Battery Charging optimizer for Electric Vehicle battery with interactions to the charging station and Power grid

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Abstract

EV battery charging optimization at charging stations is the process of optimizing the charging of electric vehicle (EV) batteries in a way that minimizes the overall cost of charging, while still ensuring that the batteries are fully charged when the EV is to be used.

One of the main challenges associated with EV battery charging optimization is managing the demand on the electric grid. When multiple EVs are charging at a charging station at the same time, the demand on the grid can increase significantly, which can lead to problems such as voltage drop and power outages. To mitigate these issues, the charging optimization system may need to consider the current grid load when determining the charging strategy for each EV.

Another challenge is the variable pricing of electricity throughout the day. Electricity prices may fluctuate based on factors such as time of day, season, and demand on the grid. The charging optimization system needs to take these price fluctuations into account in order to minimize the overall cost of charging.

In addition to these challenges, the charging optimization system may also need to consider factors such as the availability of charging infrastructure, the capacity of the batteries, and the needs of the individual EV owner (e.g., whether they need a fully charged battery by a certain time). By carefully considering these and other factors, the charging optimization system can help to optimize the charging process and improve the overall efficiency of the charging station.

1 Introduction

Electric vehicles (EVs) are becoming an increasingly popular means of transportation, and charging stations are an essential part of the infrastructure needed to support them. However, charging multiple EVs at the same time can place a significant demand on the electric grid, which can lead to problems such as voltage drop and power outages. To mitigate these issues and ensure that the charging process is as efficient and cost-effective as possible, it is important to optimize the charging of EV batteries at charging stations. First and foremost, it can help reduce the overall cost of charging by taking advantage of lower electricity prices and minimizing the demand on the grid. Beyond the personal good (i.e. cost saving), charging optimization also contributes towards the common social good by reducing the strain on the power grid.

There are, however, several key considerations when optimizing the charging process of EV batteries. One of the main challenges is being aware of the demand on the electric grid. When multiple EVs are charging at a charging station at the same time, the demand on the grid can increase significantly. Therefore, the charging controller needs to consider the current grid load when determining the charging strategy for each EV. This may involve charging the batteries at a slower rate during times of high grid demand, in order to reduce the overall demand on the grid and vice versa.

Another challenge is the variable pricing of electricity throughout the day. Electricity prices may fluctuate based on factors such as time of day, season, and demand on the grid. The charging optimization system needs to take these price fluctuations into account in order to minimize the overall cost of charging. For example, if electricity prices are lower during certain times of the day, the optimizer may choose to charge the batteries at a faster rate in order to take advantage of the lower prices. Conversely, when the electricity prices are higher, the controller may decide to wait for the prices to come down and not charge the load. However, this introduces another related problem. For instance, if the controller kept on waiting for the prices to come down and not charge the EV, it may eventually fail to charge it at all. This would violate the **liveness** condition i.e. the battery of the EV must be adequately charged by the start of the service period. The charging optimization system may also need to consider factors such as the availability of charging infrastructure and the attributes of the batteries (rated voltage, max charging voltage, etc), By carefully considering these and other factors, the charging optimization system can help to optimize the charging process and improve the overall efficiency of the charging station.

Finally, an efficient and reliable mechanism for EV battery charging increases the reliability of EVs which naturally leads towards a wider adoption of EVs and thus, helps the overall energy consumption and greenhouse gas emissions associated with ICEs.

2 Components and Methods

2.1 Parameter table

	Controller Properties
V_{in}	Voltage applied to charge the battery
V_{mp}	Voltage associated with the max allowed power draw from the grid.
TTC	Time to Charge. Time (in Hours) by which the battery should be fully charged to meet the liveness condition.
$panic$	The signal that latches when the controller goes into panic to meet liveness condition.
	Battery Properties
$V_{battery}$	Voltage across the battery
V_{ref}	Voltage upto which the battery is set to charge (can be used as an alternative to State of Charge(SoC))
V_{max}	Maximum allowable charging voltage that can applied across the battery
C	The capacitance of the battery
r	The internal resistance of the battery
TC	The time constant = $r * C$
I	The charging current flowing across the battery
	Grid Properties
$p1$	The Grid price 1. Applied when drawn power is less than optimum threshold
$p2$	The Grid price 2 (>p1). Applied when drawn power is greater than the optimum threshold.
P_{max}	The max power draw permissible from the grid.
P_{th}	The power threshold. Drawing below it results in optimal pricing.

