33^{rd} Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14 - 17, 2020

Design and implementation of a real-life peak shaving charge manager for an electric school bus fleet

Guillaume Fournier, Eng.[1]

[1]Innovative Vehicle Institute, Saint-Jérôme, Québec, Canada, gfournier@ivisolutions.ca

---

Summary

In this paper, we present the steps taken to design and implement an intelligent cloud-based manager whose goal is to charge a fleet of electric school buses optimally to reduce power peaks on the grid. Emphasis is put on the design of the different subsystems rather than the performance of the charge manager since, at the time of writing, the system is awaiting deployment.

Keywords: smart charging, demonstration, fleet, optimization, power management

---

1 Introduction

Fleet operators are increasingly turning to electric vehicles (EVs) for their operation. Although EVs often represent a significantly higher initial investment, the promise of reduced operating expenses is believed to provide a return on investment that surpasses their traditional counterparts over their lifespan. However, many operators are faced with higher maintenance costs and electric bills than anticipated. In many cases, this will curtail the purchase of further electric vehicles until a solution to these problems is found.

In the meantime, electric utility companies must cope with these emerging power-hungry isolated loads on their distribution systems. To make things worse, these loads often coincide with already saturated peak demands. To deter customers from creating these power spikes on their network, electric utility companies often turn to tariff calculations that factor in the maximum power demand of the client. A higher demand, even for a short interval of time as low as 15 minutes, can therefore impact the customer's bill for months to come.

Electric vehicle manufacturers also suffer from these predicaments since they reflect poorly on the technology and slow down the adoption of their products.

This project from the Innovative Vehicle Institute was initiated to find a solution to these obstacles for fleet operators, electric utility companies and electric vehicle manufacturers. Partners in the project are Autobus Laval (fleet operator), Hydro-Quebec (utility company) and The Lion Electric Co. (electric school bus manufacturer).

This paper will focus on the description of the designed solution. While the charge manager was designed and implemented, actual performance data is yet to come since the manager is awaiting deployment at the time of writing. Operational data should be available and presented at the conference.

1.1 Initial Challenge

When this project was being evaluated, in early 2018, the fleet operator has had one short instance where the cumulative power consumption being pulled from the grid was greater than its usual maximum by around 50 kW. This anomaly lasted for more than 15 minutes and was registered by the utility as the maximum power drawn for this month. Because of the applicable tariff, this deviation caused a cumulative 3500 CAD penalty over the next year for the operator. Since then, other instances have been registered and other fees were also involved. The challenge was to design an intelligent charge manager to make sure these events never happen again.

1.2 Loads

This section will discuss the loads to power at the fleet operator's site. It will also show how the anomalies can happen.

1.2.1 Block Heaters

At the location where the project is held, Autobus Laval, the fleet operator, has around 115 diesel school buses and seven (7) electric buses. At night, the diesel buses need to be warmed up using block heaters when the outside temperature is at -10°C or below. Drivers of diesel buses usually connect the block heater whenever they park their vehicle at the depot. Two (2) identical electrical circuits with contactors drive the block heaters. These circuits are either controlled manually or automatically activated at 2AM when the outside temperature is at -10°C or below and deactivated at 4 AM. Whenever activated, the combined power for these circuits is around 97 kW. This represents about 70% of the total possible block heater load because not all of the buses are plugged in at any given time. Fig. 1 shows the approximate power consumption for the block heaters when the outside temperature is -10°C or below. Above the -10°C threshold, power drawn from the block heaters is null unless a manual activation of one or both circuits is performed.

