Design, Safety and Deployment Experience of a Liquid-Cooled LFP Battery System for Underground Mining Applications

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Abstract

The mining industry is undergoing a significant transformation towards electrification driven by the need to reduce greenhouse gas emissions, improve underground air quality, enhance operational efficiency, and lower the lifecycle operating costs. Battery Electric Vehicles (BEVs) have emerged as a practical alternative to conventional diesel-powered mining equipment, particularly for underground operations where ventilation requirements contribute significantly to operating expenses. Among the available battery technologies, Lithium Iron Phosphate (LFP) batteries have gained widespread acceptance due to their superior thermal stability, long cycle life, and enhanced safety characteristics.

Despite these advantages, the deployment of high-voltage battery systems in underground mines introduces new engineering challenges related to thermal management, electrical safety, vibration resistance, charging infrastructure, explosion protection, and regulatory compliance. This paper reviews current and emerging battery technologies applicable to mining applications and discusses the critical safety considerations associated with battery-powered mining equipment. A practical case study describing the design and development of a **537.6 V, 230 Ah (123 kWh) liquid-cooled LFP battery pack** for an underground passenger shuttle vehicle is presented. The study highlights key design considerations including thermal management, structural robustness, relay-based battery management systems, electrical protection architecture, CCS2 DC fast-charging interface and validation through thermal and vibration analyses.

The battery pack is housed in a single enclosure containing four cell modules and a dedicated Power Distribution Unit (PDU). The PDU integrates high-voltage relays, Manual Service Disconnect (MSD), Hall-effect current sensor, pre-charge circuit, high-voltage connectors, HV DC-DC Converter, LV DC-DC Converter, and IMD required for safe power distribution.

The design approach and safety architecture presented in this paper may serve as a reference for future development of high-voltage battery systems for mining applications.

Keywords: Battery Electric Vehicle, Underground Mining, Lithium Iron Phosphate, Battery Management System, Thermal Management, Mine Electrification.

1. Introduction

The mining industry is undergoing a gradual transition from diesel-powered equipment to battery-electric vehicles to improve energy efficiency, reduce emissions, and enhance underground working conditions. Battery-powered mining equipment eliminates exhaust gases, reduces heat generation, and lowers the ventilation requirements of underground mines. These advantages contribute to safer operations and lower operating costs.

Unlike batteries used in passenger electric vehicles, mining batteries operate under much harsher conditions. Battery packs designed for underground mining must operate reliably under harsh environmental conditions characterized by elevated ambient temperatures, high humidity, coal dust, continuous mechanical vibration, water ingress, and confined operating spaces. Additionally, hazards associated with electrical faults, thermal runaway, insulation degradation, and charging operations necessitate comprehensive engineering controls and rigorous safety validation.

To address these challenges, CLN Energy Limited has developed a 537.6 V, 230 Ah lithium iron phosphate battery system with an energy capacity of approximately 123 kWh. The battery employs lithium iron phosphate (LFP) cells because of their excellent thermal stability, long service life, and proven safety performance in industrial applications. To maintain safe operating temperatures during continuous operation, the battery incorporates an active liquid-cooling system. A relay-based Battery Management System continuously monitors battery operating parameters and controls all high-voltage switching devices to ensure safe charging and discharging.

The battery enclosure accommodates four battery modules together with a dedicated Power Distribution Unit (PDU). The modular arrangement simplifies manufacturing, transportation, inspection, and maintenance while providing flexibility for future servicing.

This paper contributes to this objective by combining a review of current battery technologies with practical engineering experience gained during the development of a high-voltage liquid-cooled LFP battery pack

Fig 1. Battery System: Battery pack with PDU and BTMS mounted inside vehicle's frame

2. Battery Technologies for Mining Applications

Battery selection has a significant influence on safety, operational performance, lifecycle cost, and reliability. The battery chemistry must balance energy density, power capability, thermal stability, operating temperature, charging characteristics, and maintenance requirements.

2.1 Lead-Acid Batteries

Lead-acid batteries have historically been the preferred energy storage technology for underground mining equipment owing to their low initial cost, mature manufacturing processes, and established maintenance practices. Nevertheless, their low energy density (typically 30–50 Wh/kg), limited cycle life, lengthy charging times, and regular maintenance requirements restrict their suitability for modern battery-electric vehicles.

2.2 Lithium-Ion Batteries

Lithium-ion batteries have become the dominant energy storage technology for electric mobility due to their high energy density, long cycle life, high charge-discharge efficiency, and minimal maintenance requirements. Various lithium-ion chemistries, in different forms like cylindrical, prismatic, and pouch, have been adopted depending on application-specific requirements.

Among these, Lithium Iron Phosphate (LFP) batteries have emerged as the preferred choice for underground mining equipment because of their excellent thermal stability, superior abuse tolerance, extended cycle life, and comparatively lower risk of thermal runaway.