2.2 Simulink Model

Simulink is a simulation framework integrated in MATLAB, a popular engineering toolkit and a programming language environment. All of our modeling and analysis have been done using Simulink. Figure 1 shows the overall layout of our annotated model. Below we outline the individual components and their interfaces and discuss how the components communicate with each other.

2.2.1 Grid

The Grid component models a smart power grid. It doesn't have any input variables but it does have an output Bus (called info) that contains variables like $P_{max}, p1, p2, P_{th}$ which specify, respectively, the maximum power that you can draw from the grid, the price grid charges you if you draw below the threshold, the price the grid charges you if you draw above the threshold, and the threshold of optimal powerdraw. The threshold of powerdraw is a time-dependent signal that's modeled using a Simulink Scenario. In practice, it is assumed that Grid would calculate this threshold based upon the demand and convey it to the smart devices that's on its network.

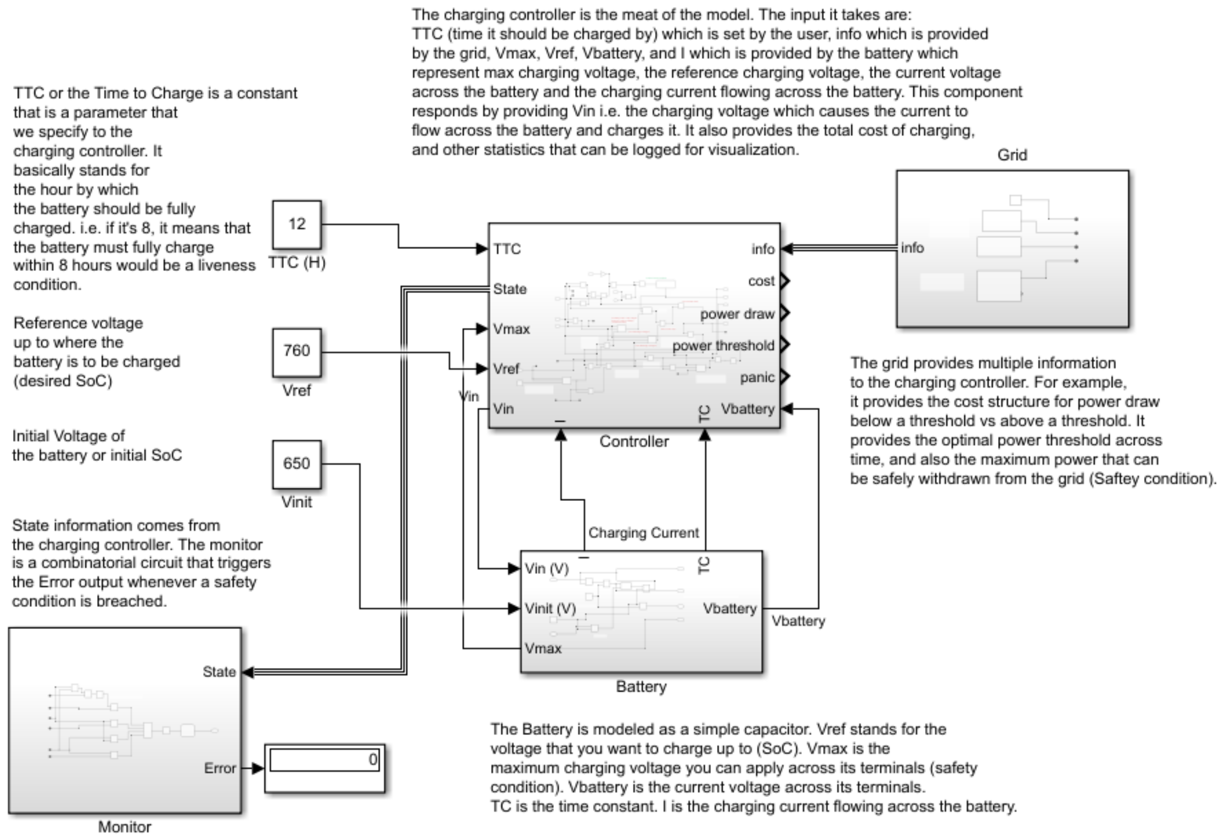


Figure 1: The complete charging model with three components a) Grid, b) Battery, c) Charging Controller, and d) Safety Monitor

2.2.2 Battery

The Battery component is modeled as a simple capacitor with a capacitance C, and internal resistance r. In our model, the battery holds some initial charge Q which means that the controller doesn't charge it from absolute 0 voltage (as is usually the case). Although, we assume that the battery specifies the maximum charging voltage, the reference voltage (to which it needs to be charged) and other parameters like its Time Constants (TC), in practice, all of these parameters would be a part of a formal specification which both the charger and the battery would need to adhere to.