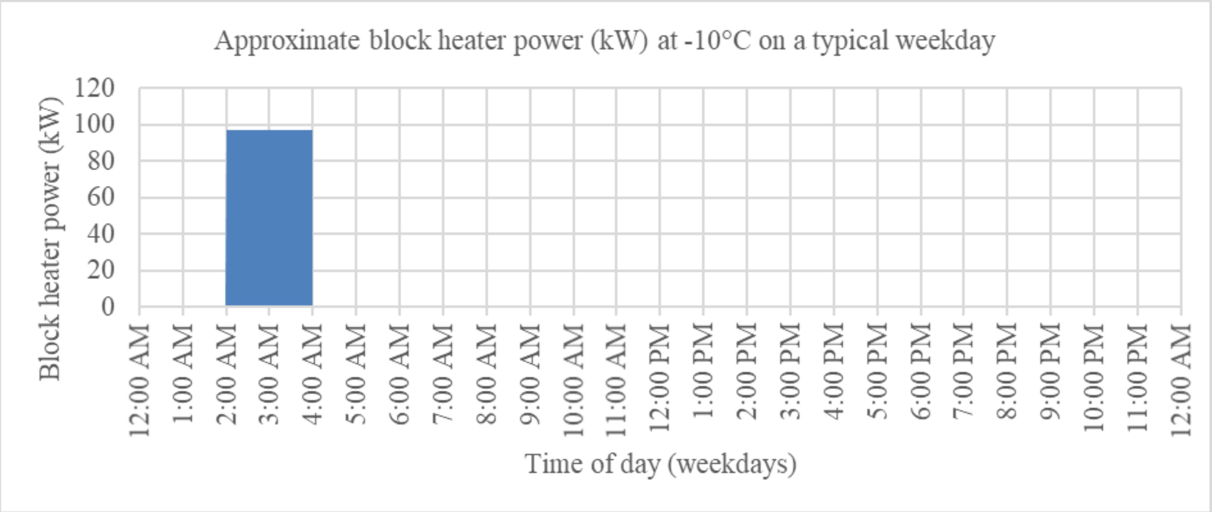


Figure 1: Approximate power consumption of the block heater circuits (< -10°C)

1.2.2 Electric buses

The seven (7) electric buses each have their own level 2 charging station (EVSE) powered by a 208 V transformer. The maximum current that can be delivered by an EVSE is 80A which accounts for a maximum charging power of 16.64 kW per bus. Drivers of electric buses connect their vehicle to their assigned EVSE whenever they park it at the depot. An electric bus usually performs either two (2) or three (3) trips per day: typically one sometime between 6:45AM and 9:15AM, an optional one for lunch between 11:10AM and 12:55 PM and finally a last one between 3PM and 5:15PM.

The current drawn from the EVSE by a bus is maximal at around 16 kW when its State of Charge (SoC) is less than 80%. When it reaches 80%, its power drawn reduces exponentially until the SOC is 100%. Finally, the bus controller must heat its batteries in cold weather or cool them in hot weather before charging them. Consequently, power losses must be accounted for at low or high temperatures to charge the batteries.

Fig. 2 shows the approximate power consumption of all the EVSEs when the outside temperature is -10°C.

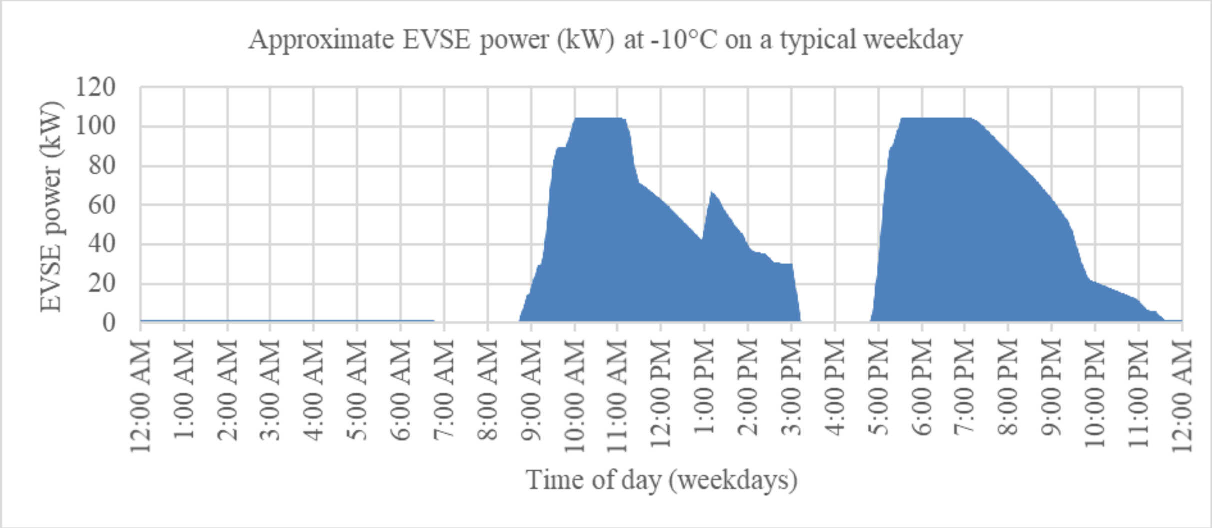


Figure 2: Approximate power consumption of the EVSEs at -10°C

1.2.3 Building

Statistical data analysis shows the building power consumption, excluding the block heater circuits and the EVSEs, can be estimated using the following formulas.

$$For\ T > 7°C, \qquad W_{building} = 50kW \tag{1}$$

$$For\ T \leq 7°C, \qquad W_{building} = (-2.67 \cdot T + 70)\ kW \tag{2}$$

As an example, when the outside temperature is -10°C, power consumption of the building is approximately 96.7 kW.

