Virtual Battery Charging Station Utilizing Power-Hardware-in-the-Loop: Application to V2G Impact Analysis

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***Abstract*- With the issues of fuel cost and environmental impact on the rise, the concept of replacing conventional vehicles with plug-in hybrid electric vehicles (PHEVs) has become essential. The main goal of PHEV implementation focuses on the ability to utilize electrical propulsion to assist the internal combustion engine. However, the batteries for the PHEV must be recharged using grid energy. This paper will study the effects of PHEV charging at the sub-transmission level through modeling/simulation and power hardware in the loop including an actively controlled drive system and controllable load.**

Index Terms—*active front-end unit, Power-hardware-in-the-loop, Shepherd's equation, voltage source inverter*

I. Introduction

Plug-in hybrid electric vehicles (PHEVs) utilize large battery packs consisting of multiple cells. These batteries have a wide voltage range depending on vehicle type and application [1]-[3]. These multi-celled battery packs can consume substantial amounts of power from the charging station in which it has to be connected when the battery is depleted [3]. A few vehicles connected to the grid via a battery charger may not have a substantial impact; however, at high vehicle penetration levels the impact on the grid will be considerable.

Most utilities have a generation capacity that exceeds the power required during normal operating conditions; however, the replacement of conventional vehicles by PHEVs certainly will result in an increased demand. This increased nonlinear power demand can lead to such problems as voltage sag, transmission line temperature increase, harmonics, and instability of the power system. To answer these questions, an experimental environment is developed in the laboratory that can be utilized to emulate multiple PHEVs being charged at random time intervals on a single source in order to model how a commercial charging station would supply energy to a group of PHEVs and to measure this impact on the grid system it is connected to.

II. Battery Modeling

Using an energy storage system comprised of multiple battery cells is a popular proposed way of providing propulsion for PHEVs. Although there are multiple battery cells involved, the energy storage system will act as a single battery and, therefore, can be modeled as such. The ability to model an energy storage system with multiple battery cells as a single battery is an important simplification that can and has been made in this work, especially since energy systems are complex and usually contain proprietary information that cannot be easily obtained in order to build a model. Through this simplification, the ability to utilize experimental data from an actual energy storage system has been made possible. In conjunction with research partners, discharge curves were produced through experimentation by dissipating a Lithium-ion battery based energy system at 10.03 A and 5.01 A chosen due to its popularity to be implemented in hybrid vehicles. The results from the experimentation are shown in Fig 1.

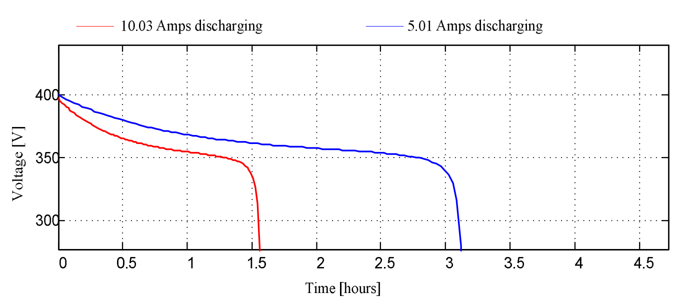

Fig. 1. Discharging curves obtained from actual battery through experimentation

Fig. 1 displays the discharging results of the 345.6 V energy storage system that was experimentally tested. Although the system is rated at 345.6 V, the system reaches a maximum of approximately 400 V when completely charged. The two curves shown in Fig. 1 represent the voltage discharge under the two constant currents previously mentioned. The energy storage system tested had a total rated capacity of 15.04 ampere-hrs, so under a 10 A load the battery would approximately take 1.5 hours to completely dissipate, as shown. In order to implement this energy system from a Power Hardware in the Loop (PHIL) aspect, it was necessary to develop a battery model in software in order to accurately reproduce the charging/discharging characteristics the physical system has.

