

Design and control of a range extender for small industrial vehicles

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Summary

In this article, we are discussing the design and control of a range extender for small industrial vehicles. We are going to review different control architectures, the selection of the major components and make a more detailed description of the selected control algorithm. The description of these subjects will allow us to present the design considerations of the team during the development process. Test results will be presented to show the success of the integration. Finally, we will discuss the future opportunities and challenges that the team is going to face for the continuation of this project.

Keywords: Range Extender, Battery Electric Vehicle, Control, Fuzzy Logic, Hybrid Electric Vehicle

1 Introduction

This paper details the design strategy of a range extender for small industrial vehicles. The market of industrial vehicles is dominated by either battery electric vehicles or Internal Combustion Engine (ICE) powered vehicles. The first example that comes to mind is the fork lift. This type of vehicle comes in a wide range of design to answer an impressive range of different applications. The vehicles built by Motrec, one of the partners in this project, are designed to answer the same range of different applications that are facing the fork lifts. This company builds many different categories of vehicles, the main ones being «burden carrier» and «tow tractors». Most of Motrec's production (more than 90%) is made of battery electric vehicles, the remaining 10% being ICE powered vehicles with different types of transmissions, depending on the application (CVT, Hydrostatic, Gearbox, etc.).

The varied offering of ICE equipped vehicles is a problem for Motrec as these different vehicles often need a dedicated space on the assembly line as well as dedicated personnel to build the vehicles and support the customer. As an effort to standardize their line-up, Motrec came up with the idea of integrating a range extender to their existing battery electric vehicle to satisfy their customers using ICE equipped vehicles. By integrating this range extender, the company would be able to fit the same kit in many different vehicle model, thus reducing space, inventory and support problem.

The range extender to be designed would need to replace existing ICE equipped vehicles where electricity supply might not be available or where the duty cycle cannot allow long recharge time. The efficiency was not a criterion for this first design but the control algorithm would need to account for future upgrades where the fuel consumption optimization would need to be taken into account.

The chosen solution is a very simple design with a stationary ICE, the same electric machine as the traction motor already used by Motrec and an inverter combined with a controller. The system output current is centered on a rule based fuzzy logic controller allowing the expert users at Motrec to tune the behavior for different applications.

1.1 Participants

1.1.1 Motrec

Motrec is a OEM designing and producing industrial vehicles since 1988. They offer different products with a customer focus. Today, Motrec offers a broad range of tow tractors, burden and personnel carriers. The business is present worldwide with the factory located in Sherbrooke, Qc, Canada where it employs around 50 employees. Motrec is in charge of the mechanical integration of the system in the vehicle. They also are in charge of tuning the range extender for the different vehicle versions.

1.1.2 Engrenage Provincial

Engrenage Provincial is a provider of hydraulic and electro-mecanic components for different off-road OEMs. They also have a consulting department helping with the control design and programming. Engrenage Provincial is supporting with the design and implementation of the control algorithm in the controller for the range extender.

1.1.3 Innovative Vehicle Institute

The Innovative Vehicle Institute (IVI) is a research centre focusing on the development of hybrid and electric vehicles. The researchers have access to a broad range of different equipment and have a strong technical knowledge in everything regarding the integration of hybrid and electric vehicles. IVI was in charge of developing the control algorithm as well as testing and tuning the range extender prototype.

1.2 Overview of control strategies

The range extender vehicle architecture is similar to Plug-In Hybrid Electric Vehicle (PHEV). The vehicle, as in a PHEV, is going to be equipped with pure electric mode, pure ICE mode and hybrid mode where a mix of electric machine and ICE is going to provide power to the vehicle. It could also be compared to a series-hybrid vehicle since the selected architecture is going to use an ICE coupled to an electric machine which is de-coupled from the original drivetrain (no mechanical effort transferred to the road).

The paper from Wirasingha & Emadi [1] is presenting a complete review and classification of the different PHEV control. The four types of control described by Wirasingha & Emadi are Rule Based Determined or Fuzzy and Optimization Based Acausal/Global or Causal/Real time.