1.2.4 Combination of all loads

An estimation of the combined power consumption of the building, the block heaters and the EVSEs at an outside temperature of -10°C is shown in Fig. 3.

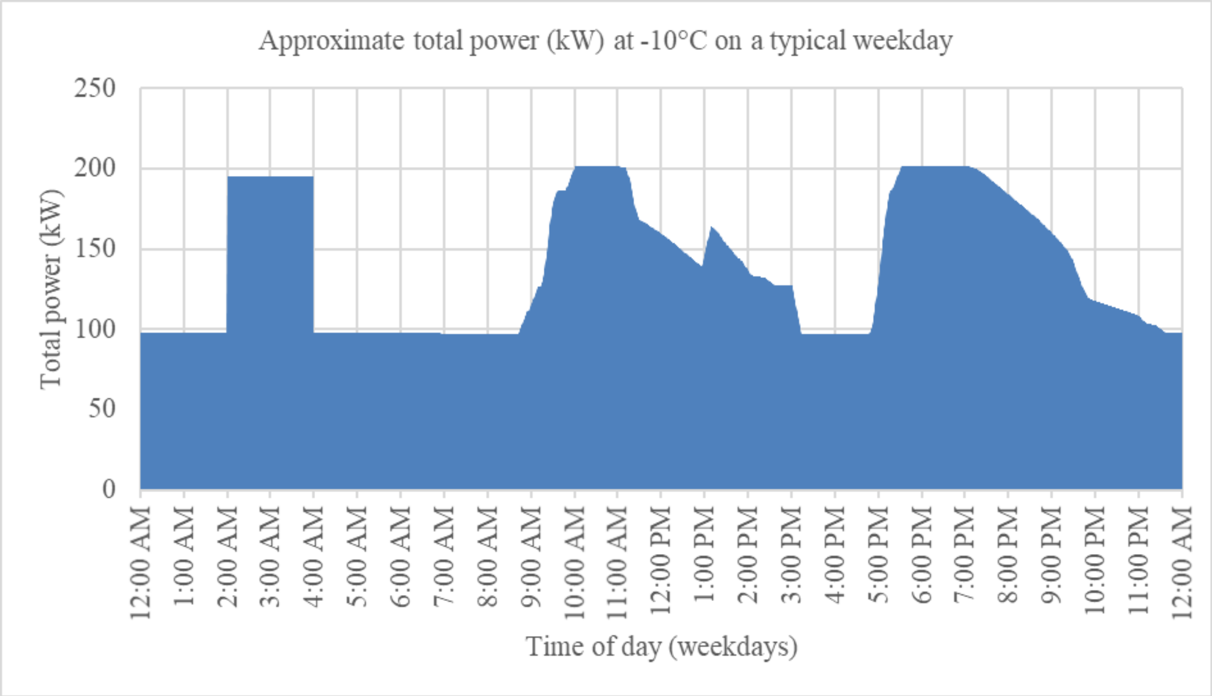


Figure 3: Estimation of the combined power consumption at -10°C

The distribution of the power drawn from the grid shown in Fig. 3 is quite optimal considering the different loads on the grid. The block heaters being powered at night once the electric buses are fully charged makes for this nice distribution. However, the block heaters can be controlled manually and activated right when the electric buses are drawing the most power from the grid, for example at 6 PM. This is what happened the first time the fleet operator created the power peak.

1.3 Load Optimization

1.3.1 Block heaters

The block heater loads are equally split between two (2) different electrical circuits, each with their own contactor. Presently, they are activated at the same time. However, we hypothesize that alternating the loads on a 15-minute cycle time for a longer duration would still maintain the block temperature to an acceptable level even on the coldest days. Doing such would halve the power peak related to the block heater. Other activating algorithms to be tested could reduce it even further.

1.3.2 EVSEs

To reduce the power demand from the charging stations (EVSEs), we can distribute the loads in time according to the needs of the different buses. This is what this project attempts to do.

2 System Overview

The system implemented aims to find the optimal charging profile for all electric buses without disrupting normal operations. To achieve this goal the information shown in Table 1 is gathered by the system. Some information is unused for now but was provisioned for future use to improve the charging algorithm.