Multiple battery model topologies were considered for the development of the charging system. Battery modeling has been a commonly researched topic with many papers/transactions published proposing a wide range of models both mathematic and circuit-based [1-5]. Since an electrical model would create complexity and slow down simulation time, a mathematical model was developed that encapsulates the full charge/discharge curve characteristics. The mathematical model is a block representation based on Shepherd's equation that was derived in order to best explain the nonlinear relationship between the State-of-Charge (SOC) and the voltage at the terminals of the energy storage system. This polynomial shaped curve can be seen in Fig. 2.

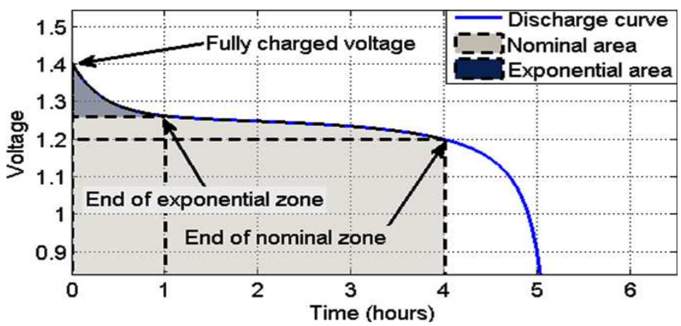

Fig. 2. Nominal current discharge characteristics of a battery

Fig. 2 shows the discharge curve of a 5 A-hr, 1.2 nominal voltage battery from an initially completely charged state to a completely dissipated final state. As shown in Fig. 2, the voltage curve of a battery during charging/discharging contains three main processes that take place: an exponential drop from full charge as the battery begins to dissipate, a slowly falling linear section around rated voltage where the battery is usually operated, and a steep nonlinear curve where the battery approaches its completely dissipated voltage level. Fig. 3 shows the same voltage discharge curves as in Fig. 1, but plotted against the amount of charge dissipated from the battery instead of plotted with time of the energy storage system experimentally tested. The curves were plotted against discharge in order to obtain the correlating SOC at specific points along the voltage curve. These points are indicated by the numerically labeled red dots in Fig. 3.

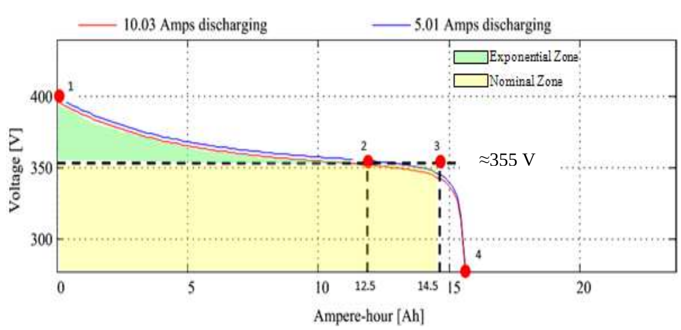

Fig. 3. Voltage discharge curve of energy system with key points

Each of the indicated points has an importance in expressing the characteristics of the energy storage system mathematically so that it may be modeled. Six values must be obtained for the purpose of modeling the system: voltage at full charge, point 1, voltage and SOC at the end of the exponential zone, point2, voltage and SOC at the end of the nominal zone, point 3, and total battery charge capacity, point 4. Obtaining these values makes it possible to calculate the coefficients in Shepherd's equation. Each of the coefficients contains the critical values that were obtained from the voltage discharge curve. These coefficients are commonly referred to as A, B, and K and are calculated using the expressions in (1)-(3).

$$A = V_{Full} - V_{Exp} \tag{1}$$

$$B = \frac{3}{Q_{Exp}} \tag{2}$$

$$K = \frac{(V_{full} - V_{Nom} + A(\exp(-B \cdot Q_{Nom}) - 1) \cdot (Q - Q_{Nom})}{Q_{Nom}} \tag{3}$$

