Analysis of Fire Safety Sensors and Controls with Design Scenarios for a Reliable Residential and Commercial Vehicle to Grid Integrated Energy Storage Systems

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Abstract
Recent safety concern for EV batteries raise concern for reliable Vehicle to Grid distributed energy system. This paper analyzes sensors monitoring temperature change, controls and components of batteries to detect safety issues sending alert before battery malfunction. Features like AutoShutOff while battery device is charging or discharging for peak grid demand impact integrated energy storage dependability to implement better V2G technologies where EV battery sensor detects safety risks early to disconnect from grid to eliminate fire danger. Further propose design scenarios of stable V2G integrated energy storage system to evaluate the performance for reliable residential or commercial distributed energy system. The objective is to compare design scenarios of large scale or microgrid with V2G integrated energy storage system with better monitoring sensors and controls tracking history of thermal, component and environmental factors to minimize impact of safety issues over lifecycle.

Keywords— Electric vehicles, Li-ion batteries, Fire protection, vehicle to grid, Energy policy, Battery Thermal Management System

I. Introduction

The shift in United States transportation market towards Electric Vehicles (EVs) poses a challenge of increased electricity demand, safety and reliability. In 2025 United States electric grid requires 18.2 GW of Energy Storage Systems for peak demand and emergency backup in which V2G mobile storage could offset 90 MW of variable power supply as per the Vehicle to Grid Integration Assessment report by Department of Energy. V2G technology is currently in testing phase with various pilot programs to study grid integration objectives, opportunities and limitations. In May 2025, vehicle to grid fire event occurred in Mountain View, California, where an EV charging system malfunction caused fire that spread to three other EVs in a commercial office building parking lot. Prior May 15, 2024, Gateway Energy Storage Facility in San Diego, California, experienced a BESS fire with continued flare-ups for seven days following the fire. The facility held about 15,000 nickel manganese cobalt lithium-ion batteries. Fire risk has been a major concern in deployment of Electric Vehicles causing human and property loss in residential and commercial sector making it essential to have better safety regulations and manufacturing standards for EV Li-ion battery storage system. Battery fires are caused due to badly manufactured parts, cheap modifications to existing batteries, poor storage and charging practices combining to create a spike in e-bike battery-related fires. When one cell of a lithium-ion battery malfunctions, it causes thermal runaway, that's when a battery cell can't dissipate the heat generated, it spontaneously ignites, causing an explosion [1], which produces particulate white toxic smoke highly flammable," said the Fire Department of New York's chief of fire prevention at a City Council hearing on e-bike battery fire safety. NYC has introduced many EV safety programs. Electric Vehicle users require E-Micromobility battery charging equipment and installation approval from the Fire Department. New York has adopted a Lithium battery Model Law to mandate use of certified battery systems, maintaining safe zoning and battery disposal practices. The U.S. Fire Administration (.gov) is actively working on changing National Fire Protection Association (NFPA) 70: National Electric Code to include emergency disconnect requirements for EV charging stations. The UL standards for V2G safety and performance include UL 1741 UL 9741 and UL3141 for power control functionality. Li-ion batteries degrade over time due to charge and discharge cycles. Other factors to consider are thermal runaway due to overheating and chemical composition as Li-ion batteries may contain volatile electrolytes when exposed to high temperature or physical damage can release flammable gases. Liquid cooling is a preferred methods of Cooling in Electric Vehicles than Air cooling with its own potential threat in running a Battery [6]. The research paper reviews and addresses the question of how to optimize the V2G technologies, EV BMS controls and sensors to better integrate with Distributed Energy system (DER) in a residential or commercial or microgrid scenario to manage safety and reliability concerns?

II. METHOD

The research paper explores methodologies to develop safer and reliable V2G enabled Lithium-ion battery management systems (BMS) integrated with stationary energy storage system for a reliable grid operation to address safety strategies during a fire event by proposing a model to predict risk factors using thermal sensors and controls. Additionally, making a case for better Fire Protection EV Policy to promote vehicle to grid (V2G), vehicle to microgrids, vehicle to home or building energy storage systems. The real time notification systems of potential fire risk include wireless, electromagnetic or Infrared tech, Thermal and Gas sensors to detect overheating and hazardous toxic gas to employ safety mechanisms. The charging coordinates of EV batteries depend on the design of batteries, their charge status, temperature, former cycle history, and usage. There are two main charging systems, constant current charging, and constant current–constant voltage charging. The constant current charging often results in overcharging the battery, thereby overheating it. The constant current–constant voltage method eliminates the risk of overcharging but increases the charging time of the battery. As an optimization, the battery is charged at a constant current until a preset voltage is reached, and then charged at a constant voltage. A battery management system (BMS) is employed to act as an overall controller of the battery health by monitoring its charge status, temperature, battery cycles, and other such parameters, providing data to and communication with other modules [4]. EV BMS Modelling Tools measures how much Battery absorbs, stores and releases energy [2] to predict Battery performance for charge and discharge characteristics and risk assessments [3]. Battery system use various control networks to analyze data points like Fuzzy logic [7] or Neural Networks for Storage systems [2]. EVs use Power share Apps to control battery needs which could provide information to optimize the Battery performance for safety and reliability. Grid to Vehicle and V2G technology solutions are limited to operation and control of grid-able vehicles, integrated energy storage and battery management systems, charging infrastructure and chargers, include load forecasting for distributed systems, V2G interfaces, communication standards, and charging topologies as well as environmental impacts and economic benefits [4].