Table 1:Information gathered by the system

Information	Supplier	Used now	Future use
Start and end time of all bus routes	Google calendar	X	
Distance for each trip planned	Google calendar	X	
State of charge of each bus	Fleet management interface	X	
Presence or absence of a bus at each EVSE	EVSE Bridge	X	
Presence or absence of a bus at each EVSE	Fleet management interface		X
Distance and energy used by every bus after each trip	Fleet management interface		X
Energy transferred to the battery while charging	Fleet management interface		X
Energy transferred to the accessories while charging	Fleet management interface		X
Current being drawn by each bus at the EVSE while charging	EVSE Bridge		X
Temperature-compensated 24-hour power profile prediction of the building without the electric buses including the profile from the diesel buses' block heaters	Electric utility interface	X	
The instantaneous power reported by the meter	Electric utility interface	X	
Peak Demand Event list	Electric utility interface	X	
Battery capacity of each bus	Web administration interface	X	
Dedicated EVSE for each bus	Web administration interface	X	
Estimation of power lost while charging*	Web administration interface	X	
Maximum power target to aim for*	Web administration interface	X	
Energy consumption per km traveled*	Web administration interface	X	
Phone numbers of emergency contacts	Web administration interface	X	
Operating mode: safe or normal	Web administration interface	X	

*These values are entered for each month of the year, based on experimental data, since they are highly correlated to external temperature.

By using this information, a multistage linear optimizer can create a charge plan for the next 24 hours for each bus and apply it through its assigned EVSE. This plan is comprised of current values between 7 A and 80 A over intervals of 15 minutes for the next 24 hours.

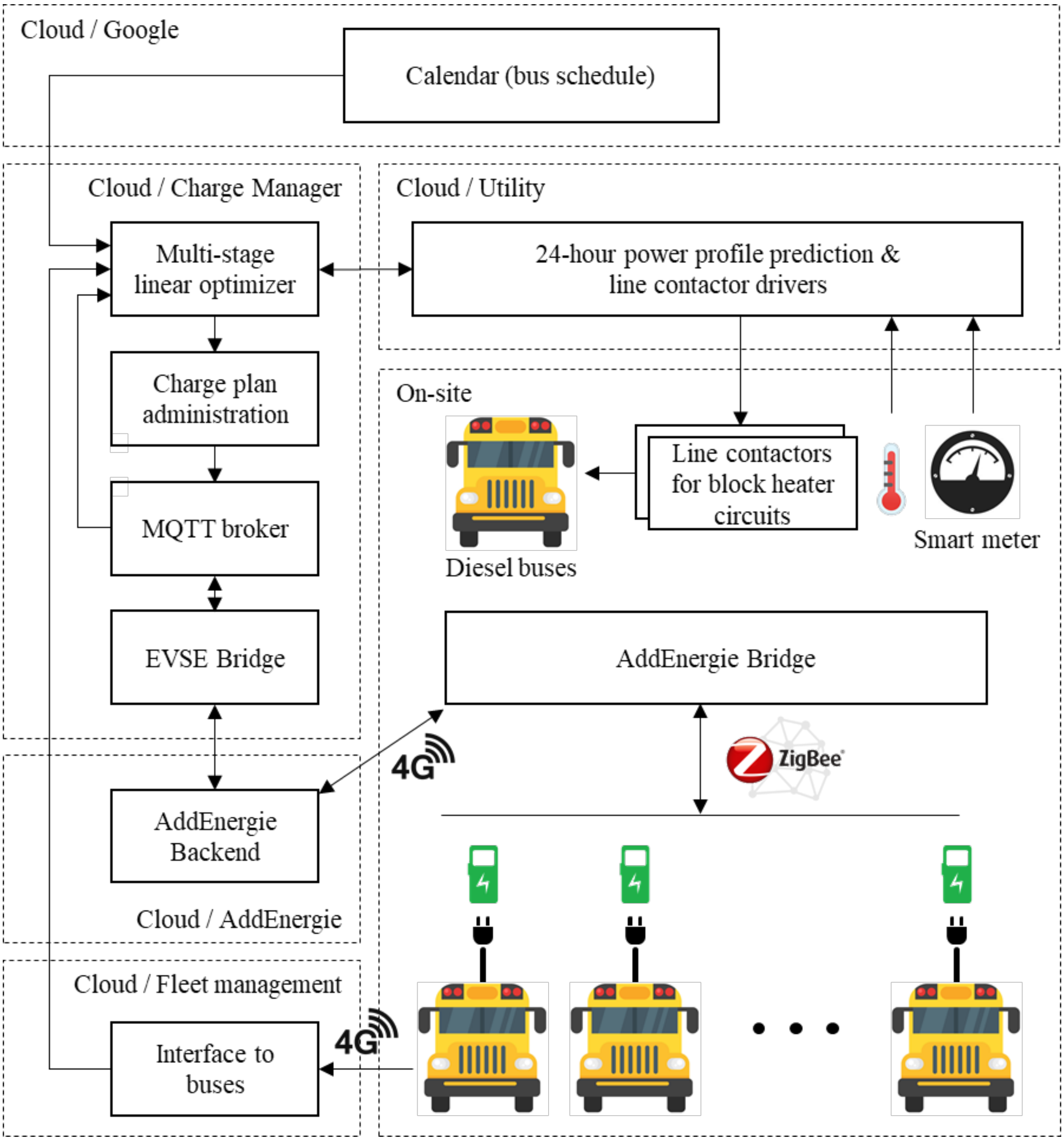
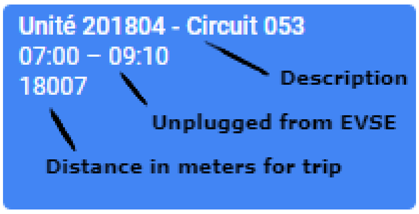