Coefficient A is defined as the exponential zone amplitude, with units of volts, and can be calculated by subtracting the voltage amplitude at the end of the exponential zone from the voltage at full charge as in (1). Coefficient B is defined as the exponential zone time constant inverse, with units of Ah^{-1}, and can be calculated using the charge at the end of the exponential zone as in (2). Coefficient K is defined as the polarization voltage, with units of volts and can be calculated as shown in (3). Shepherd's equation, as shown in (4), contains the coefficients that were obtained in order to model the energy storage system. Shepherd's equation consists of three main pieces that describe the three main sections of the charge/discharge curve of a battery.

$$E = E_0 - K\frac{Q}{Q - \int idt} + A\exp\left(-B * it\right) \tag{4}$$

Essentially, Shepherd's equation states that the voltage at the terminals of the battery, E, is equal to the nominal voltage, E_0, minus the nonlinear zone voltage, plus the exponential zone voltage. The existence of the exponential zone voltage term and nonlinear zone voltage term in Shepherd's equation allows the equation to capture the natural polynomial shape of the voltage curve produced as the battery is charged/discharged. Whether or not the exponential zone voltage term or nonlinear zone voltage term dominates the equation and dictates the shape of the curve depends on multiple parameters including the amount of current and how long it has been flowing.

One last important piece of information that must be obtained is the internal resistance of the energy storage system. The internal resistance can be acquired from the manufacturer's specification sheet or experimentally determined through impedance spectroscopy [6]. Unfortunately, internal resistance of a battery is not a constant value and depends on many factors such as temperature and current draw. Obtaining the value of the internal resistance of a battery is a tricky feat and needs to be done according to the conditions that the battery is going to be subjected to.

The internal resistance for the energy storage system modeled was obtained under nominal conditions using impedance spectroscopy since the model being used to simulate the system neglects temperature effects and unordinary dynamic restrictions that more complex models have the ability to do. Modeling these effects would not be beneficial in this work since the systems will be operated well within their rated values and not subjected to any strange transient loading conditions.

With the parameters in Shepherd's equation solved for, the mathematical model can be incorporated as a control feedback network to the electrical circuit modeling the energy storage system. The electrical portion of the system model is represented as a simple series circuit with a dependent voltage source and a resistor. The dependent voltage source is used to model the stored energy that the system can supply while the resistor in series with this source is used to represent the internal resistance of the physical system. The complete model setup can be seen in Fig. 4.

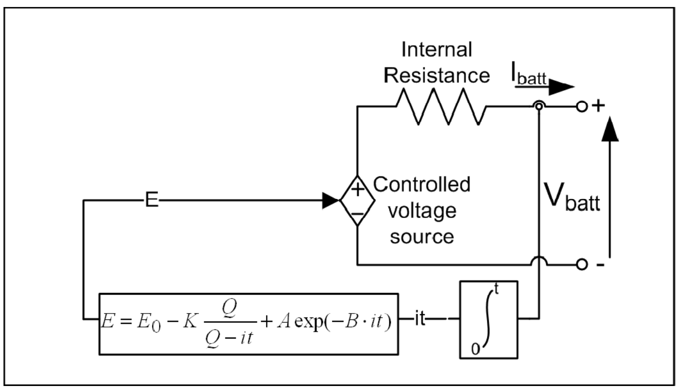

Fig. 4. Energy storage system model representation in software

The model is setup such that the current being drawn from/supplied to the energy storage system is measured with an ammeter, integrated with respect to time to obtain a continuously compounding rate of charge/discharge, and substituted into Shepherd's equation.

Shepherd's equation is then used to calculate the voltage command, E, that is sent to the dependent voltage source to represent the voltage at the terminals of the energy storage system.