1.2.1 Rule based

The rule based control is the simplest form of controller that will work with the range extender. This type of control is built by a set of rules that will start the ICE and send pre-selected current levels into the system. An example of rule based control would be: when the battery voltage (or state of charge) reaches 48V, start the ICE and charge the battery at a fixed current level of 25A until the voltage reach 54V. This type of control is very simple and works fine in a pure ICE mode but lacks some flexibility when it comes to hybrid mode.

The fuzzy logic controller is designed to select the best current at the output of the range extender as a function of the vehicle load, the state of charge of the batteries and the ICE efficiency. This type of controller first classifies the input values in different membership function, for example, the battery state of charge can be low, medium or high. The membership function value is then used to evaluate a rule set and find the related output function. The designer can add as many rules as needed to obtain the required behaviour. In the case of a PHEV, one rule could be: If the state of charge of the batteries is low and the traction motor current consumption is high then you should provide maximum current (or high) from the range extender. By

changing either the shape of the membership functions or the rule set, you will modify the range extender's behaviour. A complete presentation of fuzzy logic controllers can be found in reference [2].

1.2.2 Optimization based

The optimization based controllers have one common goal: trying to find the minimum consumption either offline or online from a model, past experience and/or sensors. Several methods exist for this type of controller like Dynamic Programming [3], particle swarm optimization [4], genetic algorithm [5], etc. Three different implementation approaches are described by Wirasingha & Emadi: Dynamic Programming, Artificial Neural Network and Stochastic Optimization.

The Dynamic Programming (DP) method tries to minimize a cost function by calculating the required inputs from a known drive cycle. The DP has the obvious disadvantage to require a known drive cycle to be able to find the optimal solution which is usually not the case unless the vehicle is equipped with different sensors to know its location and the destination.

The Artificial Neural Network (ANN) method is a learning algorithm that will update its behaviour based on past experience. This type of controller does not need the full drive cycle to achieve best fuel economy but will require extensive training sets as a starting point. It will be less influenced by different drivers or topology changes than DP. The main disadvantages will come from the training set requirements and the large computational cost for online training.

Stochastic Optimization is similar to DP since it will evaluate a cost function to find the required inputs. The main difference is that "part of the input is specified in terms of a probability distribution rather than by deterministic data given in advance" [1]. This type of optimization is a way to account for variability in input data.

These optimizations based controllers could be used in many different industrial vehicles applications as the loads and routes are often similar. These controllers could lower significantly the fuel consumption. Unfortunately, the application we chose for the range extender is a bit different from the standard industrial vehicle in the sense that we are trying to build a system that will fit many different applications, thus requiring many different controller designs. Many of these applications also have random load and road profiles (as an example, off-road tow tractors or outdoor burden carriers) which will increase the computational burden to find an optimal solution. The simpler fuzzy logic controller was thus selected.

2 Architecture

The architecture is based on the ICE powered vehicles actually produced by Motrec. These vehicles come in different sizes and shapes. As a starting point, to develop the working logic and build a prototype, we chose the MC-480 burden carrier vehicle.

MC-480	Passengers	Load Capacity	Towing Capacity	Speed	Turning Radius
48 V	2	3,000 lbs.	6,000 lbs.	10 mph	124"



2.1 Requirements

	Minimum	Maximum
Net Power (approx.)	-	6 kW
Voltage	45 V	55 V
Charge current	20 A	120 A
Operating temperature	0°C	45°C

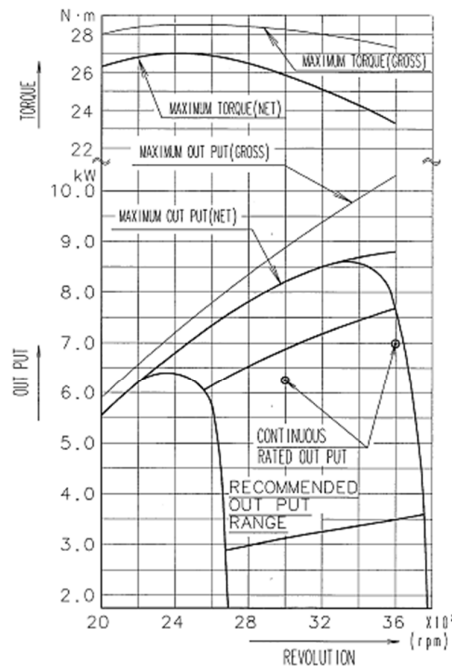
The net output power was selected by measuring the mean energy consumption in this type of vehicle to achieve a charge sustaining cycle. The voltage and charge current are requirements for the battery. The upper limit for the operating temperature is chosen by the battery limit. The lower limit was set after several ICE starting tests in an environmental chamber. The minimum temperature limit was chosen as the lowest temperature where the ICE would start without activating the choke command.