Figure 4: Overview of the system

2.1 Bus Schedule

For the optimizer to prepare a charge plan, it must know when the electric vehicles will be connected to an EVSE and when they will be on the road. To save design cost, reduce time to market and leverage powerful features already designed such as recurring trips, we decided to use a known-to-work solution, Google Calendar. The fleet operator enters the different trips as meetings in each managed bus's calendar. The location field of the meeting is used to store the distance in meters that is planned for each trip. The manager then uses the Google Calendar API to retrieve the trips for the next 24 hours.



Unité 201804 - Circuit 053
07:00 – 09:10
18007

Figure 5: Example of calendar entry

2.2 Electric Utility Power Profile Prediction

Hydro-Quebec, the electric utility partner in this project, provides the charge manager with a temperature-compensated 24-hour power profile prediction for the combined building and block heaters loads at the site by using the information exposed in section 1.2.1 and section 1.2.3. The profile is a set of power values at 15-minute intervals for the upcoming 24 hours (96 values). The temperature of the site is pulled from a free weather API accessible on the web. The profile reaches the multistage linear optimizer that uses it to determine how much power can already be assumed as consumed on loads other than the buses.

An energy accumulator from the smart meter is also made available to the system once every five (5) minutes. From this accumulator, the average power consumption between two (2) readings is computed. This information is used to adjust the power offered to the buses according to the real power at the meter while administering the charge plan to the EVSEs. If the total load read from the meter is lower than predicted, for example if the building draws less power than anticipated, more power is offered to the buses. On the other hand, if the load read from the meter is more than anticipated, less power is offered to the buses. At this time, the power is split proportionally between all connected buses. Future improvement could compute a priority for every bus and give more power (or remove less power) to the highest priority one.

Finally, the electric utility partner provides a list of times where a Peak Demand Event is expected. A Peak Demand Event is defined as a time interval during which Hydro-Québec has determined that demand will be very high. This list is a set of Boolean values at intervals of 15 minutes for the next 24 hours (96 values). The charge manager will try to draw as little power as possible during the events listed.

The information is passed through JSON files and secure REST API endpoints.

2.3 Fleet Management Communication

The electric school buses that are part of the project are each fitted with a fleet management modem that is hooked up to the CANBus of the vehicle. The modem is parsing certain CANBus messages then formatting and forwarding them to a cloud service through a cellular network.

Although the vehicles were already fitted with modems at the beginning of the project, the amount of data that was being pushed to the Cloud was scarce and most of the time erroneous. Both the Vehicle Control Module (VCM) and modem had to be modified to provide relevant information such as state of charge and energy flowing to and from the battery and traction system (*cf.* Table 1).

The charge manager communicates with the third-party fleet management Cloud by exposing REST API endpoints that are called anytime new information is available. Therefore, the information is pushed to the charge manager.

No incoming messages to the bus are used in this project.

2.4 Charging Stations (EVSEs)

2.4.1 Tesla Wall Connectors (TWC)

When the project was first started, the fleet operator had seven (7) slightly modified Tesla Wall Connectors (TWC) charging stations supplied by the electric bus manufacturer, one per bus. These EVSEs were modified to use a J1772 cable that could fit the electric buses instead of the custom Tesla connector. Since they are capable of delivering 80 A at 240 V at a very competitive price, they were a great choice to charge the buses.

The TWC has load sharing capabilities where one master EVSE controls the current that can be offered by up to three (3) slaves through an RS485 link between all EVSEs. This functionality is commonly used to share a single circuit breaker across multiple charging stations as shown in Fig. 6.

