);grid on;
        xlabel('Time [Hour]');ylabel('Power [kW]');
subplot(4,1,2);
    plot(simulation_time/3600,Battery_Current);grid on;
        xlabel('Time [Hour]');ylabel('Current [Amperes]');
subplot(4,1,3);
    plot(simulation_time/3600,Battery_Voltage);grid on;
        xlabel('Time [Hour]');ylabel('Voltage [Volts]');
subplot(4,1,4);
    plot(simulation_time/3600,Battery_SOC);grid on;
        xlabel('Time [Hour]');ylabel('SOC [%]');

p2=figure('Name','Battery Limits','NumberTitle','Off');

subplot(4,1,1);
plot(simulation_time/3600,Battery_Min_SOC_Limit,...
    simulation_time/3600,Battery_Max_SOC_Limit);grid on;
    xlabel('Time [Hour]');ylabel('SOC Limit Logic');
    legend('Minimum','Maximum');

subplot(4,1,2);
    plot(simulation_time/3600,Battery_Min_Voltage_Limit,...
    simulation_time/3600,Battery_MAX_Voltage_Limit);grid on;
    xlabel('Time [Hour]');ylabel('Voltage Limit Logic');
    legend('Minimum','Maximum');

subplot(4,1,3);  %     subplot(3,1,1:2);
    plot(simulation_time/3600,Battery_Min_Current_Limit,...
    simulation_time/3600,Battery_Max_Current_Limit);grid on;
    xlabel('Time [Hour]');ylabel('Current Limit Logic');
    legend('Minimum','Maximum');

subplot(4,1,4);  % subplot(3,1,3);
    plot(simulation_time/3600,Battery_Min_Temperature_Limit,...
    simulation_time/3600,Battery_MAX_Temperature_Limit);grid on;
    xlabel('Time [Hour]');ylabel('Temperature Limit Logic');
    legend('Minimum','Maximum');

p3=figure('Name','Battery SOC','NumberTitle','Off');

  %     subplot(3,1,1:2);
    plot(simulation_time/3600,Battery_SOC);grid on;
    xlabel('Time [Hour]');ylabel('SOC [%]');

  % subplot(3,1,3);
    % plot(simulation_time/3600,Battery_Min_SOC_Limit,...
    %     simulation_time/3600,Battery_MAX_SOC_Limit);grid on;
    % xlabel('Time [Hour]');ylabel('SOC Limit Logic');
    % legend('Minimum','Maximum');
p4=figure('Name','Battery Voltage','NumberTitle','Off');

subplot(3,1,2);
plot(simulation_time/3600,Battery_Voltage);grid on;
xlabel('Time [Hour]');ylabel('Voltage [Volts]');

subplot(3,1,3);
plot(simulation_time/3600,Battery_Min_Voltage_Limit,...
simulation_time/3600,Battery_Max_Voltage_Limit);grid on;
xlabel('Time [Hour]');ylabel('Voltage Limit Logic');
legend('Minimum','Maximum');

p5=figure('Name','Battery Current','NumberTitle','Off');

subplot(3,1,2);
plot(simulation_time/3600,-Battery_Current,...
simulation_time/3600,Requested_Current);grid on;
xlabel('Time [Hour]');ylabel('Current [Amperes]');
legend('Battery','Requested');

subplot(3,1,3);
plot(simulation_time/3600,Battery_Min_Current_Limit,...
simulation_time/3600,Battery_Max_Current_Limit);grid on;
xlabel('Time [Hour]');ylabel('Current Limit Logic');
legend('Minimum','Maximum');

p6=figure('Name','Battery Current Limits','NumberTitle','Off');

subplot(3,1,2);
plot(simulation_time/3600,Battery_Voltage);grid on;
xlabel('Time [Hour]');ylabel('Voltage [Volts]');

subplot(3,1,3);
plot(simulation_time/3600,Battery_Min_Current_Limit,...
simulation_time/3600,Battery_Max_Current_Limit);grid on;
xlabel('Time [Hour]');ylabel('Current Limit Logic');
legend('Minimum','Maximum');