III. Experimental Setup

Figure 5 shows the experimental test setup in the laboratory [7]. The setup is a power-hardware-in-the-loop (PHIL) based concept that consists of both hardware and software components interfaced via digital-to-analog (D/A) outputs and analog-to-digital (A/D) inputs. The hardware environment highlighted in orange is comprised of the power electronic building block (PEBB) as highlighted in blue, containing an active front end unit (AFU) and voltage source inverter (VSI). Connected to the PEBB is an active load bank, highlighted in green, which will be used to draw the current from the PEBB.

The PEBB is essentially a drive cabinet made up of power electronics and controls so that it can be used to realize any feasible entity that can be modeled through simulation and electronics. Its two main components, the AFU used to control the DC link voltage and the VSI that is used to synthesize an AC or DC output based on a pulse width modulation scheme.

At this point it is important to clarify that although voltage source inverters are normally used for three-phase applications by converting the DC link voltage into sinusoidal waveforms, the controls to the inverter in this system have been setup so that the A and B phases are 180° out of phase and constant thus creating the positive and negative leads of a DC system, while the C phase was set to zero. Since connecting a three-phase source to a DC battery would be illogical, the inverter had to be controlled such that it created a DC output.

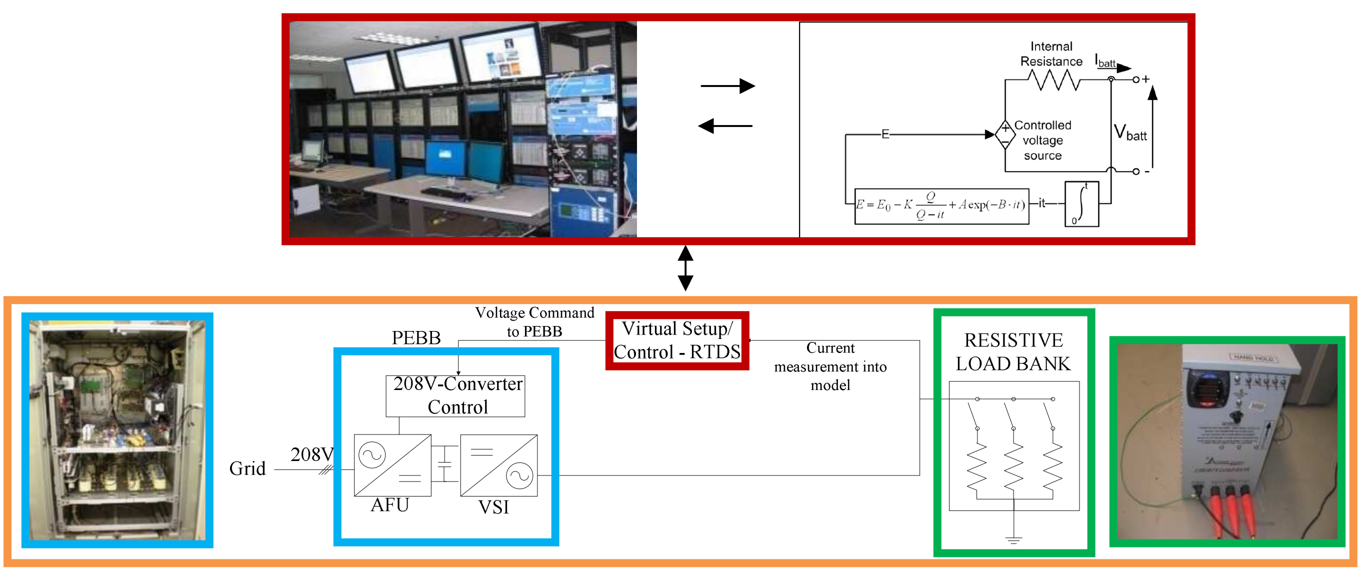

Fig. 5. Experimental test bed of virtual charger with load

As shown in Fig. 5, the PEBB is connected to an active load bank while the measured load current is sent to the simulation program, highlighted in red via A/D input where it is used in the model in Fig. 4 to obtain the battery voltage for each energy storage system developed in simulation.