2.2.3 Controller

The Controller is the main component of this model. It takes in parameters from both the user, the grid, and the Battery and figures out the optimum way to charge the battery in such a way that both the safety conditions and the liveness requirements (specified in further sections) are met while also simultaneously optimizing (minimizing) the incurred cost of charging. The inside of the controller is outlined in Figure 2. As is shown in the figure, it has multiple circuits that calculate the optimum charging voltage and compares it against maximum permissible voltages (as defined by both grid and the battery) and uses these to calculate the final charging voltage that's applied across the battery. An assumption that's made here is that the controller can vary its voltage across the battery but this can easily be achieved by using Voltage regulator.

2.2.4 Safety Monitor

To verify that our system never violates the safety condition and to detect it as soon as possible if it happens, we use a device called Safety Monitor. The monitor takes in the information about the controller state via a Bus and has inbuilt combinatorial circuits that detect whenever a safety condition is breached. If the monitor discovers that the safety conditions have been violated, it raises an indicator signal which is latched high via a state machine and is then

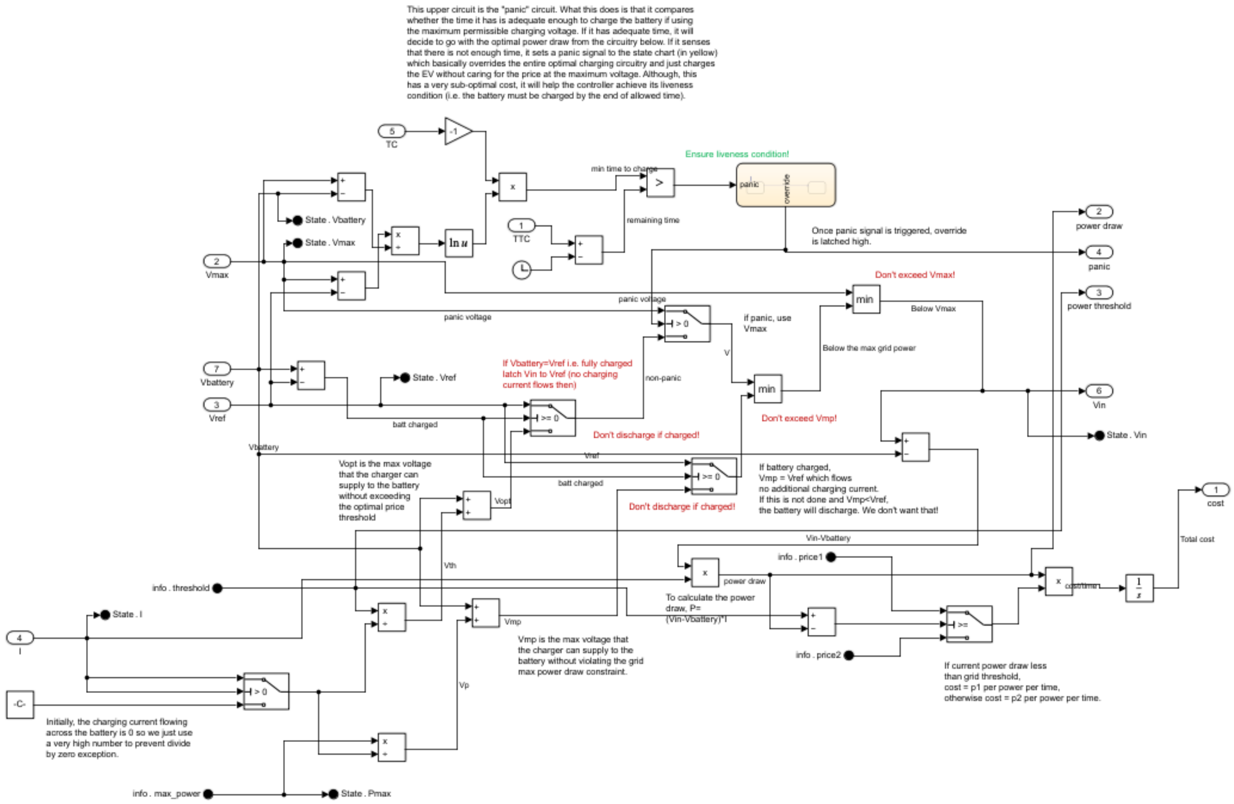
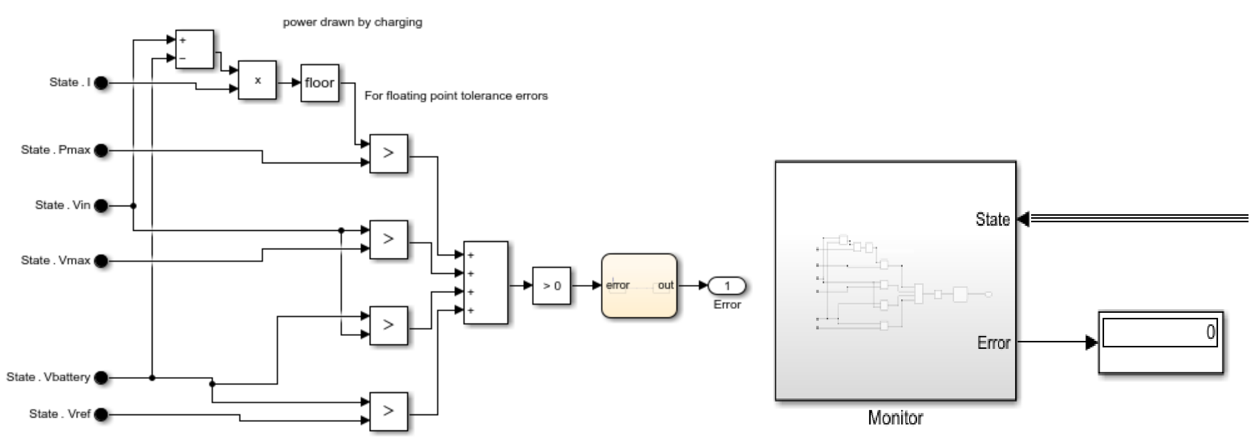