2.2 Internal combustion engine

The chosen ICE is the Subaru EX40. This engine is air-cooled, 4-cycle with a horizontal shaft. The continuous power is approximately 6.3 kW at 3000 RPM which is close to the required power for our system. This type of ICE is not expensive and is easy to source. Below is a picture of the engine and the torque and power curves as a function of the RPM.



Figure 1: Subaru EX40 ICE



NOTE) 1. ABOVE PERFORMANCE DATA ARE CONVERTED INTO
STANDARD ATMOSPHERIC CONDITION'S DATA.
2. ABOVE PERFORMANCE CURVES ARE ESTABLISHED IN ACCORDANCE WITH JIS B-8017.

Figure 2: Torque and Power curves - Subaru EX40

2.3 Electric machine (generator)

The electric machine is provided by Advanced Motors & Drives, model ACX-3164. This motor is air cooled and is able to provide up to 6.9 kW at 3200 RPM. Below is the picture of the ICE and electric machine assembly.

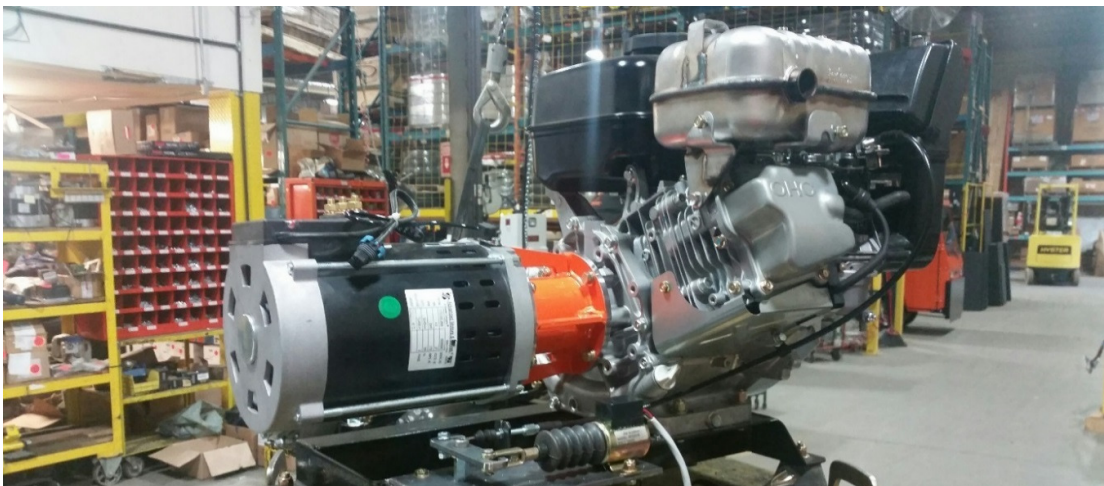


Figure 3: Electric machine and ICE sub-assembly

2.4 Inverter

The inverter is a Schwarzmüller MI04-S-48/300-P. This inverter is equipped with a PLUS+1 controller from Sauer Danfoss. This drive was selected because of the embedded controller that would allow the team to implement the logic of the system and have an easy interface to work with when tuning for the prototype and for the different vehicle models when in production (different batteries, drivetrain sizes, voltage and current limits).



Figure 4 : Schwarzmüller MI04-S-48/300-P inverter

The next table presents the different specifications of the Schwarzmüller inverter.

Table 1: Schwarzmüller MI04-S-48/300-P inverter specifications

Type: MI04-S-	48/300
Nominal voltage	36 – 48 Vdc
Input voltage range	38..62 Vdc
Nominal current	150 Arms
Maximum current S2 – 2 min	300 Arms
Boost current (10 sec)	330 Arms
Output voltage	3 x 0...24 (@36V input V) 3 x 0...32 (@48V input V)
Power connectors	M8
Weight	2.8 kg [6.17 lb]

3 Software architecture

In this section, we will present the different algorithms implemented for the control of the range extender and the design intent behind each choice. Many of the decisions were taken by taking into account the unique features and limitations proper to the Motrec vehicles and the intended use of the range extender.