p7=figure('Name','Battery Temperature','NumberTitle','Off');
subplot(3,1,1:2);
plot(simulation_time/3600,Battery_Temperature);grid on;
xlabel('Time [Hour]');ylabel('Temperature [Celsius]');
subplot(3,1,3);
plot(simulation_time/3600,Battery_Min_Temperature_Limit,...
simulation_time/3600,Battery_Max_Temperature_Limit);grid on;
xlabel('Time [Hour]');ylabel('Temperature Limit Logic');
legend('Minimum','Maximum');

p8=figure('Name','Generator','NumberTitle','Off');
subplot(4,1,1);
plot(simulation_time/3600,Generator_Power_kW);
xlabel('Time [Hour]');ylabel('Power [kW]');grid on;
subplot(4,1,2);
plot(simulation_time/3600,Generator_Voltage);
xlabel('Time [Hour]');ylabel('Voltage [Volts]');grid on;
subplot(4,1,3);
plot(simulation_time/3600,Generator_Current);
xlabel('Time [Hour]');ylabel('Current [Amps]');grid on;
subplot(4,1,4);
plot(simulation_time/3600,Generator_Fuel_Flow_Rate);
xlabel('Time [Hour]');ylabel('Fuel Flow Rate [kg/sec]');grid on;

% Plot Power Results
p9=figure('Name','Power','NumberTitle','Off');

subplot(4,1:2);
plot(simulation_time/3600,Battery_Power_kW,...
    simulation_time/3600,Dynamic_Brake_Power_kW,...
    simulation_time/3600,Generator_Power_kW,...
    simulation_time/3600,Power_Trace);
xlabel('Time [Hour]');ylabel('Power [kW]');
legend('Battery','Dynamic Brake','Generator','Power Trace');
grid on;
str=['Energy Captured = ', num2str(Battery_kWh_In(end)),' [kWh]', ' Energy Offset = ', num2str(Battery_kWh_Out(end)), ' [kWh]', ' Diesel Offset by the Battery = ',num2str(gallons_diesel_offset),' [Gallons]';
title(str);

subplot(4,1,3);
plot(simulation_time/3600,power_error);
xlabel('Time [Hour]');ylabel('Power Error [%]');
grid on;
subplot(4,1,4);
plot(simulation_time/3600,Battery_SOC);grid on;
xlabel('Time [Hour]');ylabel('SOC [%]');

p10=figure('Name','Propulsion','NumberTitle','Off');

subplot(4,1,1);
plot(simulation_time/3600,Battery_Power_kW);
xlabel('Time [Hour]');ylabel('Battery Power');
legend('Battery');
grid on;
subplot(4,1,2);
plot(simulation_time/3600,Dynamic_Brake_Power_kW);
xlabel('Time [Hour]');ylabel('Dynamic Brake');
legend('Dynamic Brake');
grid on;
subplot(4,1,3);
plot(simulation_time/3600,Generator_Power_kW);grid on;
xlabel('Time [Hour]');ylabel('Generator Power');
legend('Generator');
grid on;
subplot(4,1,4);
plot(simulation_time/3600,Power_Trace);grid on;
xlabel('Time [Hour]');ylabel('Power Trace [kW]');

%% Power Gain

% subplot(2,1,1);plot(simulation_time,Charge_Power_Gain,simulation_time,Discharge_Power_Gain);
% subplot(2,1,2);plot(simulation_time,Battery_SOC);

% p10=figure('Name','Battery Current','NumberTitle','Off');
% histogram(Battery_Current,10)

%% Print to PDF

% print(p1,-dpdf);
% print(p2,-dpdf);
% print(p3,-dpdf);
% print(p4,-dpdf);
% print(p5,-dpdf);
% print(p6,-dpdf);
% print(p7,-dpdf);
% print(p8,-dpdf);
% print(p9,-dpdf);
% print(p10,-dpdf);
% Sort Data

time = I_OUT(:,1);
current = I_OUT(:,2);
V = V_BATT(:,2);
SOC=PC_SOC(:,2);

%%% Find Pulses

delta_current = time * 0;
for i = 2:length(current)
    delta_current(i) = abs(current(i) - current(i-1));
end

index=1;
delta_voltage = time * 0;
for i = 2:length(V)
    delta_voltage(i) = abs(V(i) - V(i-1));
    if delta_voltage(i) > 6
        point(index) = i-1;
        point(index+1) = i;
        index = index + 2;
    end
end
point = point';