The goal of the setup is to exhibit how the characteristics of a charging station would operate and affect the grid by monitoring the charging curves of each of the PHEV battery models in software and observing the line current that will be measured at the input side of the PEBB, particularly looking at the transient qualities of the current waveform during load changes. The active load bank will be changed in decreasing sequential steps so that current between the PEBB and load bank is increased as to represent PHEVs being added to the virtual charger.

IV. Simulation and Experimental Results

To validate our virtual battery model, the battery was connected directly to a resistive load to perform a controlled discharged test whose results were then compared to those of the physical energy storage system in Fig. 4. To obtain a constant current discharge a simple DC-DC converter was developed in software to control the energy system's current so that it was held constant despite the system's changing voltage throughout its discharge cycle. This control method is an important implementation to apply for the model validation because it allows the system to discharge in a manner in which it actually would in practice that is within its rated values and that does not fluctuate so the calculated internal resistance of the system is consistent with the actual internal resistance. The model's accurate representation of the physical energy system can be seen in Fig. 5.

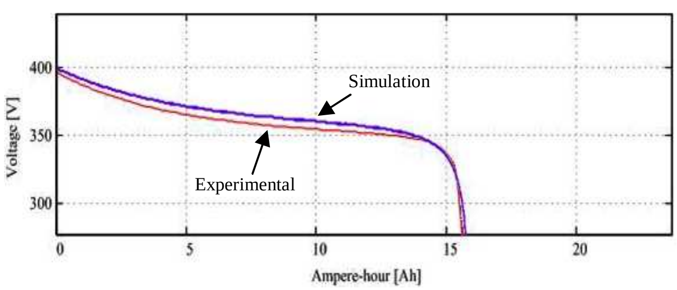

Fig. 5. Validation of software model with model

In Fig. 5 the red line represents the experimental curve obtained from the energy storage system where as the purple line represents the results obtained from the controlled current discharge in simulation, both for the 10.01 A case. Notice that the simulated curve accurately follows the experimental curve for most of the discharge confirming that our model is sufficient enough for this case where temperature, dynamics, and extreme charging rates are not considered.

Once validated, the energy system model was used in simulation in cooperation with the experimental test setup in order to analyze the effects on the grid resulting from PHEVs connected to the charger. As shown in Fig. 6 a simple step load test was conducted with sensors measuring the load current, the line current to the input of PEBB, and the "virtual charger" (VC) voltage. In the test case the load was stepped up from 15 A to 20 A at approximately 15 seconds representing an addition of PHEVs to the charger until approximately 65 seconds at which point the load was stepped back down to 15 A representing the removal of those additional vehicles.

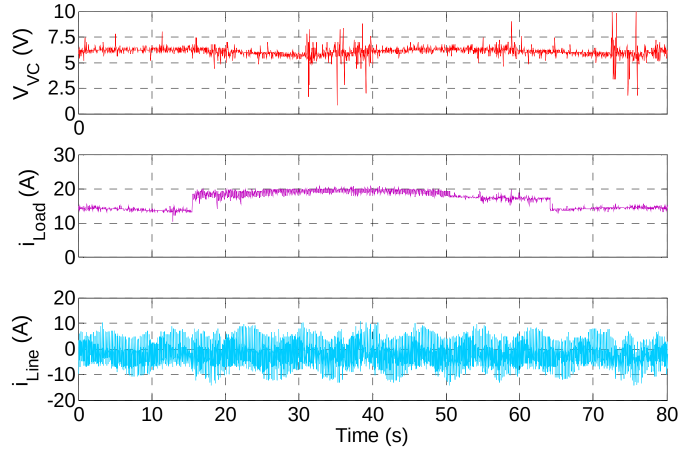

Fig. 6. Representation of PHEVs connecting/disconnecting through load bank step changes; DC link voltage (V)-red; load current (A)-purple; and line current (A)-blue.