Table 1. Comparison of Battery Technologies for Underground Mining

Parameter	Lead-Acid	LFP	NMC	Sodium-ion	LTO	Solid-State (limited)
Energy Density	Low	Medium	High	Low	Low	Very High
Cycle Life	Low	Excellent	Good	Promising	Exceptional	Expected High
Thermal Stability	Excellent	Excellent	Moderate	High	Outstanding	Expected Very High
Charging Speed	Slow	Moderate–Fast	Fast	Moderate	Ultra-Fast	Fast
Maintenance	High	Low	Low	Low	Very low	Low

3. Case Study: Design and Development of a 537.6V 230Ah Liquid-Cooled LFP Battery Pack

3.1 Design Objectives

The increasing adoption of battery-electric vehicles (BEVs) in underground mining inspired the **537.6V, 230Ah (123 kWh) liquid-cooled LFP battery pack** development. The principal design objectives were:

- Deliver a nominal energy capacity, about **123 kWh** for extended vehicle operation.
- Ensure reliable operation at ambient temperatures up to **45 °C**.
- Maintain cell temperature uniformity through active liquid cooling.
- Minimise likelihood of thermal runaway propagation through careful thermal design.
- Withstand severe mechanical vibrations encountered in underground mine haul.
- Provide comprehensive electrical protection against over-voltage, under-voltage, over-current for charging, over-current for discharging, over-temperature, under-temperature, short-circuit, insulation faults, and emergency operating conditions.

3.2 Battery Pack Architecture

Table 2. Battery Pack Specifications

Parameter	Specification
Cell Chemistry	Lithium Iron Phosphate
Cell Format	Prismatic
Cell Capacity	230 Ah
Cell Nominal Voltage	3.2 V
Configuration	168S 1P
Nominal Voltage	537.6 V
Maximum Voltage	604. V
Minimum Voltage	470.4 V
Nominal Energy	123 kWh
Continuous Discharge Current	230 A
Peak Discharge Current	400 A (30 s)
Continuous Charge Current	55 A

Maximum Charge Current	115 A	 **Fig 2. Battery Assly.**
Depth of Discharge	90%	

3.3 Mechanical Design

The battery enclosure was fabricated from IS 513 CR1 cold-rolled steel, selected for its structural strength, manufacturability, and cost-effectiveness.

To minimise the transmission of mechanical loads from the vehicle chassis to the battery pack, the enclosure is mounted using dedicated structural brackets incorporating anti-vibration elastomeric isolation pads (Neoprene sheet). This vibration isolator attenuates high-frequency vibrations and impact loads generated during vehicle operation. As an additional safety feature, the enclosure incorporates pressure relief vents to manage abnormal internal pressure rise resulting from a cell venting event or thermal runaway.

3.4 Battery Management System & High-Voltage Electrical Architecture

The Battery Management System (BMS) serves as the central supervisory controller responsible for ensuring the safe operation of the battery throughout its operating life. An Indian-developed BMS was integrated with the battery pack to provide continuous monitoring of electrical and thermal parameters like:

- Individual cell voltage monitoring
- Pack voltage monitoring & pack current measurement
- Monitoring of **16 for module & 5 PCB board temperature sensors**
- State of Charge (SOC) estimation, fault diagnosis
- Protection logic execution & CAN-based communication with the vehicle controller
- Insulation monitoring interface

Whenever predefined safety thresholds are exceeded, the BMS initiates protective actions including opening of the main contactors to electrically isolate the battery. *The system continuously supervises abnormal operating conditions including, Cell over-voltage, Cell under-voltage, Pack over-current, Over-temperature, Under-temperature, Insulation faults, HVIL interruption.*

Further, the battery system incorporates a high-voltage architecture designed to ensure safe energisation and de-energisation of the traction system under both normal and fault conditions. A **dual-contactor configuration** was adopted together with a **pre-charge circuit** to minimise inrush current during system start-up.

- Main positive and negative contactors rated at **500 A**
- Pre-charge contactor and resistor
- Manual Service Disconnect (MSD) rated at **630 A**
- High Voltage Interlock Loop (HVIL) & Insulation Monitoring Device (IMD)

3.5 Power Distribution Unit (PDU)

A dedicated Power Distribution Unit is installed to manage high-voltage power distribution and protection. The PDU serves as the interface between the battery, vehicle, and charging system. The BMS controls all relay operations through the PDU and integrates the following components: Manual Service Disconnect (MSD), Main positive relay, Main negative relay, Charge relay, pre-charge relay, pre-charge resistor, Hall-effect current sensor, High-voltage connectors, Auxiliary wiring interfaces

Fig 3. PDU

3.6 Thermal Management System

The battery incorporates an active liquid-cooling system to maintain the temperature of the cells within the recommended operating range of 25±3 °C during normal operation despite ambient temperatures reaching 45 °C. Consequently, the battery pack was designed with an active liquid-cooling system to maintain uniform cell temperatures under demanding operating conditions.