Figure 2: The internals of the charging controller. Annotations on red are the safety conditions. Annotations on green are the liveness conditions.



(a) The internal circuit of the monitor (b) The interface of the monitor

Figure 3: Safety Monitor

connected to the display. The component interface and the internals of the monitor are shown in Figures 3a and 3b respectively.

3 Analysis

3.1 Safety Condition

There are basically four safety conditions that are considered while designing the controller. The first safety condition states that: *The controller will never supply the battery more voltage than V_{max}.* This can be expressed in LTL as follows:

$$\Box V_{in} \leq V_{max}$$

The second safety condition states that *the power drawn from the grid will never exceed P_{max}*. This can be formalized in LTL as:

$$\Box P_{max} \leq (V_{in} - V_{battery}) * I$$

The third safety condition specifies that *the battery will never overcharge than the reference voltage*. This condition can be written in LTL as:

$$\Box V_{battery} \leq V_{ref}$$

The last requirement states that *the battery will never discharge* (i.e. it will only ever charge or not charge at all). This requirement ensures that the controller doesn't inadvertently discharge the battery (which may damage the battery). In LTL:

$$\Box V_{in} \geq V_{battery}$$

3.2 Liveness Requirement

There is one very important liveness requirement i.e. *The controller will ensure that the battery is charged to full levels within the specified time range*. In terms of LTL:

$$\Diamond V_{battery} = V_{ref}$$

However, it must be noted that this is a conditional liveness requirement. Which means that it is not always certain that this will be met. For example, if the Time To Charge window is very small (say 1 hour), the controller will never be able to draw enough power to charge the battery within such a short window due to the safety criteria. Therefore, this liveness requirement is only completely fulfilled when a reasonable time limit is specified. Otherwise, the controller can only do its best and charge to the maximum permissible limit without violating the safety requirements.

3.3 Determining Optimum Voltage

To determine the optimum voltage that'll draw just enough power to not exceed the optimum price threshold.

$$V_{opt}^{t} = V_{battery}^{t-1} + \frac{P_{th}^{t}}{I^{t-1}} \ \ s.t. \ I_0 = \infty$$

where, I_0 is used when the current draw is 0A.

