



Modelling, Control and Battery State Evaluation of A Grid-Interactive Bidirectional Fast DC Charger for Electric Vehicles

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Abstract - This paper presents a comprehensive study on electric vehicle (EV) battery modelling, state estimation, and bidirectional charging infrastructure through the development of an integrated MATLAB Simscape framework. With the rapid adoption of EVs, challenges surrounding accurate battery management, reliable charging strategies, and grid stability have become increasingly critical. The research addresses these challenges by combining advanced battery modelling, Extended Kalman Filter (EKF)-based estimation, fast DC charging design, and vehicle-to-grid (V2G) interaction into a unified system. A detailed battery pack is modelled to capture electro-thermal dynamics, resistance behaviour, and degradation trends. EKF algorithms were implemented to estimate both State of Charge (SOC) and State of Health (SOH), demonstrating high accuracy and robustness against nonlinearities. At the charging system level, a fast DC charging station was designed with bidirectional power capability, enabling both grid-to-vehicle (G2V) and V2G operations. Converter design, LCL filtering, and harmonic analysis were incorporated to ensure grid compliance and efficient energy transfer. Beyond individual components, the framework was extended to evaluate grid-level implications of large-scale EV integration. Optimized charging and discharging schedules were proposed to mitigate peak demand, support renewable balancing, and minimize transformer loading, while simultaneously preserving battery longevity. Simulation results confirmed stable operation across diverse scenarios, validating the feasibility of the proposed strategies.

Keywords - Constant Current (CC), Constant Voltage (CV), Electric Vehicle (EV), Grid to Vehicle (G2V) and Vehicle to Grid (V2G)

I. INTRODUCTION

In recent decades, modern electricity supply infrastructure has been planned with the intention of not only strengthening operational efficiency and service reliability but also improving daily living standards for a substantial population that relies on continuous energy availability. For effective realization of an intelligent electricity management environment, upgrading of the present utility framework is required together with the systematic adoption of emerging technological solutions within the current operating structure. Electric vehicles (EVs) are widely recognized as a crucial contributor in supporting the evolution toward advanced digitally coordinated energy systems.

. Benefits of EV make it a suitable option for customers as well. V2G feature is the most the important EV characteristic in the current smart grid scenario. When state of charge (SOC) of battery reduces to minimum limit, energy is taken from supply by EVs to recharge the battery. From smart grid point of view beneficial features of EV are,

- During peak load, power requirement can be supplied by EV with bi-directional power flow characteristic.
- Furthermore, the ability for reversible power flow makes it possible to charge a vehicle at an optimal point in time based on system load conditions so that the vehicle could be charging at a time when loads are low..
- System stability and quality of power also improved with real and reactive power management when necessary.
- With V2G mode customer can earn revenue.
- Efficiency of EVs on account of fuel is more as

compared to conventional vehicles. This leads to customer savings because of vehicle related expenditure reduction.

The rapid expansion of electric vehicles in modern transportation systems has created a strong need for advanced charging and discharging strategies. In the above context, this work concentrates on the development of bidirectional fast charging system that utilizes the V2G property of EV efficiently.

This work focuses on the design and analysis of a fast DC charging station supporting two-way power exchange between the vehicle and the power utility grid. The model of the above-mentioned system is proposed, in the environment of MATLAB/Simulink. It includes converter on supply side, controller on EV side, model of battery, local controller and the interface with the grid.

The system supports operation of both modes of charging and discharging based on the load condition. Under normal conditions, it ensures efficient charging of EV batteries. In contrast, during V2G operation, the stored energy in vehicle batteries can be delivered back to the grid when needed. This feature supports power demand, improves load balancing, and enables reactive power compensation.

The control strategy is designed with user preference as the highest priority. In particular, when a user initiates charging, the system prevents any discharge from the vehicle. Thus, participation in V2G operation remains entirely optional and does not interfere with the user's charging requirements.

The Battery Management System (BMS) is often described as the brain of the EV battery. Its main role is to monitor, protect, and optimize the use of the battery cells, ensuring that they operate within safe and efficient limits. Without a reliable BMS, the performance of even the best battery technology would be compromised.