3.1 State of charge calculation

Motrec can fit the vehicles with many different battery packs. These packs come in a wide range of voltage, capacity and even chemistry. Most of the vehicles come equipped with a simple state of charge (SOC) that is updated during discharge but is only updated in charge when the on-board charger is plugged in. This imply that the SOC would not go back up when the range extender charges the batteries. To make sure the base vehicle would stay as similar to an electric version as possible, we decided to add a state of charge calculation to the range extender control and not modify the state of charge calculation algorithm in the base vehicle.

The SOC calculation algorithm is based on the measured voltage compared to tabulated data. When the measured voltage is below the data for a given SOC during an adjustable period of time, the SOC is reduced by 1 and the timer is reset. It's the same behaviour when the measured voltage is higher than the tabulated value. If the measured voltage is higher during a given period of time, the SOC value is increased by 1.

The following Stateflow diagram shows the state of charge calculation algorithm. In this diagram, the BDI variable is equal to the tabulated voltage value.

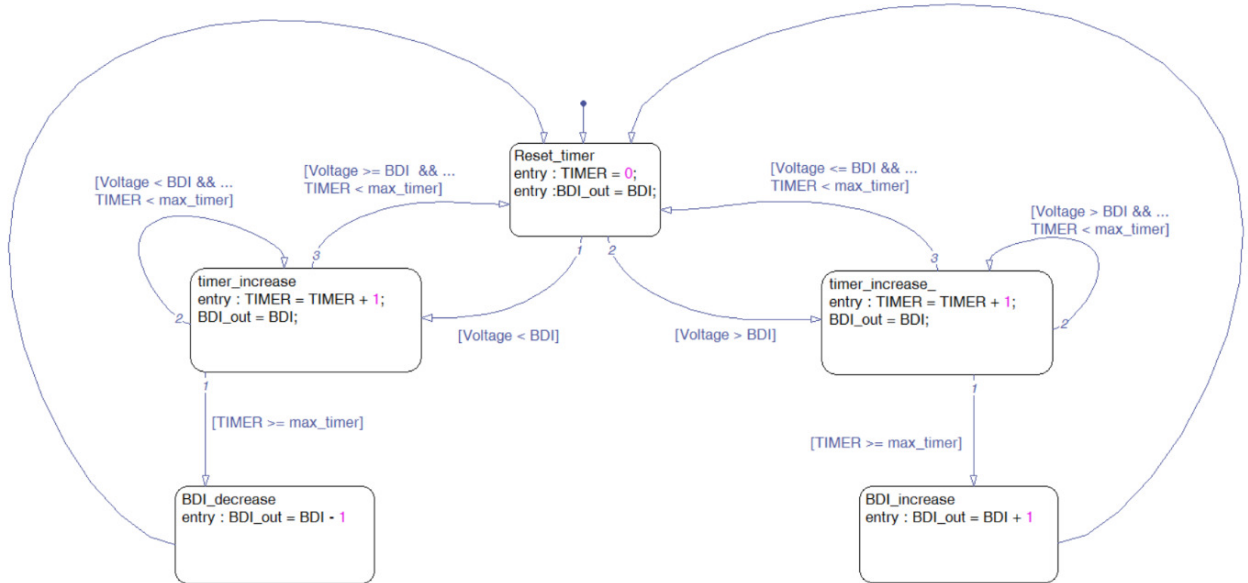


Figure 5: Stateflow diagram of the SOC calculation algorithm

This algorithm was chosen over coulomb counting for the SOC calculation since the coulomb counting method was proven to lead to massive errors when used in lead-acid battery systems, a type of battery that is frequently used in Motrec vehicles. It's also been compared to ANN and Kalman filtering, both of which required too much time to tune for different systems.

The SOC algorithm would need to be revised if the manufacturer decides to use Li-Ion batteries with the LFP chemistry since the proposed algorithm would not work with the relatively flat voltage vs SOC curve. This type of battery is not currently used in Motrec vehicles.