When the battery charges to full i.e. $V_{battery}$ rises to V_{ref}, then we cannot supply a voltage that's different than V_{ref}. This is because this will either cause the battery to discharge or overcharge, which would violate our safety conditions. Therefore, a more complete equation would be:

$$V_{opt} = \begin{cases} V_{battery}^{t-1} + \frac{P_{th}^{t}}{I^{t-1}} & \text{if } V_{battery} \leq V_{ref} \\ V_{ref} & \text{otherwise} \end{cases} \tag{1}$$

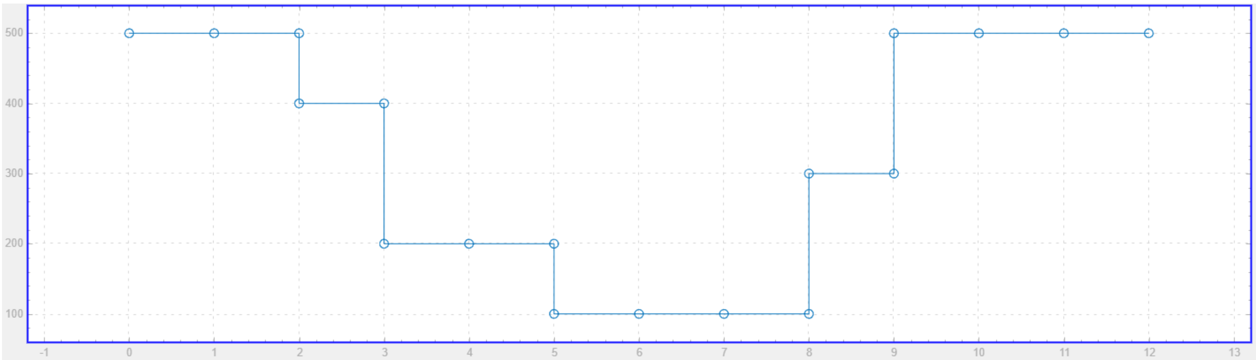


Figure 4: Variable power threshold for the selected duration (12 hours). Y-axis values are in watts.

3.4 Deciding on panic signal

The panic signal is raised when the controller feels that the only way to meet the liveness criteria is to charge using the maximum permissible voltage (constrained by both battery V_{max} and the grid V_{mp}). 'Panic' is raised if the following inequality becomes True:

$$panic = TTC \leq T - \tau * log(\frac{V_{max} - V_{ref}}{V_{max} - V_{battery}})$$

Where τ is the time constant of the battery (TC) and T is the time elapsed since charging.

3.5 Determining V_{mp}

V_{mp} is the voltage that would cause the controller to draw P_{max} (maximum permissible power) from the grid. So, V_{mp} actually serves as a voltage limit along with the battery-enforced limit V_{max}.

$$V_{mp}^{t} = V_{battery}^{t-1} + \frac{P_{max}^{t}}{I^{t-1}} \;\; s.t. \; I_0 = \infty$$

3.6 Determining V_{in}

Once we have the equations, we get the actual voltage applied across the batteries as

$$V_{in} = \begin{cases} min(V_{max}, V_{opt}, V_{mp}) & panic = False \\ min(V_{max}, V_{mp}) & panic = True \end{cases} \tag{2}$$

4 Results

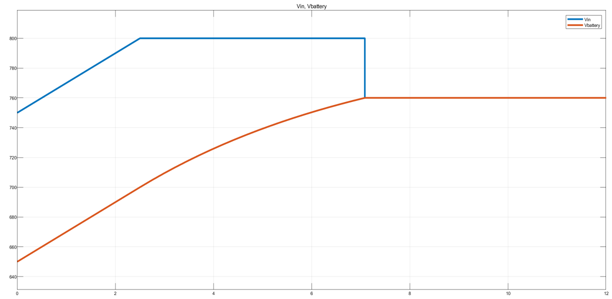
The conditions we take into consideration are: Time duration is 12 hours, $P_{max} = 1000W$, $V_{max} = 800V$, $price_1 = 10$ cents/Wh , $price_2 = 20$ cents/Wh. Power threshold, P_{th} varies through the day as shown in Fig. 4 We assume that the system starts its internal clock once the charging has begun, hence the charging profiles start from 0, and end after simulating the behavior for 12 hours.