Accurate SOC estimation helps drivers know the remaining driving range, while SOH estimation is important for long-term maintenance and warranty decisions. Traditional methods such as Coulomb counting or open-circuit voltage measurement often fail under fast charging or dynamic driving conditions because of nonlinear battery behaviour. More advanced approaches, such as the Extended Kalman Filter (EKF), combine mathematical models with real measurements to improve accuracy.

In addition, the BMS plays a crucial role in grid interaction. If an EV is to support Vehicle-to-Grid (V2G) operations, the BMS must coordinate charging and discharging cycles in a way that minimizes additional stress on the battery. Thus, efficient battery management is not just important for the vehicle but also for its role in the wider energy ecosystem.

• *Role of MATLAB Simscape Toolbox*

Practical experimentation with EV batteries and grids is expensive, time-consuming, and sometimes unsafe. For this reason, simulation tools have become an essential part of EV research. Among these, MATLAB Simscape offers a highly flexible and integrated environment to model physical systems, test control strategies, and evaluate

performance under different conditions.

The Simscape Battery Toolbox provides ready-to-use models for different battery chemistries, allowing researchers to capture both electrical and thermal behaviours. By parameterizing models with real test data, one can simulate realistic conditions such as cell imbalance, temperature rise, or degradation over cycles.

Some of the key advantages of using MATLAB Simscape include:

- The ability to create detailed models of cells, modules, and packs.
- Integration of thermal and electrical domains, enabling studies of heating effects.
- Implementation of advanced estimation methods such as EKF for SOC and SOH.
- Testing of bidirectional charger designs, including AC-DC and DC-DC converters.
- System-level studies that include grid dynamics, charging schedules, and load profiles.

Using this toolbox, strategies for G2V and V2G can be validated virtually before deployment in the field. This saves cost, improves safety, and accelerates innovation.

A. *Research Aims and Objectives*

Despite progress in EV technology, there are several gaps that limit large-scale adoption:

1. Battery degradation: Uneven cell performance and thermal stress reduce the lifespan of packs, increasing costs.
2. SOC/SOH estimation limitations: Traditional estimation techniques lack accuracy under fast charging and dynamic driving.
3. Simplified models: Many studies rely on overly simplified battery models that fail to capture nonlinear behavior.
4. Charger design gaps: While G2V chargers are common, efficient and grid-compliant bidirectional chargers for V2G are still underdeveloped.
5. Grid impact: Large-scale uncoordinated EV charging can destabilize power networks, and uncontrolled V2G may accelerate battery wear.

Hence, there is a strong need for an integrated framework that combines accurate battery modelling, advanced estimation algorithms, robust charger design, and smart grid interaction strategies.

B. *Research Aims and Objectives*

The overall aim of this research is to develop a comprehensive framework for EV battery modelling, SOC/SOH estimation, and bidirectional grid interaction using MATLAB Simscape. The specific objectives are:

1. To model EV cells and packs with various electrical characteristics.
2. Use tabulated data and datasheet to extract battery parameters for modelling using MATLAB/Simscape.
3. To implement the EKF for accurate SOC and SOH estimation.
4. To design bidirectional chargers that support both G2V and V2G operations while meeting efficiency and grid compliance standards.

To evaluate the impact of large-scale EV integration on the grid and control strategies.

5. To validate all strategies using MATLAB Simscape simulations under realistic conditions.

By achieving these objectives, the research aims to provide a practical solution that addresses both the challenges of EV operation and their integration with the energy system.

C. Research Contributions

Although there is growing research on electric vehicles, many existing studies tend to focus on isolated aspects such as battery modelling, SOC estimation, or charging infrastructure. Very few studies bring these different elements together into a single integrated framework that considers both the vehicle-level challenges and the grid-level impacts. This thesis makes a unique contribution by bridging that gap.