A. Designing a Reliable V2G Residential and Commercial scenario integrated with Energy Stirage systems

As part of my research for Smart Energy Enterprise Development Zone (SEEDZ) Program with a Silicon Valley nonprofit in collaboration with Bay area corporate stakeholders Fig. 1, a V2G scenario shows how networked Electric Vehicle Supply Equipment (EVSE) is connected to cloud-based services for EV charging infrastructure for residential or commercial users. EVSE Systems include the electrical conductors, related equipment, software and communications protocol that deliver energy efficiently and safely to and from electric vehicles. EVSE equipment is classified as Level1 (120 Volts AC), Level 2 (240 Volts AC), Level 3 DC Fast Charger (480 Volts DC and higher). National Electrical Manufacturers Association (NEMA) published EVSE Power Export Permitting Standard NEMA EVSE 40011-2024, defining the technical parameters to allow electric vehicle owners to utilize EVs as mobile energy storage units and sell back to the grid. The standard outlines characteristics in electrical, communication, cybersecurity, permitting power export between EVSE and electric power system and provides safety guidelines for EV installations to ensure bi-directional V2G charging allowing EVs supply power back to grid [8]. The Smart Building will interact with the Utility, Demand Response (DR) and Demand Management (DM) interface for acknowledging DR requirements as set by the utility.

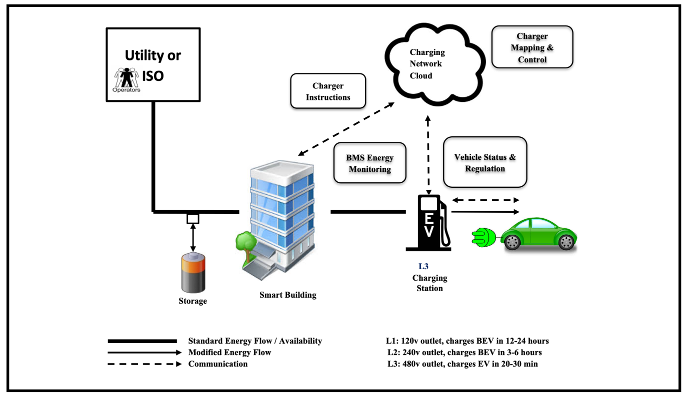

Fig. 1. SEEDZ EV BMS integrated Residential and Commercial scenario with EVSE control and storage

Fig. 1, V2G scenario integrates with local renewable sources to balance the grid load may act as microgrid in times of emergency without disrupting powerr services.

B. Components for V2G Fire Safety Management Model

a) Battery Thermal Management Systems (BTMS)

Temperature sensors: Essential for monitoring battery cell temperatures and detecting abnormal heating, a key indicator of potential thermal runaway as shown in Fig. 2.

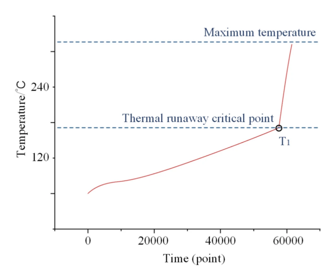

Fig. 2. Electric Vehicle Thermal Runaway Model [14]

Off-gas detection: Sensors that identify and detect the presence of flammable gases released from batteries during thermal runaway, providing an early warning of a developing fire.
Active Air-Sampling Smoke Detection (ASD): Systems that proactively sample the air for early signs of smoke particles, enabling early intervention and prevention.

Flame detectors: Utilize ultraviolet, infrared, or combined sensors to detect radiation produced by flames even before visible smoke or significant heat buildup.

Thermal cameras: Provide continuous surveillance by detecting the heat map associated with thermal runaway before visible flames or smoke appear.

b) Advanced controls and V2G integration Systems

Intelligent control systems: Integrate data from various sensors to analyze battery conditions, identify potential risks, and trigger appropriate safety measures.