We tested the developed battery charging optimizer under the following scenarios, primarily based on the **panic** condition, wherein the battery charges as fast as possible, to keep up with the time constraint. They are as follows:

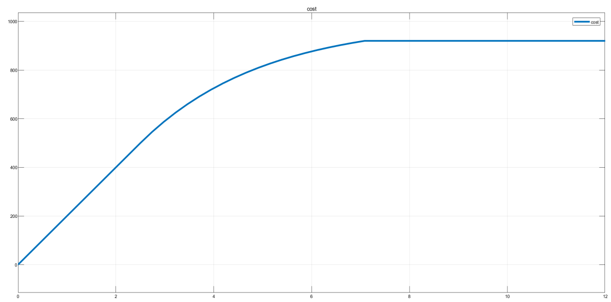
4.1 Baseline Scenario

Setting: Regular charging: Charge battery till $V_{ref} = 760V$, from $V_{init} = 650V$, such that it can complete charging under the time to charge, $TTC = 12$ hours.

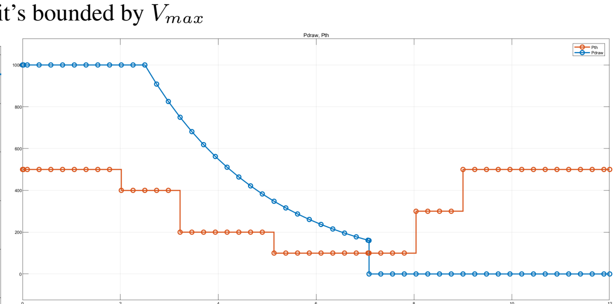
Outcome : Total time taken to charge the battery = 7.094 hours. Total cost incurred = 920 cents



(a) V_{in} and $V_{battery}$ over time. V_{in} is bounded by P_{max} for a while, after which, it's bounded by V_{max}

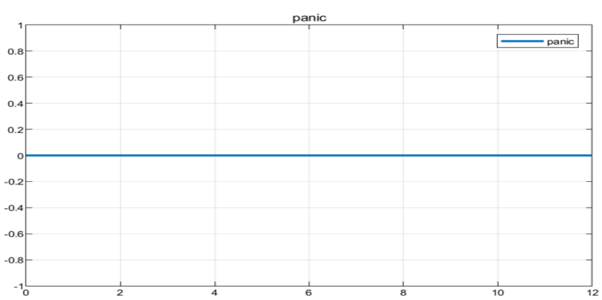


(b) The cumulative cost. It's linear until the charging voltage becomes bounded by V_{max}

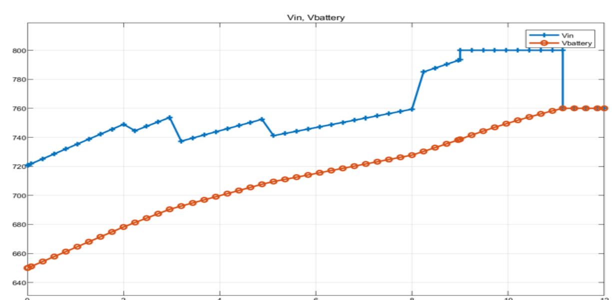


(c) P_{draw} and P_{th} over time. P_{draw} is mostly above the threshold due to greedy charging and only comes down because of bounded charging voltage.

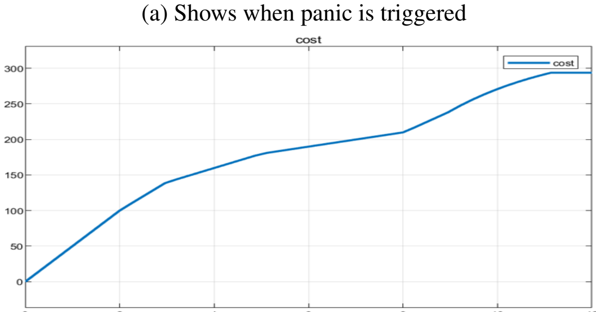
Figure 5: The baseline charging (no optimization) scenario. The controller still respects the safety conditions.