%%% Plot data

figure(1)
subplot(2,1,1);plot(time,current);xlabel('time (seconds)');ylabel('current (Amps)')
subplot(2,1,2);plot(time,V);xlabel('time (seconds)');ylabel('Voltage (volts)')
% subplot(2,1,1);plot(time,current,time(point),current(point),'o');xlabel('time (seconds)');ylabel('current (Amps)')
figure(2)
subplot(2,1,1);plot(time,delta_current);
subplot(2,1,2);plot(time,delta_voltage);

%% Calculate Resistance and


R=dV./150;
ESR_discharge = R(1:2:57);
ESR_charge = [0,R(2:2:56)];

%% Create table of OCV, SOC, ESR

OCV = [800,788,780,772,765,759,752,745,739,731,725,719,715,711,708,705,702,700,697,694,691,689,686,682,679,675,670,666,660];

SOC_1=[interp1(OCV,SOC,800)
interp1(OCV,SOC,788)
interp1(OCV,SOC,780)
interp1(OCV,SOC,772)
interp1(OCV,SOC,765)
interp1(OCV,SOC,759)
interp1(OCV,SOC,752)
interp1(OCV,SOC,745)
interp1(OCV,SOC,739)
interp1(OCV,SOC,731)
interp1(OCV,SOC,725)
interp1(OCV,SOC,719)
interp1(OCV,SOC,715)
interp1(OCV,SOC,711)
interp1(OCV,SOC,708)
interp1(OCV,SOC,705)
interp1(OCV,SOC,702)
interp1(OCV,SOC,700)
interp1(OCV,SOC,697)
interp1(OCV,SOC,694)
interp1(OCV,SOC,691)
interp1(OCV,SOC,689)
interp1(OCV,SOC,686)
interp1(OCV,SOC,682)
interp1(OCV,SOC,679)
interp1(OCV,SOC,675)
interp1(OCV,SOC,670)
interp1(OCV,SOC,666)
interp1(OCV,SOC,660)];

\[\text{table(:,1)} = \text{OCV}; \text{table(:,2)} = \text{SOC}\_1; \text{table(:,3)} = \text{ESR}\_\text{charge}; \text{table(:,4)} = \text{ESR}\_\text{discharge};\]

%% plot ESR vs SOC

figure(3)

SOC\_1 = \text{linspace}(0,100,29)';
plot(SOC\_1,ESR\_charge)
hold on
plot(SOC\_1,ESR\_discharge,'g')
xlabel('SOC')
ylabel('ESR')
legend('ESR charge','ESR discharge')
title('ESR vs SOC')
Preprocessing Power Profile

% Pre-Process Power Profile
% load user selected power profile and save the same profile with forward
% looking data called "data" in a matrix format

%% Clear All
close all; clc; clear all;

%% Load Data

% user selects power profile to be processed
file_name=(uigetfile({'*.mat'},'Select Power Profile'));

% load power profile
load(file_name);

% MAKE SURE input power signal = kW!

%% Proces Power Profile
Sample_Time = 1; % [seconds]

number_of_strings = 3;

Ah_Capacity = 150; % [Ah]

Max_SOC = 80; [%]
Min_SOC = 60; [%]

nominal_battery_voltage = 192 * 3.6; %[Volts]
peak_charge_current = 450; %[Amps]
peak_discharge_current = 500; %[Amps]
cont_charge_current = 300; %[Amps]
cont_discharge_current = 500; %[Amps]

mode = 3; %[1= continuous limited, 2 = peak limited, 3 = AV900 limited]

if mode == 1; % Battery Continuous 30 second rating
    max_battery_discharge = nominal_battery_voltage * cont_discharge_current;
    max_battery_charge    = nominal_battery_voltage * cont_charge_current;
end

if mode == 2; % Battery Peak rating
    max_battery_discharge = nominal_battery_voltage * peak_discharge_current;
    max_battery_charge    = nominal_battery_voltage * peak_charge_current;
end

    max_battery_discharge = 250000; %[Watts]
    max_battery_charge    = 250000; %[Watts]
end

power_threshold_discharge = 100;
power_threshold_charge    = -100;

max_battery_discharge = max_battery_discharge * number_of_strings;
max_battery_charge    = max_battery_charge * number_of_strings;

sim('Process_Power_Profile_12_8_15');