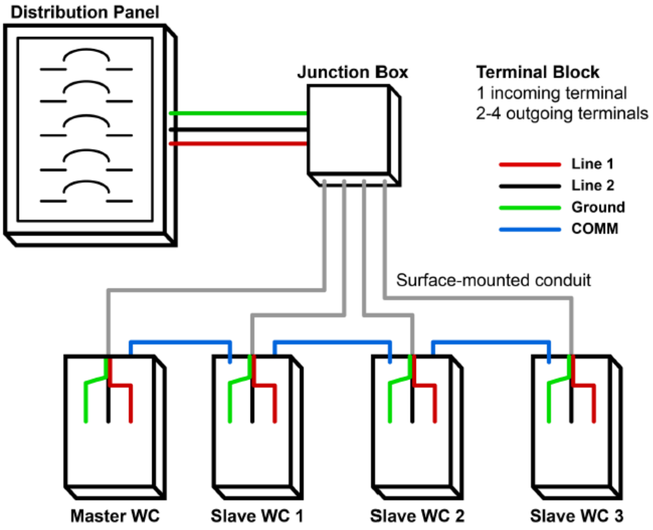


Figure 6: Typical TWC installation for load sharing applications

However, we considered using this current-sharing capability with multiple electrical circuits (one 100A breaker per EVSE) to throttle the current supplied to each and every vehicle by emulating a master TWC through the RS485 protocol. The strategy was to use an embedded Linux based computer with three (3) USB to RS485 dongles to emulate three (3) masters controlling respectively three (3), three (3) and one (1) slave TWCs.

An online project to reverse engineer the protocol used on the RS485 [1] was promising and we decided to take this route.

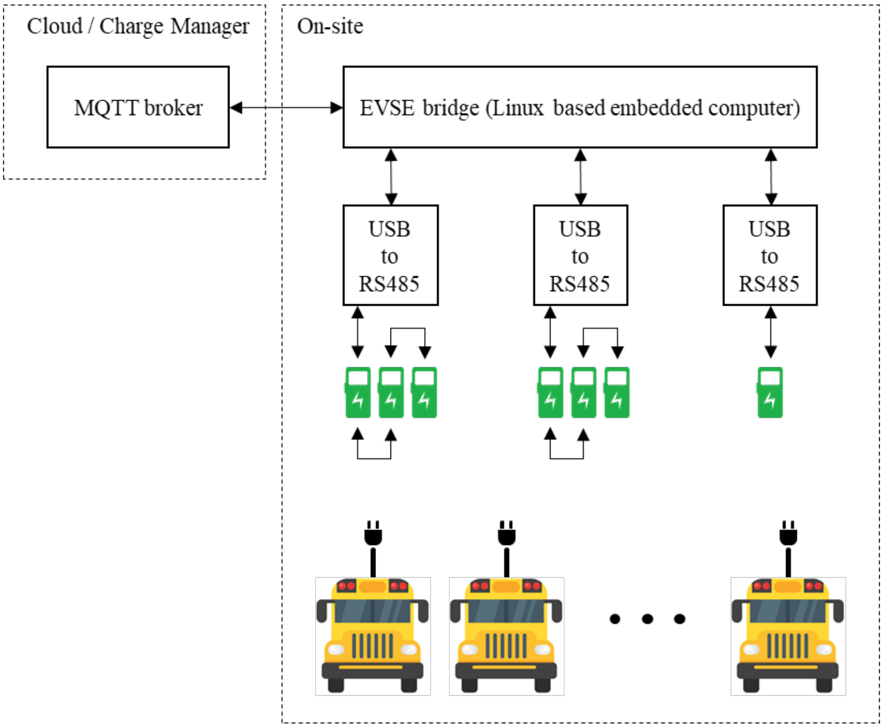


Figure 7:Initial architecture for EVSEs current throttling

However, after painstaking efforts to reverse engineer and implement the load sharing RS485 protocol into an EVSE bridge, we were still faced with occasional slave disconnection issues. These relatively frequent (once per hour) but very short disconnection periods (in the order of 30 seconds) would not have been an important obstacle if not for the behavior of the slave TWC. When the slave TWC encountered such a loss of communication with its master, it would open its contactor under load and risk causing damage to the contactor in the process. This was unacceptable since the contactor would be damaged relatively quickly.

We then sought another solution to throttle the current supplied to the vehicle. Finding an EVSE that could supply 80A and control the pilot signal to modulate the current proposed through a connected protocol (wired or wirelessly) was complicated. We could not find an off-the-shelf solution, so we turned to AddEnergie, a manufacturer of EVSEs in the province of Quebec, Canada and a partner of ours in other previous projects.

2.4.2 AddEnergie

AddEnergie already has an off-the-shelf 32A connected EVSE for sale and they agreed to build seven (7) 80A prototype EVSEs based on the same architecture. Some hardware, mechanical and software changes to their standard EVSE were required.