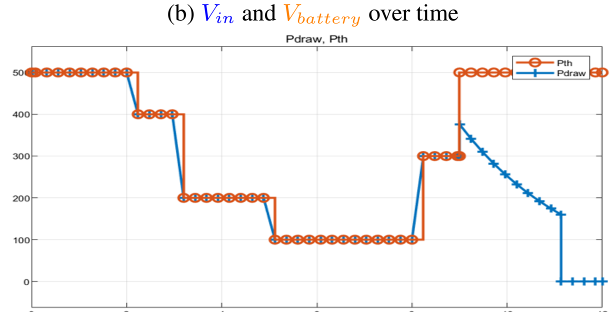
(a) Shows when panic is triggered



(b) V_{in} and $V_{battery}$ over time

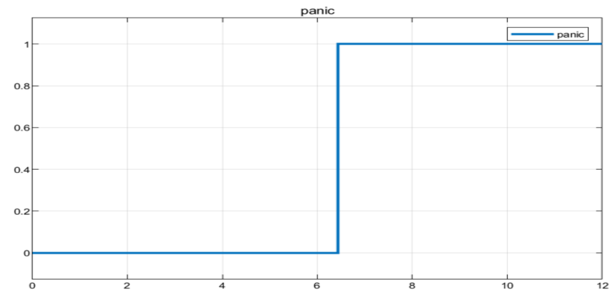


(c) The cumulative cost

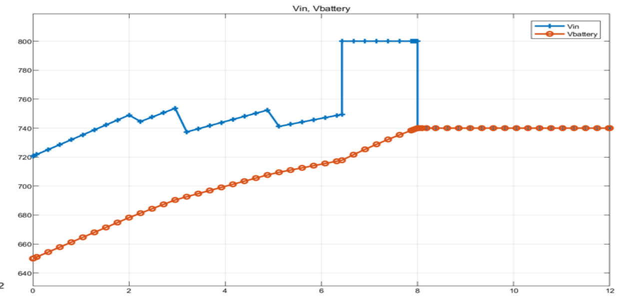


(d) P_{draw} and P_{th} over time

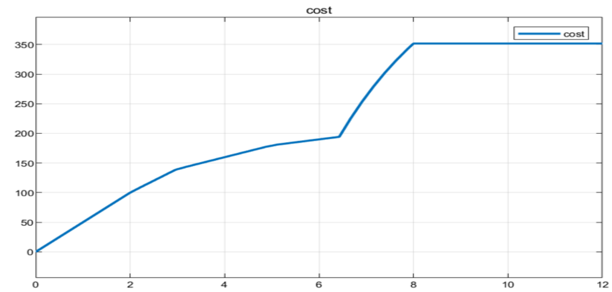
Figure 6: The charger does not go into 'Panic' mode and charges the battery always under the power threshold, and charging is fully optimized. The charging cost is the lowest.



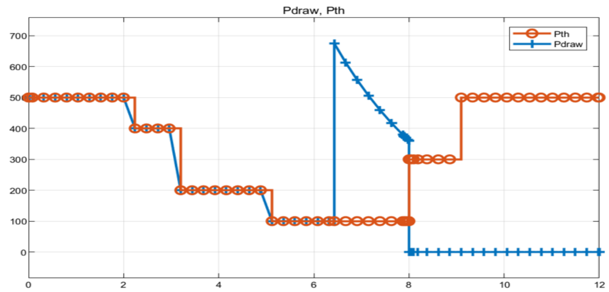
(a) Shows when panic is triggered



(b) V_{in} and $V_{battery}$ over time



(c) The cumulative cost



(d) P_{draw} and P_{th} over time

Figure 7: The charger hits the 'Panic' mode quite late when it realizes that it won't have enough time to completely charge the battery if it remains under the optimal power draw threshold. Once the panic hits, it draws higher power ($P_{th} < P < P_{max}$) bounded by the maximum charging voltage V_{max}. Charging is sub-optimal and the charging cost is higher than optimal.

4.2 Scenario 1: No panic

Setting: Regular charging: Charge battery till $V_{ref} = 760V$, from $V_{init} = 650V$, such that it can complete charging under the time to charge, $TTC = 12$ hours.

Outcome : Shown in Fig. 6. Total time taken to charge the battery = $11.138\ hours$. Total cost incurred = $293.8 cents$. The is more than 3x reduction in the charging cost than the baseline. The controller achieves this by waiting for the grid load to subside so that it can charge in optimum rate premiums. Fig. 6a, Fig. 6c charger and Fig. 6b, Fig. 6d shows the response of the battery, for the duration we considered.