3.2 Electric mode

One of the requirements for the range extender was to be able to work with the vehicle as an original battery electric vehicle. This mode works as if there is no range extender. It could also be called Charge Depleting mode.

3.3 ICE mode

This mode is designed to make the vehicle work as an ICE powered vehicle. The range extender tries to keep the batteries full at all time. It could be called Charge Sustaining mode.

The range extender is controlled by a simple rule set. The engine will start if the SOC is below 85% and, if the vehicle is moving, will stop if the SOC is higher than 95%. If the vehicle is standing-by in ICE mode, it will try to finish the charge by going from constant current mode to constant voltage mode. It will stop when the current drops below a set value, typically 2 or 3 A. This will allow the batteries to equalize if the vehicle does not use the on-board charger. The range extender's output current is selected by adding the measured current consumption from the drive motor to a constant value. This constant value is set by the manufacturer and should be equivalent to the capacity of the on-board charger. This means that when the vehicle is moving around and consuming energy, the range extender should be able to charge the batteries as if it was standing still and using the on-board charger.

The next figure resumes the SOC variations as a function of time in this mode:

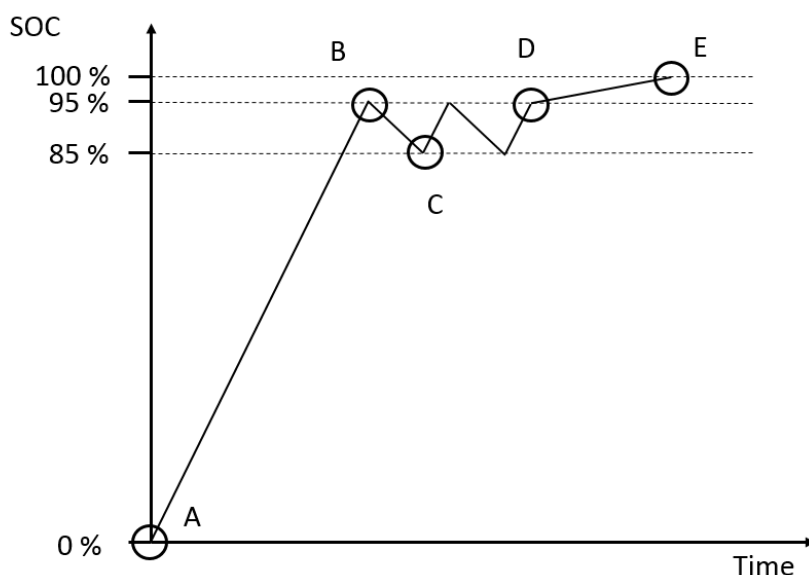


Figure 6 : SOC function of time in ICE mode

In the last figure at point A, the battery is fully discharged. The ICE will start and provide a net value of, as an example, 25A to the battery. At point B, the battery reaches 95% SOC and the vehicle is moving. The ICE will stop until the SOC drops to point C. At this point, the ICE will restart and resume charging. At point D, the vehicle reached 95% SOC but is not moving, allowing the range extender to switch into constant voltage mode and finish the charge. At point E, the battery is fully charged, the charging current is below the threshold value and the range extender will sleep until the vehicle moves again.

3.4 Hybrid electric mode

The Hybrid Electric mode should be the default behaviour of the range extender. In this mode, the vehicle will start by depleting the charge until the SOC reaches approximately 25%. When this value is reached, the range extender will switch to a charge sustaining mode and try to keep a constant SOC until the vehicle is plugged-in to a power outlet and fills the batteries through the on-board charger.

The control algorithm for this mode is based on fuzzy logic. To minimize the fuel consumption, the idea is to use the ICE to a minimum that could allow the user to finish the work shift or to reach a charging station.

To achieve this, we built a fuzzy logic system with two input variables (the SOC and the measured drive current) and one output variable (the range extender charge current). Each of the input variable possess 5 membership functions to allow the manufacturer to tune the charging behaviour. The output variable also possesses 5 membership functions. The fuzzy logic control algorithm was first developed with the Matlab Fuzzy logic toolbox [6] and then transferred into the selected controller's language.