%%% Sort Data
% data is preprocessed or forward looking information extracted from the
% user selected power profile

% event time = end time - start time
data(:,7) = data(:,3) - data(:,2);

% time in which full power (charge or discharge) is not available from the
% profile. Note, mode(cont. or peak) will vary this result...
% time load is below battery abilities = event time - available time, where
% available time is the duration in which the load profile is beyond battery
% capabilities.
data(:,8) = data(:,7) - data(:,5);

% percentage time of the profile in which the load is within battery
% capabilities.
Per_time_win_Batt_Power_Limits = (sum(data(:,8))/sum(kW(end,1))) * 100; % [%]

% Amount of energy the battery can not capture under any scenario
data(:,9) = data(:,4) - data(:,6);

%% plot data
% remove "-" from file names so the plot title feature works properly
title_str = strrep(file_name,'_','-');

time = kW(:,1);
power = kW(:,2);

% plot power profile
figure(1)
plot(time/3600,power);title(title_str);ylabel('Power [kW]');xlabel('Time [hours]');
%%% Save data in new "processed file"

[path file] = fileparts(file_name);
str = [file ' processed'];
save(str, 'kW', 'data');

%%% Clear all data

% clear all; close all; clc;

HIL Initialization

%%% Model Sample Time

% These parameters define the operation of the Simulink Real-Time Target
% used to run the HIL code

sample_time=0.1; % Seconds, the SLRT device will cycle at this rate

%%% Load Power Trace

load('Power Traces\Atlanta_Memphis_Atlanta_2 processed');

%%% Corvus Battery System Definition

% Units: %, Volts, Ohms, Ah, Amperes, Celsius, Watts

% This section is used to define all battery related parameters for both
% HIL testing, Current Limiting, as well as maximum/minimum allowable
% parameters for safe testing.
%% Corvus Pack Characterization Data

load('Supporting Information/Corvus_Pack_Characterization');

SOC_Index = OCV_Map(:,1);
OCV_Map = OCV_Map(:,2);
ESR_Charge = interp1(ESR_Charge(:,1),ESR_Charge(:,2),SOC_Index);
ESR_Discharge = interp1(ESR_Discharge(:,1),ESR_Discharge(:,2),SOC_Index);

string_capacity = capacity_ah; %[Ah]

%% Model Parameters

nP_strings = 3;

% #1 =
% #2 =
% #3 =
% #4 =
% #5 = ECM_Discharge_Onlu
% #6 = MPC

Controller_Selection = 6; %MPC
initial_SOC = 80;
initial_SOH = 1;
battery_life = 10000*string_capacity;
initial_voltage = interp1(SOC_Index,OCV_Map,initial_SOC);

pack_capacity = string_capacity * nP_strings;

% Control Parameters

min_SOC = 20;
max_SOC = 80;
\begin{verbatim}
min_cell_voltage = 3.3;
max_cell_voltage = 4.1;

min_current = -300; % charge (AV900 Limit, 220 kW)
max_current = 300; % discharge (AV900 Limit, 220 kW)

min_temperature = -40;
max_temperature = 50;

% Define...!!!
bufferSOC = 20; %

%% Original Controller (used in other controllers)
split_percentage_discharge = 30/100;
split_percentage_charge = 70/100;

%% Decay Controller
SOC_High = 65; % [%]
SOC_Low = 35; % [%]

%% EC Minimization ./ MCP

goal_SOC = 40; % [%]
Kp = 0.1;
Ki = 0.2;

% Fuel consumption lookup data
fuel_rate = [0,0.00293575,0.00991603,0.02110465,0.05433029,0.07448995,0.10750139,0.13275137,0.15166365,0.18042897];

% Forward Looking
\end{verbatim}
number_of_strings = nP_strings;

Ah_Capacity = capacity_ah; % [Ah]

Max_SOC = max_SOC; %[%]
Min_SOC = min_SOC; %[%]

nominal_battery_voltage = 192 * 3.6; [%Volts]