Battery Management Systems (BMS): Act as the brain of the battery pack, monitoring vital parameters like voltage, current, state of charge (SOC), and temperature.

BTMS integration: BMS designs include advanced thermal management to regulate battery temperature and prevent overheating.

Safety features: BMS integrates safety features such as overcharge protection, short circuit prevention, and cell balancing to maintain optimal performance and prevent hazards.

Predictive fault diagnostics: Advanced BMS systems can employ predictive analytics to anticipate thermal runaway events before they occur.

Automated fire suppression: When a potential hazard is detected, the BMS can activate fire suppression systems or trigger alerts to homeowners or emergency services.

Isolation of affected modules: Some systems can isolate the problematic module or cell within the battery pack to prevent the spread of thermal runaway or fire.

c) Battery thermal management systems (BTMS) for fire prevention

Regulating battery temperature: BTMS's primary goal is to ensure the battery operates within its optimal temperature range (typically 15°C to 35°C).

Cooling and heating: BTMS employs both cooling (passive or active) and heating mechanisms to maintain ideal temperatures in varying environmental conditions.

Preventing accelerated degradation: Efficient thermal management prevents uneven performance, degradation of internal components and the risk of thermal runaway, which can lead to fires and even explosions.

Enhanced lifespan and efficiency: Maintaining optimal battery temperature ranges through effective thermal management contributes to extending the battery's life and improving overall efficiency.

C. Designing an Electric Vehicle AI Battery Managemnt Fire Event Model

Fig. 3, Battery Fire Event flowchart shows the process of an AI electric vehicle BMS with advance sensor system to detect probability of a fire event and disconnect battery from a vehicle to grid system sending notification to EV user of a potential battery malfunction. The AI EV BTMS Model and computing algorithm used to detect safety issues for an EV battery can predict real time and the probability to estimate a safety event prior to occurrence. The integration of Thermal Energy Storage and Machine Learning [11] for enhancing fire protection in EV batteries represents much-advanced research in energy storage, thermal management, and artificial intelligence.

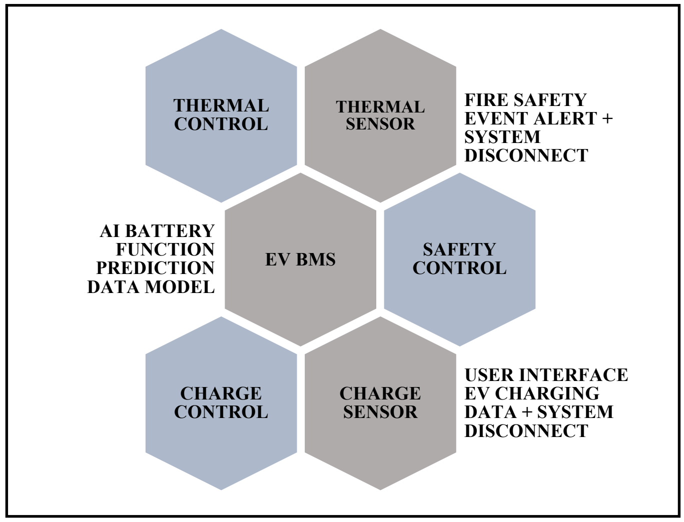

Fig. 3. Elements of an Electric Vehicle AI Battery Managemnt Fire Event Model

The proposed sensor/control model is in early phase of testing for field study or state pilot programs to address quantitative results, like detection times, false-alarm rates, or risk-reduction metrics, that demonstrate mitigation and fire prevention.

TABLE I. EV BTMS SAFETY MODEL VALIDATION

	Battery Management System Model	*Key Parameters*
I	Risk Management Model	SOC, DOD, Thermal Runaway Fault Detected
II	Battery System Monitoring	Battery Thermal & Charge Sensor and Control Network
III	V2G AI Pilot Testing	Real Data Analysis + Prior Event History

Fire Risk Assessment: AI can analyze data from various sources including user reports, environmental conditions, and battery performance metrics, to assess the overall fire risk associated with electric vehicles as indicated in Table I. EV Battery Thermal Management System Safety Model Validation.