Fig. 4 shows how the AddEnergie architecture fits into our system. The EVSEs communicate through ZigBee to an AddEnergie locally installed bridge. This bridge communicates with AddEnergie's backend through a cellular network. Finally, the EVSE Bridge in our system creates a link between AddEnergie's backend API and our MQTT broker.

2.5 EVSE Bridge and MQTT Broker

An MQTT broker is used to communicate the optimizer's charge plan and to retrieve information from the EVSEs. MQTT stands for Message Queuing Telemetry Transport and is an extremely simple and lightweight publish/subscribe messaging protocol designed for constrained devices and low-bandwidth, high-latency or unreliable networks. The design principles are to minimize network bandwidth and device resource requirements whilst also attempting to ensure reliability and some degree of assurance of delivery. These principles also turn out to make the protocol ideal for "machine-to-machine" (M2M) connected devices.

The MQTT broker used in this project is a server in the Cloud that allows subscriptions and publications to distinct "topics". For example, if four (4) devices subscribe to the topic "/house/laundry_room/temperature", when any device, like a thermostat, publishes to this topic, the message will be sent to all four (4) devices that subscribed to it.

The system uses this broker to interface with the physical world. The charge manager and the EVSE bridge publish and subscribe to the topics defined in Table 2. The EVSE number is also part of the topic but is not shown in the table (*i.e.* /[base_topic]/[EVSE number]/Current).

The EVSE bridge's role is to interface with all the EVSEs on site through the AddEnergie's API.

Table 2:MQTT topics per bus

Topic	Charge manager		EVSE Bridge	
	Subscribe	Publish	Subscribe	Publish
backend		X	X	
Current		X	X	
Overriding			X	
gateway	X			X
Supplied_Current	X			X
kwh_volt	X			X
Plugged	X			X
Status	X			X

2.5.1 backend

This topic is published by the charge manager to indicate if it is online. The Last Will and Testament feature of MQQT is used to automatically publish an offline condition if the charge manager gets disconnected from the broker. When a disconnection is published, the bridge puts all EVSEs to their maximum current (80 A) to deactivate the system (reverts to original strategy before the project was implemented).

2.5.2 Current

This topic is published by the system to send the current that this EVSE should offer to the vehicle (0 to 80A). The EVSE bridge sends this information to the AddEnergie API.

2.5.3 Overriding

The EVSE bridge subscribes to this topic that is used to manually override the system. When overriding is enabled manually (not through the system), the EVSE bridge puts all EVSEs to their maximum current (80A), thus reverting to the original strategy before the project was implemented.

2.5.4 gateway

This topic is published by the EVSE bridge to indicate if it is online. The Last Will and Testament feature of MQQT is used to automatically publish an offline condition if the bridge gets disconnected from the broker. When a disconnection is published, the charge manager can generate an error to the user.

2.5.5 Supplied_Current

This topic, published by the EVSE bridge, is the current that the vehicle is presently drawing from this EVSE.

2.5.6 kwh_volt

This topic, published by the EVSE bridge, contains an energy accumulator and a voltage measurement. The accumulator represents the amount of energy in kWh that has been transferred during this charge session to the vehicle. The voltage published is the AC voltage at the EVSE. This measurement can be used to approximate power delivered.

2.5.7 Plugged

This topic, published by the EVSE bridge, indicates if a vehicle is plugged onto this EVSE and when the transition happened using a timestamp. The current implementation does not automatically detect which vehicle is connected to which EVSE; it rather relies on static assignments (a bus is always connected to a specific EVSE). However, using timestamps from both the fleet management interface and EVSE bridge, it would be possible to match a vehicle to any EVSE.

2.5.8 Status

This topic, published by the EVSE bridge, transmits the current status of the EVSE bridge for this EVSE (*i.e.* communication failure, plain text message).

2.6 Multi-stage Linear Optimizer and Charge Administration

The core of the manager is the six (6) stage linear optimizer. The result of each stage is a new, further refined, charge plan optimized to meet additional criteria introduced at each stage. The charge plan is a 24-hour plan of power values to offer to the vehicle through its EVSE with a 15-minute resolution. This plan is re-evaluated every 15 minutes.

2.6.1 Stage 1 – Minimize the "Maximum Power Demand"

Objective: for the next 24 hours, minimize the "maximum power demand" at the site.

Constraints:

- Charge power for each EVSE cannot be lower than 0 or greater than 16640 watts at all times.
- Charge is allowed only when a bus is connected to an EVSE, otherwise charge power must be 0.
- For every bus, the energy in the battery cannot be less than 0 or greater than 100 kWh at all times. This energy is computed from expected travel distances and times, energy consumption per km, power delivered while charging and initial battery energy.
- For every bus and for every expected trip, the energy in the battery must be sufficient to complete the trip.