The key contributions of the thesis can therefore be summarized as:

1. Development of a detailed EV battery pack model with electrical dynamics.
2. Implementation of EKF for SOC and SOH estimation adapted to EV conditions.
3. Design of a bidirectional charger capable of G2V and V2G operations.
4. Evaluation of grid impacts of large-scale EV adoption.
5. Proposal of smart scheduling strategies for charging and discharging that balance grid support with battery longevity.
6. Validation of the entire framework through MATLAB Simscape simulations.

This combination of contributions demonstrates the originality and significance of the research. It not only advances academic understanding of EV battery-grid integration but also provides practical solutions that can support the growth of electric mobility in emerging.

II. BATTERY MODELLING

The overall performance of an electric vehicle mainly depends on the quality and behaviour of its battery pack. Important factors such as travel distance per charge, charging duration, vehicle acceleration, operational safety, and long-term reliability are directly influenced by the selected battery cell. Due to its good efficiency, mechanical strength, and ease of manufacturing, the Molicel cell is widely considered as a strong candidate for EV applications.

In addition to battery modelling, included the use of the Extended Kalman Filter (EKF) as an effective estimation method. The EKF is applied to estimate State of Charge (SOC) and State of Health (SOH). By combining detailed cell data with system-level estimation techniques, a strong base is created for accurate simulations and intelligent battery management design.

The MATLAB-based plots below show the important performance characteristics of the Molicel P45B cell. These graphs explain voltage behaviour, resistance change, thermal variation, and ageing trends. All these are necessary for accurate battery modelling and EKF-based state estimation.

Figure 1 : Discharge Rate Characteristics.

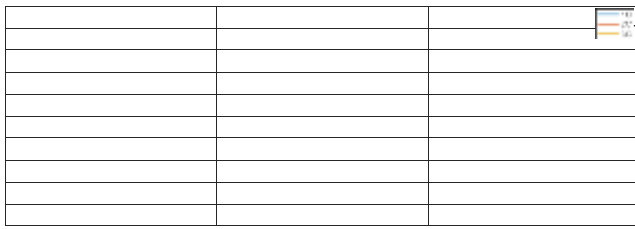


Figure 2: CC-CV Charging Voltage.

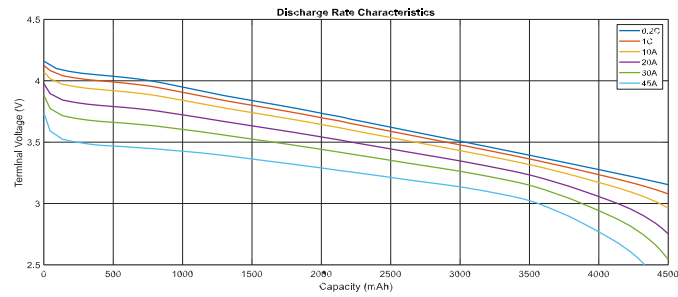


Figure 3: CC-CV Current During Charging.

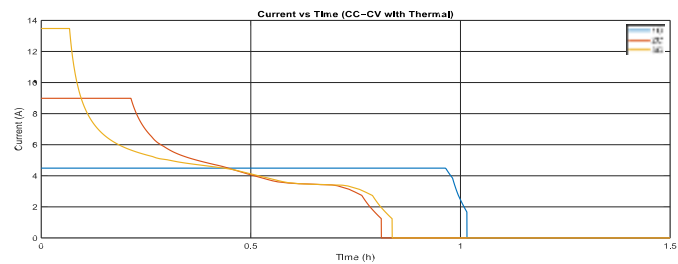


Figure 4: SOC Variation at Various Charging Rates.