D. Quantifying EV battery degradation from V2G to predict Thermal runaway

V2G battery degradation models quantify effect on battery by simulating impact of charging, discharging, Depth of Discharge (DOD) and State of Charge (SOC), temperature and cycle count [9]. Control algorithms may be formed using the velocity error and the error change as fuzzy inputs. Battery current, voltage, and temperature inputs are measured to calculate State of Charge [7]. Temperature and SOC impact battery calendar degradation and aging. Eq. (1), (2), (3), The capacity loss by cycling is calculated using a exponential factor depends on SOC, b is battery discharge cycle factor, c is charge rate, d is discharge rate [10], Irate is current, Ah is cumulative Amp hour throughput over all cycles. Eq. (4), example of Vehicle Grid Integration (VGI) simulation algorithm from Lawrence

Berkeley National Lab EV smart grid working group to predict Thermal Runaway Q(t) using total capacity loss over time Qloss caused by cycling and by calendar aging due to battery degradation over a period by creating resistance which causes overheating. The objective was to develop a platform and test to define charge/ discharge V2G control approach to simulate Lithium Battery degradation model for predicting fire safety risk events.

$$a = a_{0,cyc} \cdot (SOC_0 - SOC) \quad (1)$$
$$b = b_{0,cyc} \cdot (DOD_0 - DOD) \quad (2)$$
$$c = c_{0,cyc} \cdot (DCH_0 - DCH) \quad (3)$$
$$Q_{loss}^{total} = (a \cdot T^2 + b \cdot T + c) e^{(d \cdot T + e) \cdot I_{rate}} \cdot A_h + f \cdot e^{-E_a/RT} \cdot t^{1/2}$$

Capacity loss by cycling capacity loss by aging (4)

The capacity loss by aging is calculated by f is cycles of failure at given DOD, exponential e reaction rate, Ea is activation energy of the reaction causing degradation, R is ideal gas content, T is temperature and t is time. A study on electric vehicles battery performance for over a period of 10 years measured the battery capacity loss was 45%, around 5% capacity loss every year BEVs reaching end of life at 30% capacity loss [12]. In Eq. (5) and Eq. (6), the factors associated with temperature degradation is given by: the battery lifetime $L(tm)$ describes the charging power influence on temperature, factor related to Depth of Discharge (DOD) degradation is considered only when discharging occurs, and it is

Given by: $E_{deg,soc} = \varepsilon \Delta SOC_{dod} E_{batV2G}$ (5)

Wherein: $\Delta SOC_{dod} = SOC_{possible} - SOC_{EVV2G}(t_m)$ (6) [5]

The gain includes a relative DOD weight; ΔSOC_{dod} is the difference between possible values of SOC tested in optimization ($SOC_{possible}$) and the calculated SOC (SOC_{EVV2G} (tm)) according to the control law applied from the possible values of power ($Pev_{possible}$). The $SOC_{possible}$ represents all quantized levels in the SOC state variable, while $Pev_{possible}$ represents the quantized levels in the control law. The main idea of this factor is to balance the battery discharging, while minimizes the SOC difference [5].

E. Grid Interconnection Testing and V2G Performance

The battery-based V2G power electronics requires a test procedure that will maintain IEEE interconnection standards, evaluates the electrical performance of the vehicle working as a DR [9]. Response to abnormal Frequencies and Voltage tests are used to ensure the V2G power electronics disconnect from the utility whenever the frequency falls outside of the ranges or voltage levels go out to the ranges [9]. V2G protection tests are obtained from UL Standard as for Inverters, Converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources during output overload, short circuit and loss of control circuit.

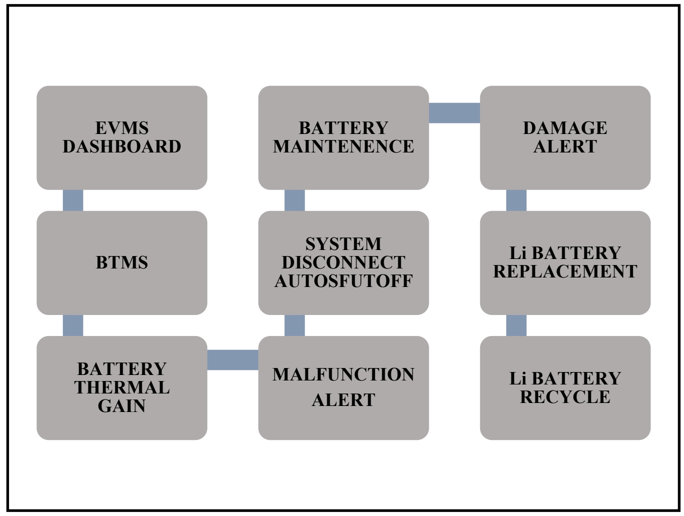

Fig 4. Safety Data Flow Model of Electric Vehicle Li-ion battery

F. Safety Data Flow Model of Electric Vehicle Li-ion battery

Fig. 4, models how data flows, collecting and processing V2G battery status for early fire hazard detection. BTMS manages V2G system AUTO-SHUT OFF on detecting overheating thermal runaway. The data processing while charging and grid-feeding could be used for future study.