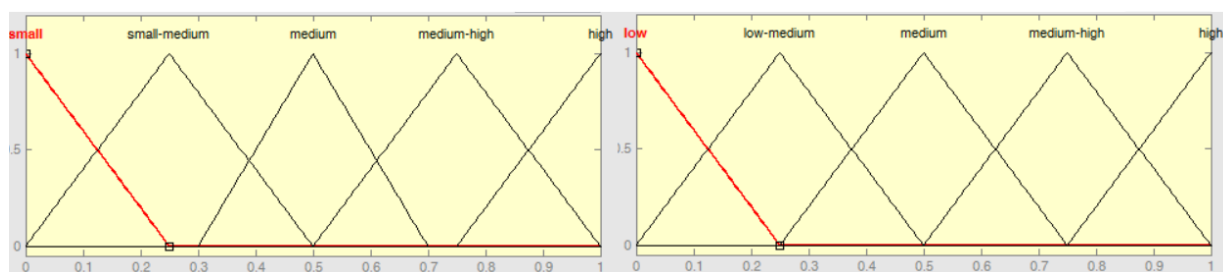


Figure 7: Input membership function Traction Drive Current and SOC

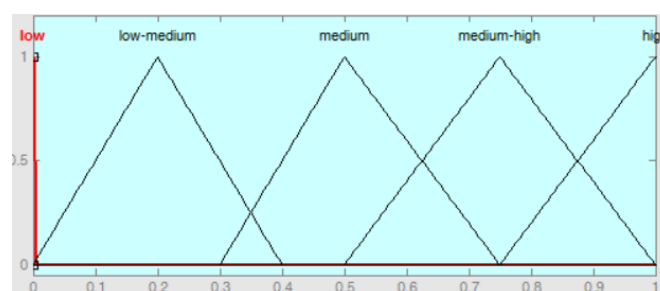


Figure 8: Output membership function - Range Extender Current

This big number of membership function gives huge flexibility to the manufacturer to tune the behaviour of the range extender. For the prototype vehicle MC-480, we tuned the vehicle for a charge sustaining strategy when the SOC is around 25%. The output current climbs higher if the SOC drops below this level.

Another feature that was included into the fuzzy logic controller design is the ability for the range extender to supply current when the load on the vehicle is very high. This behaviour was included to account for possible battery downsizing where the total tractive force would be too much for the battery alone to handle. This could prove very useful in Li-ion battery systems to improve the total cost of the vehicle.

The following figure shows the resulting output current from the fuzzy logic controller:

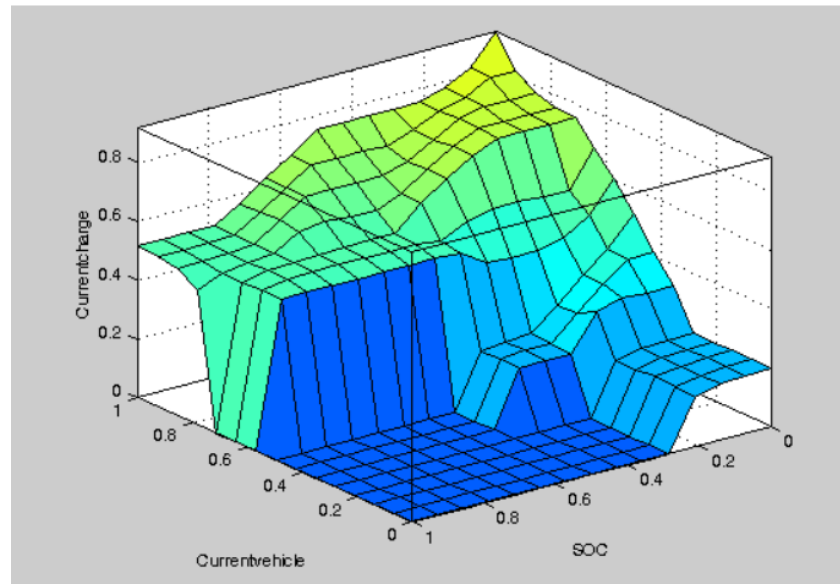


Figure 9: Output current given by the fuzzy logic controller

We can see that with small vehicle current and medium to high SOC, the range extender will not provide any sort of power to the vehicle. With low SOC, the range extender will provide a small charging current regardless of the vehicle load. Same behaviour with high vehicle load where the range extender will provide power regardless of the SOC.