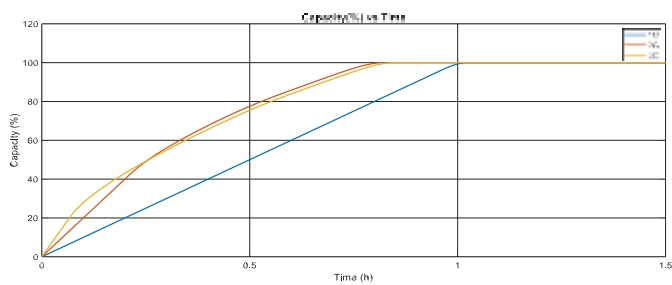
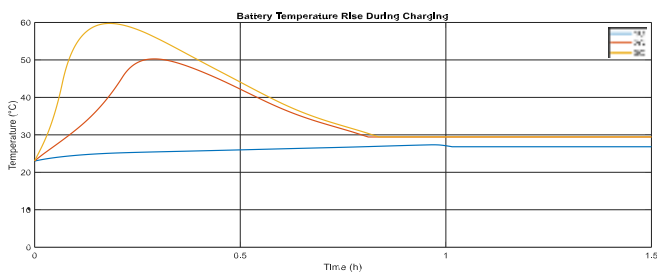


Figure 5: CC-CV Charging Temperature Profile.



vehicle. High charging rates can be achieved and onboard conversion is minimized in each EV to reduce system cost.

The overall schematic of EV charging station is presented in Fig. 15. The grid connection is established with an inverter and an LCL filter in between and a transformer is incorporated. There is a common DC bus where several electric vehicle chargers can be plugged in parallel. The simultaneous charging of multiple EVs is feasible, along with bidirectional power flow. During the operation under V2G condition, the plugged-in vehicles provide energy to the grid whereas during other situation it can also be exchanged between the cars.

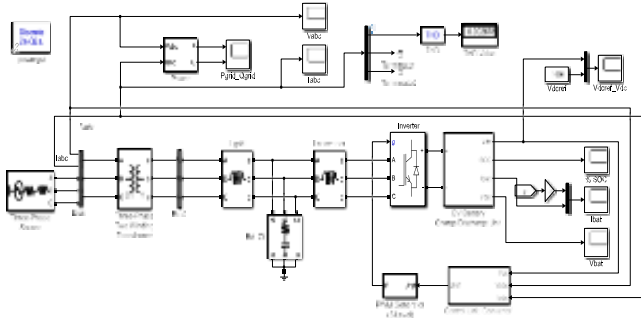


Figure 15: MATLAB/Simulink Model of a Fast DC Charging Station.

In grid-to-vehicle mode, electrical power flows from the utility grid to the EV battery and charging takes place using the CC-CV method. The initial state of charge is set at 70%. During this process, the battery voltage slowly increases while the charging current follows the reference command accurately. This ensures that charging happens in a controlled and efficient way without exceeding safe operating limits.

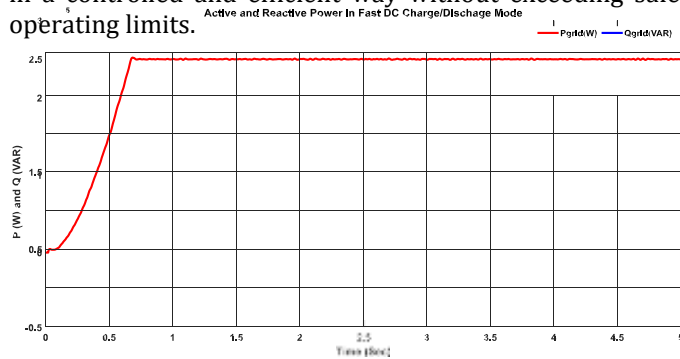


Figure 16: Active and Reactive Power in Charging Mode.

In Fig. 16, active power is positive, which indicates that power flows from the grid to the battery. Reactive power remains close to zero throughout the operation, which means the charger works at nearly unity power factor. This improves system efficiency and reduces stress on the grid.

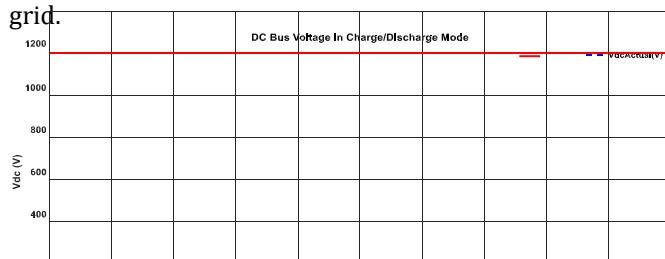


Figure 17: DC Link Voltage in Charging Mode.