III. RESULTS AND DISCUSSION

Vehicle to Grid Fire Safety Model development is in early testing design phase. Table II., compares relative merit and drawbacks of each sensor control approach.

TABLE II. COMPARATIVE ANALYSIS EV BMS SENSOR AND CONTROL SYSTEM

Sensor Type	Comparative Analysis EV Battery Sensors			
	Detection Range	***False Alarm Rate***	***Power Consumption***	***Trade Offs***
Voltage	Cell or Pack Level to System Level (V)	High with Aging/Degradation Low with Advance Algorithms	Low	Analog to Digital Converters, Critical for SOC, SOH
Current	Charging to Discharging Amps Range	Low for Direct Current	Moderate High Power Heat Dissipates	Crucial for SOC values Requires Thermal Management
Temp-erature Thermo Resistnce Detector	Operation Range -80c to 150c	-40°C to +125°C	Low	Thermal Management preventing Thermal Runaway
Gas Pressure Metal Oxide, Infrared Electro chemical	High Sensitivity to Trace amounts, Accurate	Fluctuates, Low to target Gas	Moderate	Targets Volatile Organic Compound, Hydrocarbon

Total heat release in a fire event is found to be linearly related to the stored electrical energy in Lithium EV battery. Iincreasing the SOC level cause the battery fire to produce higher radiative heat fluxes, in case of NMC batteries as well for large format LFP batteries with 68 Ah and 3.22 V batteries, where at SOC levels of 0, 50, 75 and 100%, the peak radiative heat fluxes measured at a distance of 0.3 m were 1, 2.5, 14.2, and 23.9 kW/m^2, respectively [13]. Hhigher the radiative heat flux, the faster the surrounding objects will heat up, and this in turn increases the probability of failure in other battery cells.

RISK ASSESSMENT	RESULT	
Voltage Measurement Accuracy	±0.05V	
Temperature Detection Response	3.2 Sec	
Gas Detection Response Time	1.8 Sec	
Suppression Activation Delay	2.3 Sec	[15]

A. Modelling Li-ion battery health to predict V2G Failures

The results from LBNL simulation toolkit to address V2G dependability on ambient battery health provides feedback on safety, efficiency and reliability of V2G system over time [12]. The simulation flow quantifies variability in efficiency with type of electric vehicle. One study suggests that optimal charging strategies and discharging within a specific State of Charge (SOC) range (47.5% to 52.5%) can minimize safety risk potentially extend battery life, according to ScienceDirect.com.

B. EV Infrastructure Safety Survey Results

Table III, presents EV User and Stakeholder survey taking information from various EV Infrastructure and safety working groups and national agencies for deployment challenges of V2G Technologies. V2G scenarios introduce additional complexities for responders according to the Idaho National Laboratory (.gov). First responders face risks like electric shock from high-voltage components and thermal runaway, uncontrolled temperature and pressure increase leading to fire from damaged batteries.

TABLE III. KEY FINDINGS EV BMS INFRASTRUCTURE SAFETY SURVEY RESULTS

Category	EV BMS SURVEY REVIEW		
	Key Findings	***Acceptance***	***Status***
EV User	EV Battery Safety Concern	High	EVs Deployed
V2G Policy	Battery Fire Safety Regulations and Standards	High	In Progress
V2G AI BMS	V2G AI Pilot Testing	High	Under Development

IV. CONCLUSION

To conclude, ensuring fire safety in V2G systems approach involves advance sensors for early detection and BTMS for monitoring, control and fire suppression capabilities. These comprehensive strategies are crucial for mitigating risks and enabling safe operation of V2G technology. Various state wide programs and initiative in EV infrastructure deployment prioritize development of fire prevention strategies.

A. Better EV policy with state wide programs and grants

To promote EV Infrastructure deployment and EV battery fire safety initiatives, New York state provides public and agencies with regular, transparent, and effective access to information and decision-making regarding various EV Infrastructure Programs. The Fire Department partners with New York State Energy Research Development Authority on EV battery fire safety funding opportunities [1]. UL standards for Fire safety are recommendations by Fire Safety Research Institute.

B. Limitations of V2G technologies

- Life cycle of batteries will shorten as the charge–discharge process will increase internal resistance considerably.
- Fast-charging method causes breakdown of batteries potential safety concern [4].

C. Opportunities of Safe V2G technologies

Battery management system use optimization and control algorithms, software and hardware to measure battery health status to estimate the service life of batteries and fire prevention. The owner of the electric vehicle is informed about real time fire event and power disconnect [4].

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