4 Testing and tuning

During the initial tuning of the vehicle, we were able to log the current coming from the range extender as well as the current drawn from the batteries. The next picture shows the measured current during a test with the battery at 60% SOC.

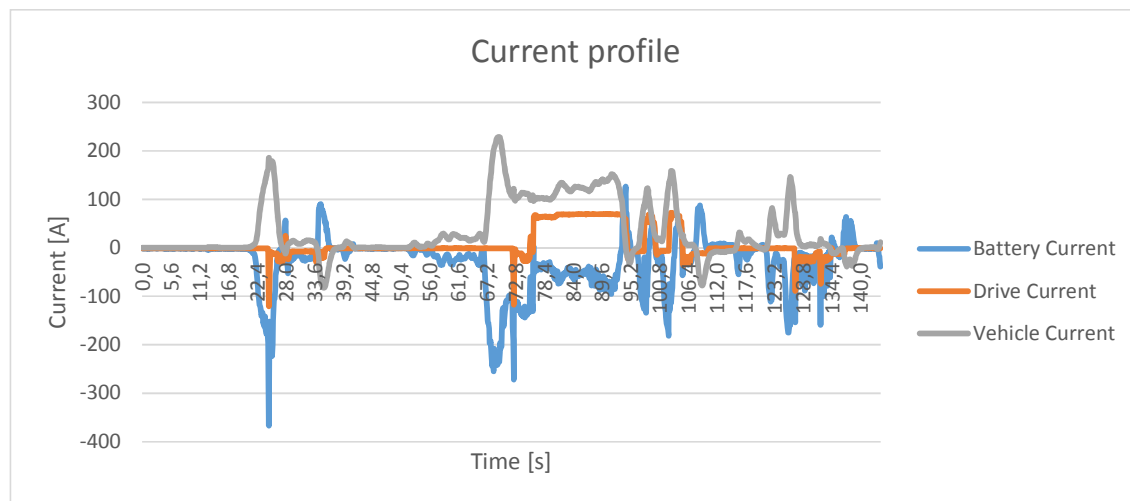


Figure 10 : Current profile in Hybrid Mode

In this figure, the negative Battery Current means energy is drawn from the battery. The positive Drive and Vehicle Current means that energy is provided by the range extender and energy is consumed by the drivetrain to move the vehicle. In this short test, since the SOC is in the mid-range, the range extender starts only when the current consumed by the drivetrain is high during a sustained period of time. In this case, the vehicle was driving uphill at its maximum acceleration. The range extender was trying to reduce the load on the batteries. It is interesting to note that there is an added load to the batteries when the range extender's ICE is starting. At 25 second, a short current spike at the drivetrain meets the condition to start the ICE but is too short to allow the range extender to reduce the current seen by the batteries. This behaviour is a tradeoff between the responsiveness of the range extender to external loads and the ICE starting sequence frequency. The team tried to minimize the number of time the range extender would need to start without providing any energy to the system.

5 Future work and conclusion

With the first prototype tuned and tested in a controlled environment, the team is now going to put the vehicle into the hand of real world customers. The objective of this test is to review the robustness of the solution and the sizing of the major components. Since the drive cycles of different customers can be very different from one another, several different businesses were selected to receive the vehicle for a limited period of time. Data logging will enable the team to quickly find and address any issue occurring during the test.

During this project, the team was able to successfully develop and test a range extender for the Motrec industrial vehicle line-up. During the process, the members of the project were able to put their skills to the best use and learn new skills from the other participants leading to new business opportunities for each teams. The range extender should be integrated to the Motrec line-up in Fall 2016.

Acknowledgments

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Pierre-Luc Lapointe graduated in mechanical engineering at Université Laval. He has many years of experience in multidisciplinary digital simulation (structural, thermal and fluid analysis via finite element and 1D multidisciplinary analysis on vehicle dynamic behaviour and energy efficiency). His fields of interest are lithium-ion battery modeling and dimensioning, particularly the influence of various parameters such as temperature, electric current and voltage levels on the service life of accumulators. He also works on mechanical power transmission for the dimensioning and control of different types of transmission (CVT, hydrostatic, automatic and automated manual transmissions).