2.6.2 Stage 1.5 – Find Maximum Power Available per Interval

The objective is to compute, for each interval, the maximum power available that can be drawn without increasing the maximum power demand already registered for this billing cycle.

Using the newly calculated charge plan from stage 1, the sum of all expected loads (including predicted building, EVSE and block heater power) is calculated for each interval. The maximum power available for a certain interval is the greatest value between the maximum power demand already registered for this billing cycle and the previous maximum power available interval value.

Example (using a hypothetical smaller charge plan of 5 instead of 96 intervals for conciseness):

- Sum of all expected loads using charge plan from stage 1: [120, 128, 132, 139, 134] kW
- Maximum power demand already registered for this billing cycle: 130 kW
- Maximum power available per interval: [130, 130, 132, 139, 139] kW

2.6.3 Stage 2 – Minimize Power Demands on Peak Demand Events

Objective: for the next 24 hours, minimize the sum of the energy drawn from the grid when a Peak Demand Event (cf. section 2.2) is flagged by the utility company.

Constraints:

- All constraints from stage 1.
- For each interval, never go above the maximum power available computed on stage 1.5 for that interval.

2.6.4 Stage 3 – Maximize the time when the buses are ready for their next trip

Objective: for the next 24 hours, for each bus and for each expected trip, compute how long before the next trip the bus has enough energy to perform it. This will give an array of n values where n is the number of expected trips for all buses in the next 24 hours. The objective is to maximize the smallest time in this array. For example, if there are only two (2) buses doing two (2) trips each in the next 24 hours, the array is going to have 4 entries. If bus #1 is ready 15 minutes before its first trip and 35 minutes before its second and if bus #2 is ready 3 hours before its first trip and 45 minutes before its second, then the smallest time in this array is going to be 15 minutes. The objective is to maximize the smallest time in the array (here, increase 15 minutes to its maximum).

Constraints:

- All constraints from stage 2.
- The sum of the energy drawn from the grid when a Peak Demand Event is flagged by the utility company is equal or smaller than the sum result of stage 2.

2.6.5 Stage 4 – Maximize the amount of energy in the buses before each trip, step 1

Objective: for the next 24 hours, for each bus and for each expected trip, compute the energy available in the battery just before the trip. This will give an array of n values where n is the number of expected trips for all buses in the next 24 hours. The objective is to maximize the smallest energy in this array.

Constraints:

- All constraints from stage 3.
- For each trip, the amount of time before the bus is ready must be greater or equal than the result of stage 3.

2.6.6 Stage 5 – Maximize the amount of energy in the buses before each trip, step 2

Objective: for the next 24 hours, for each bus and for each expected trip, compute the excess energy that should remain after the trip and sum all values together. The objective is to maximize the sum of excess energy before trips in the next 24 hours.

Constraints:

- All constraints from stage 4.
- For each trip, the amount of excess energy must be greater or equal than the result of stage 4.

2.6.7 Stage 6 – Minimize power variations

Objective: for the next 24 hours, minimize the variations of power offered to the vehicles between two adjacent intervals.

Constraints:

- All constraints from stage 5.
- The sum of excess energy before trips in the next 24 hours must be greater than or equal to the result of stage 5.

2.6.8 Charge plan administration

At the end of stage 6, the optimizer has an optimized charge plan that dictates the amount of power that should be provided to the electric school buses in 15-minute time increments for the next 24 hours. The buses are charged according to this plan through the MQTT broker and EVSE bridge. Finally, any discrepancy between expected power and the instantaneous power read from the meter is proportionally distributed between the connected buses (positive or negative differences) using a feedback loop. This ensures that unexpected load variations will not cause a greater than calculated peak demand or a below optimal charging profile.

Acknowledgments

The author would like to acknowledge the government of Quebec and Hydro-Québec for their financial support to the overall project as well as The Lion Electric Co. along with Autobus Laval and Hydro-Québec for their participation. A special thanks to Hydro-Quebec for their continued technical and financial involvement throughout the project.

References

[1] *TWCManager*, https://github.com/cdragon/TWCManager, accessed on 2019-08-27

Presenter Biography

Guillaume Fournier, Eng.

Guillaume is an engineer graduated from ÉTS in Electrical Engineering and has 20 years of experience in design. His career has led him to develop multidisciplinary skills in embedded systems, Linux, PC and FPGA programming, communication protocols and project management. Since joining the institute in May 2017, he has designed BMSes for lithium batteries, put together electric vehicles, retro-engineered vehicular systems and managed large-scale projects related to smart charging.