The DC-bus voltage remains tightly controlled around its reference value while charging is taking place. Even though power flows from the grid to the battery, the control system maintains stable DC voltage. This stability ensures proper operation of the inverter and safe charging of battery cells.

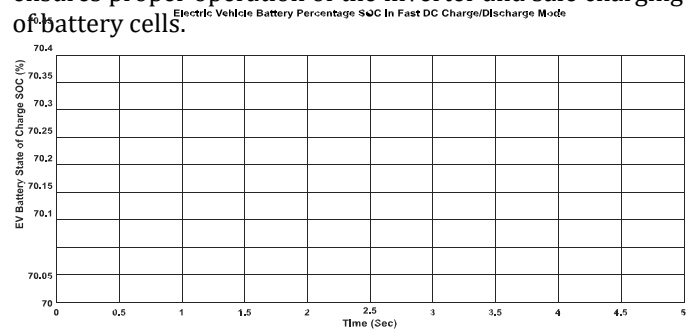


Figure 18: SOC Rise in Charging Mode.

The SOC increases gradually as the battery receives energy from the grid. During constant current charging, the SOC curve rises almost linearly. When the constant voltage stage begins, the slope becomes smaller because the current reduces. This behaviour reflects realistic CC-CV charging characteristics.

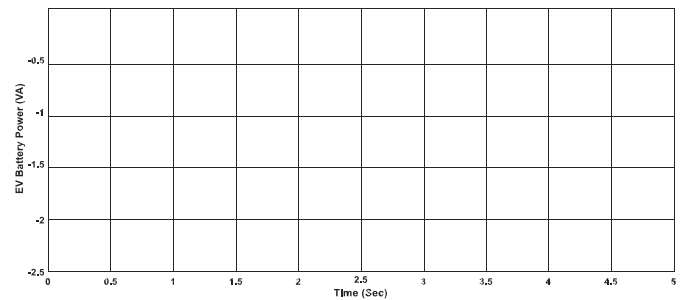


Figure 19: Battery Power in Charging Mode.

Fig. 19 shows battery power during grid-to-vehicle charging. The power value remains nearly constant throughout the short simulation period. The negative sign indicates that power is flowing into the battery. The flat profile shows stable charging without sudden changes in power level.

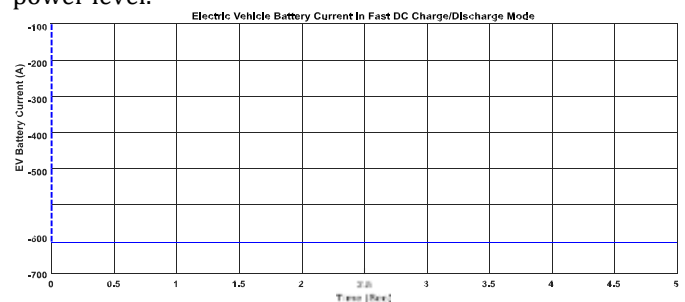


Figure 20: Current in Charging Mode.

Fig. 20 compares reference current and actual current during charging. Both values quickly reach the required level and remain steady. The close matching of the two curves shows that the current controller works accurately and maintains stable charging current.