Observe that the VC voltage in the top plot remains constant regardless of the changes in the load and line current as expected under properly operating controls of an AFU. The ability for the AFU to keep the voltage of the PEBB stable is analogous to a PHEV's charger ability to maintain a constant voltage regardless of the PHEV load it is subjected to within its rated values.

Figure 7 is a closer look at the dynamics that the charging station undergoes when a PHEV load is added to the system. Again the top plot displaying the DC link voltages undergoes negligible change when introduced to a worst case scenario, a step change in the load. The middle plot shows the 5 A step load increase along with its affects on the line current portrayed in the bottom plot.

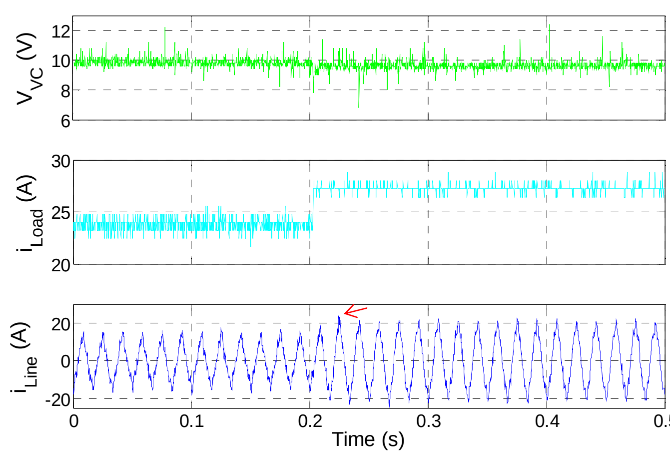

Fig. 7. Transient affects of line current as a result of step load changes; DC link voltage (top); load current (middle); line current (bottom).

Note that the 5 A load increase is representative of at most only 1 charging PHEV according to the charging infrastructure terms proposed in [8]. However, even at this minimal amount of PHEV introduction the affects are evident on the charger notated by the arrow in bottom plot labeling the initial peak in the line current created by the step change.

Although the initial peak is only approximately 2 A larger than the succeeding peaks, this value could become increasingly large with additional PHEV loads creating an undesirable impact on both the charger, and under extreme conditions, the grid.

Fig. 9 displays the results from the test case where 3 PHEV models were developed in simulation and charged with different initial connection times. In order to emulate this scenario, the PEBB command voltage was set to a constant and the load was changed in steps as shown in the top plot of Fig. 9. Also, it is evident from Fig. 9 that the point when the load is increased the next successive PHEV has been connected by observing the increase in the state of charge and voltage, or the decrease in the current sent to each of the models.

Note that the bottom plot does not display the current to each of the vehicles but instead displays the measured current from the VC to the load that is representative of the total charging current. This total current is equal to the individual vehicle current only in the case where 1 PHEV model is being charged. Although the bottom plot does not show each current, the step increase that occurs each time the load was changed is representative of how much current that single PHEV is drawing from the system.

As shown in the SOC plot in Fig. 9, the storage system models were charged from 0 to 100% SOC. However, since the energy storage system will never really reach 0 V, each of the modeled energy system's voltages started from a nonzero value as shown in the V_{batt}.

Also notice that when the batteries reached 100% SOC that they were not disconnected from the simulation but were instead limited to maintain that maximum constant value regardless of whether or not they continued to be subjected to a current.

V. Conclusion

This work presents a novel methodology and experimental test setup for the study of V2G interaction by application of PHIL. As demonstrated, the battery model and controls for the hardware implementation for the virtual battery charging station are correctly emulating the charging scenario where only a few vehicles are being charged. These results, although not at a high penetration level, could easily be extrapolated to understand the undesirable affects that mass charging could introduce to the grid without some means of correction.

It should be mentioned that previous works on the topic of grid impacts due to PHEV interaction have been published [9]; however, the majority of those works was conducted merely in a simulation environment that included little or no hardware implementation. The primary purpose of this project was to include the hardware aspect in order to observe affects that occur from a more realistic setup versus the idealistic setup produced through the use of simulation.