To maximise heat extraction from the battery cells, each prismatic cell was thermally coupled to the cooling system through a high thermal conductivity gap filler (thermal pad). The thermal pad compensates for manufacturing tolerances and surface irregularities between the cell casing and the cold plate, thereby minimising thermal contact resistance and ensuring efficient heat conduction. The cooling assembly comprises stacked *aluminium cold plates incorporating macro-channel flow passages*. Aluminium was selected as the cold plate material because of its high thermal conductivity, low density, corrosion resistance, and excellent extrudability.

Specs: Single integrated unit with a cooling capacity of 5kW and COP of ≥2.5, R134a as refrigerant, high voltage range 400-800V dc, coolant 50:50 water-glycol and communication CAN 2.0.

4. Thermal Performance Evaluation

To evaluate the thermal performance of the developed battery system, Computational Fluid Dynamics (CFD) simulations were carried out using ANSYS Fluent. The thermal model incorporated cell heat generation, coolant flow characteristics, battery geometry, and operating conditions representative of underground coal mining. The simulation results demonstrated that the active liquid cooling system effectively controlled battery temperature throughout the operating cycle. The maximum predicted cell temperature remained below 30°C, while the minimum cell temperature was approximately 25°C, resulting in a maximum temperature variation of 3°C across the battery pack.

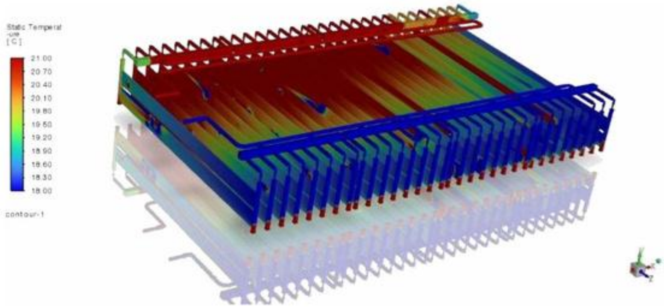

Fig 4. *Temperature contour of the battery pack obtained from ANSYS Fluent.*

5. Charger

The developed battery system is designed for 60kW DC fast charging, enabling efficient recharge during planned operational intervals. However, high-power charging introduces additional thermal and electrical stresses that must be carefully managed through coordinated control of the charger and Battery Management System. Charging stations intended for underground mining applications should incorporate multiple safety features including insulation monitoring, emergency shutdown capability, over-current protection, earth fault detection, and appropriate ventilation where required.

6. Safety Features

Battery safety in underground mining extends beyond cell chemistry and encompasses multiple independent protection layers. The developed battery pack adopts a defence-in-depth philosophy, where mechanical, electrical, thermal, and electronic safeguards work together to minimise the likelihood and consequences of faults. The principal safety features include *Intrinsically stable LFP cell chemistry, Active liquid cooling system, Dual high-voltage contactors with pre-charge, Manual Service Disconnect (630 A), High Voltage Interlock Loop (HVIL), Insulation Monitoring Device (IMD), Pressure relief vent, Emergency disconnect mechanism, IP67 sealed enclosure, Continuous temperature monitoring of the cells, Real-time fault detection through the BMS.*

7. Conclusion

Among the commercially available battery chemistries, Lithium-ion batteries have emerged as the preferred technology for mining applications due to their superior energy density, high power capability, long cycle life, and lower maintenance requirements compared to conventional lead-acid batteries. Within the lithium-ion family, Lithium Iron Phosphate (LFP) chemistry offers the most suitable balance of safety, performance, and lifecycle cost for underground mining. Its excellent thermal stability, lower susceptibility to thermal runaway, long service life, and high abuse tolerance make it particularly well suited for high-voltage battery systems operating in hazardous mining environments where personnel safety and system reliability are paramount.

Recent advancements in **Battery Management Systems (BMS)** have significantly enhanced the safety and reliability of lithium-ion battery packs. Modern BMS platforms extend beyond conventional protection functions by continuously monitoring individual cell voltages, pack current, insulation resistance, and distributed temperature measurements while providing accurate estimation of State of Charge (SOC) and State of Health (SOH). The integration of fault diagnostics, predictive maintenance algorithms, CAN-based communication, cloud connectivity.

Equally important is the establishment of safe and standardised **charging practices** for underground battery-electric mining equipment. High-power DC fast charging should be supported by coordinated communication between the charger and the Battery Management System to dynamically regulate charging current based on battery temperature, State of Charge, and operating conditions. Charging infrastructure should incorporate insulation monitoring, earth fault protection, emergency shutdown capability, over-current protection, adequate ventilation where required, and clearly defined operating procedures.

*Images for illustration purpose only