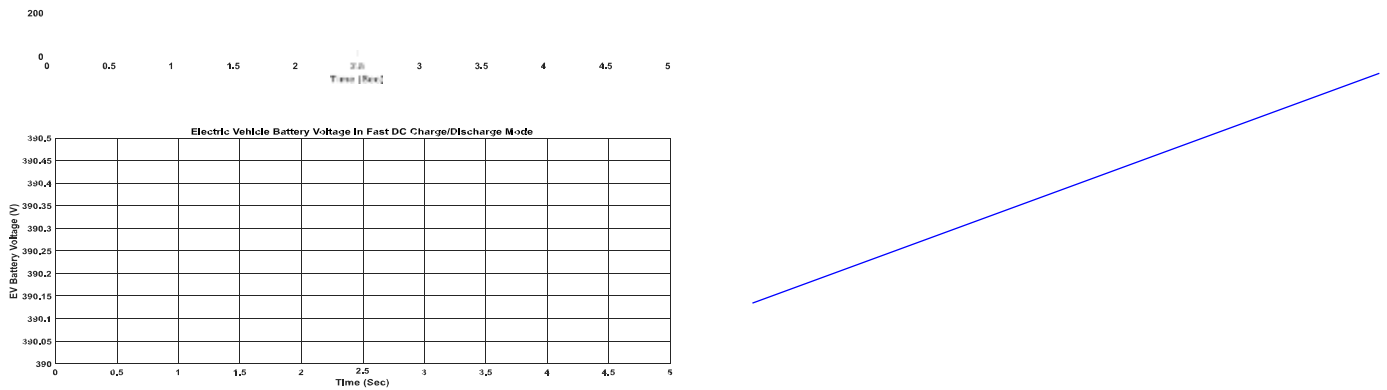


Figure 21: Battery Voltage in Charging Mode.

The battery voltage slowly increases with time as energy is stored inside the battery. The gradual rise in voltage confirms proper charging behaviour. This smooth increase also shows that the CC-CV method prevents sudden voltage jumps.

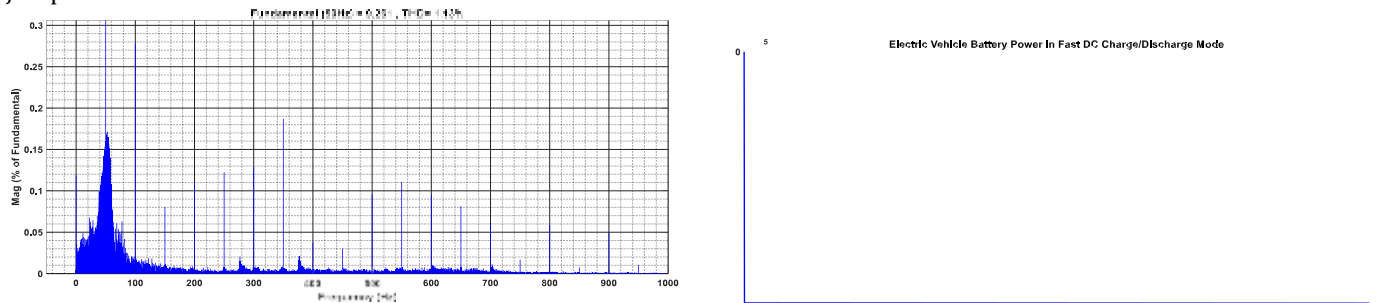


Figure 22. THD in Charging Mode.

The total harmonic distortion (THD) of the grid current remains low during charging. This indicates that the inverter switching and filter design are effective. Low THD ensures that the charging station does not introduce unwanted harmonics into the grid.

I. CONCLUSIONS

This work has presented an integrated investigation into the modelling, estimation, and grid interaction of electric vehicle (EV) batteries, with an emphasis on ensuring reliable operation under real-world conditions. Beginning at the cell level, a high-fidelity cell level model of is developed and extended to a battery pack configuration. This detailed representation captured nonlinear electrical dynamics, resistance variations, and thermal characteristics, thereby forming a strong foundation for system-level analysis. A Simscape-based model of a lithium-ion battery pack is developed, incorporating constant current-constant voltage (CC-CV) charging method, along with electro-thermal behavior and state estimation through an Extended Kalman Filter (EKF). The model effectively captures nonlinear battery dynamics such as voltage-SOC characteristics and internal resistance. Simulation outcomes confirm the reliability of EKF-based monitoring for SOC and SOH, making it suitable for real-time battery management systems.

At the infrastructure level, a bidirectional fast DC charging station was designed and validated. The inclusion of both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations highlights the dual role of EVs as consumers and providers of energy. The proposed system achieved stable DC link regulation, near-unity power factor operation, and compliance with harmonic distortion standards, confirming its readiness for grid integration. Importantly, the charger design was not



only efficient but also protective of battery health, balancing fast charging demands with longevity considerations.

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