4.3 Scenario 2: Late panic

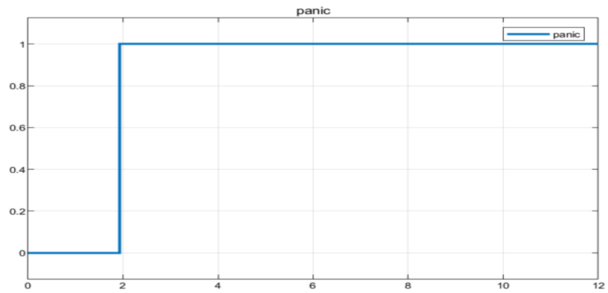
Setting: Regular charging: Charge battery till $V_{ref} = 740V$, from $V_{init} = 650V$, such that it can complete charging under the time to charge, $TTC = 8$ hours.

Outcome : Shown in Fig. 7. The controller starts charging the battery under the power threshold, but then it realizes that it does not have enough time remaining to complete the charging within desired TTC. This causes it to trigger 'Panic', and starts charging at the maximum voltage, and maximum power it can safely draw. The cost of charging increases ($351.8 cents$), compared to the previous scenario, as the higher rate of charging causes it to pay at $price_2$ rates (as shown in the higher sloped region in Fig 7c, between hours 6 and 8).

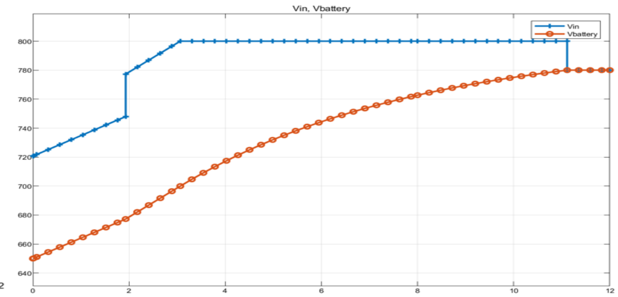
4.4 Scenario 3: Early panic

Setting: Regular charging: Charge battery till $V_{ref} = 780V$, from $V_{init} = 650V$, such that it can complete charging under the time to charge, $TTC = 11$ hours.

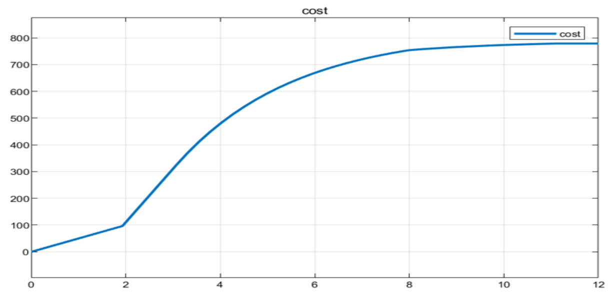
Outcome: Shown in Fig. 8. Under these conditions, the charger hits maximum voltage early, as shown in Figure 8b, and turns on the panic mode (Figure 8a). This results the maximum power draw available, for the entire duration after panic is 1. The cost of charging goes exponentially higher, to 800 cents.



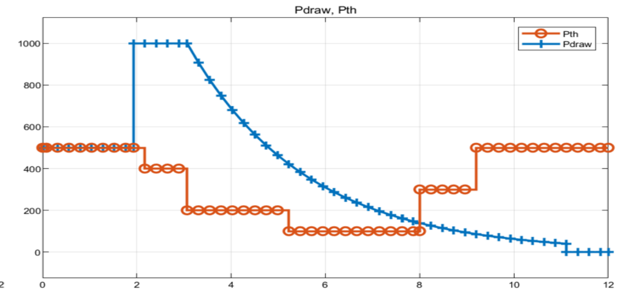
(a) Shows when panic is triggered



(b) V_{in} and $V_{battery}$ over time



(c) The cumulative cost



(d) P_{draw} and P_{th} over time

Figure 8: The charger triggers the 'Panic' mode very quickly. The charging cost is very high.

5 Conclusion

As we can see optimizing for the charging of electric batteries is challenging, especially considering the evolving background conditions, like price and grid's power constraints. We need to carefully make the decision when to charge to make full use of the lower prices. For future work, we plan to add improvements to the optimization implementation, by introducing a predictive price model, and base the charging on the price model.

In conclusion, EV battery charging optimization at charging stations is an important consideration for charging station operators, EV owners, and the wider community. By optimizing the charging process, we can help to reduce the overall cost of charging (upto 3x in our simulation), improve the reliability and stability of the electric grid, and improve the overall efficiency of the charging station.