Additional work to be done on this project will be to increase the number of models connected to the charger, to vary the initial conditions of the models, and have the models auto-disconnect when they reach their specified maximum SOC so that current can be re-distributed among the remaining vehicles connected to the charger. Also it will be imperative to create models based on different battery topologies, chemistries, and capacities to test what affects those differences may create on the charger as well.

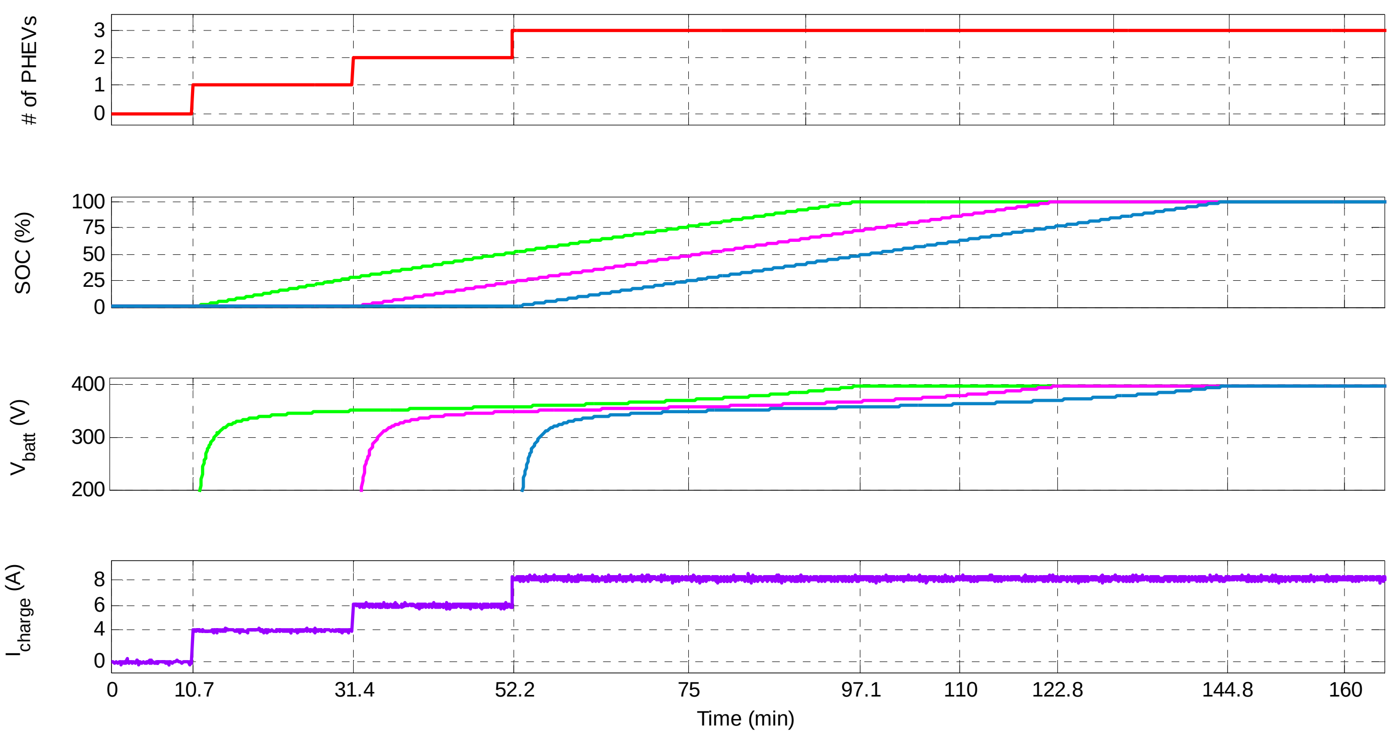

Fig. 9. Charging characteristics for the modeled PHEV energy storage systems

VI. References

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