Intelligent Battery Sensor Technology in Commercial Vehicles: Benefits, Limitations, and Applications

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ABSTRACT

Low-voltage batteries are power supplies in vehicles, which have become increasingly essential due to the growing demand for electrical/electronic systems. Therefore, battery management is becoming more and more important to ensure the availability of power in commercial vehicles. The intelligent Battery sensor (IBS) is capable of monitoring crucial information, such as voltage, current consumption, capacity and data from which it is possible to determine battery's state of health, ensuring proper functioning of the electrical system and keeping a minimum energy reserve for cranking.

We will discuss in this paper the benefits and limitations of using the IBS of a commercial vehicle. The data provided supports predictive maintenance by enabling the diagnosis of electrical system malfunctions and battery performance issues. The driver does not experience 100% of the functionalities of IBS, as it currently only provides battery charge level information and relies on an Electronic Control Unit to manage the generated data. However, its application is effective for charge reserve and analysis of electrical faults in the power generation system, such as issues with the alternator's voltage regulator.

INTRODUCTION

A few years ago, vehicles were mostly composed of mechanical components, with only a few electrical systems and virtually no embedded electronics. With technological advancements, new systems were gradually incorporated, significantly driving the growth of electrical and electronic components, even in low-voltage commercial vehicles.

The increasing demand for infotainment, monitoring, safety, and comfort systems has directly contributed to a rise in energy consumption in vehicles, significantly impacting battery performance and durability. This growing energy demand required new ways to monitor the State of Health (SOH) and State of Charge (SOC) of 12V lead-acid batteries. The SOH indicates the overall condition of the battery, that is, how much of its useful life remains. Technically, it is determined by parameters such as current capacity compared to original capacity, internal resistance, charging and discharging efficiency, number of charge cycles completed, and operating temperature [1].

Meanwhile, the SOC represents how much energy is still available in relation to the battery's total capacity - it works similarly to a "fuel gauge," but for the electrical system.

One of the earliest solutions for monitoring battery status was the so-called "charge eye", a visual indicator embedded in lead-acid batteries. By analyzing the color displayed, it was possible to get an idea of the SOC. However, this method had significant limitations, as it evaluated only one of the six battery cells and was unable to accurately represent the overall condition of the battery, compromising the accuracy and representativeness of the data obtained [2].

Due to the growing need for more efficient and accurate monitoring, the IBS was developed. This sensor plays a fundamental role in the vehicle's energy management system, intelligently balancing energy supply and consumption. The widespread use of lead-acid batteries, mainly due to their low cost, made it feasible to integrate IBS sensors into energy management systems. This integration enabled real-time battery monitoring, tracking of discharge events, and consequently, extended battery lifespan [3]. Additionally, implementing an IBS allows for early fault detection and contributes to the overall efficiency of the energy storage system, helping to prevent vehicle downtime.

However, for energy management to be truly effective, it is important to understand that balancing energy demand and supply goes beyond simple measurement. The sensor alone is not capable of making decisions, interpreting data, or accurately estimating the SOH and overall battery performance. Therefore, it is essential that it be integrated with an Electronic Control Unit, which is responsible for collecting, analyzing, and correlating data such as current, voltage, temperature, and battery capacity.

IBS CONCEPT

The first implementation of an IBS integrated into the battery pole clamp occurred in 2003 [1]. This type of structural design offers several advantages: it requires less space, allowing for broader vehicle applicability; it eliminates the need for an external temperature sensor due to the high thermal conductivity of the lead pole material; and it supports low-cost communication through a single-wire LIN (Local Interconnect Network) interface [7].

Since no external components are required to support the measurements, the IBS enables precise and direct monitoring of battery voltage, current, and temperature under various vehicle operating conditions.

The IBS integrates several critical electronic components that allow real-time monitoring and diagnostics of battery health. Each component has a specific functionality to ensure precise measurements and robust communication. The components that make up the IBS are listed below and visually represented in Figure 1.

SHUNT RESISTOR - A shunt is a precision low-resistance resistor used to measure electric current through the voltage drop generated across its terminals. In automotive applications, it enables precise measurement of charging and discharging currents, being essential for energy management. The shunt must have high thermal stability and low temperature coefficient to ensure accuracy under varying conditions [4].

ANALOG-TO-DIGITAL CONVERTER (ADC) - The ADC transforms continuous analog signals of voltage, current, and temperature, into digital values that can be processed by a microcontroller. In IBS it allows physical signals to be digitized for real-time diagnostics and control. High-resolution ADCs are essential in IBS for detecting small voltage and current variations critical to battery diagnostics [5].

VOLTAGE REGULATOR - The voltage regulator is a circuit that maintains a stable output voltage regardless of the variations in input voltage and noise-free supply voltage. It ensures that all components receive the proper and stable voltage, avoiding overvoltage and electrical noise that could compromise measurement accuracy [6].

LIN TRANSCEIVER - The LIN (Local Interconnect Network) transceiver enables serial communication between electronic devices via a single-wire serial interface with reduced system complexity and cost. The transceiver converts digital signals from the microcontroller into LIN-compliant protocol specification for reliable vehicle communication [7].

OSCILLATOR - The oscillator is a circuit that generates the clock signal required to synchronize operations of the microcontroller and LIN transceiver. It defines the system's operating frequency, directly impacting response time and task performance. Accurate timing is essential for consistent sensor sampling and LIN messaging [8].

MICROCONTROLLER UNIT (MCU) - The microcontroller is the core processing unit of embedded systems, integrating a CPU, memory, peripherals, and communication interfaces into a single chip. In IBS, it executes algorithms based on current, voltage, and temperature data. Automotive-grade MCU has low power consumption and robustness for vehicle operation [9,10].

FLASH AND RAM MEMORY - Flash memory is used to store IBS firmware and keep data when power is off while RAM (Random Access Memory) is used for temporary data storage during algorithm execution with fast for real-time operations. Together, they support dynamic algorithm execution and event logging [10] being fundamental for microcontroller operations.

RESET / WATCHDOG / WAKEUP CIRCUITRY - These components enhance system reliability. The reset circuit initializes the system under abnormal conditions or during power-up. The watchdog monitors software execution and resets the system in case of a malfunction or freeze. The wakeup function enables the system to resume from low-power sleep modes upon detecting vehicle activity [11], triggered by an internal or external event.

INTEGRATION WITH ENERGY MANAGEMENT SYSTEM - The IBS must be integrated with an Electronic Control Unit (ECU) that includes an energy management system (EMS) capable of accessing alternator communication and relevant electrical consumers. This integration enables real-time decision-making based on the SOC, SOH and battery temperature, enhancing system reliability and prolonging battery life. In cases of critical battery charge levels, EMS switch off low-priority electrical loads, thereby preserving the battery’s capacity for essential functions such as engine cranking [11] and avoiding vehicle breakdown.

The integration of the IBS with a high-level EMS enables the following functions:

- Control of engine idle speed: Adjust the idle speed based on battery condition and load demand, fuel consumption can be reduced during idle phase. This strategy is beneficial in stop-and-go driving, contributing to lower emissions and improved energy balance [12].

- Regulation of alternator voltage: The EMS can dynamically control the alternator's output voltage according to real-time battery state and vehicle load, enhancing charging efficiency and reducing mechanical load on the engine [13].

- Optimized energy distribution and charge conservation: The EMS prioritizes energy delivery to critical systems and switch-off power supply to low-priority consumers, such as 12V power outlet or infotainment system, in critical conditions [14].

- Diagnosis of the vehicle’s electrical system: Continuous monitoring of voltage, current, and temperature allows the EMS to detect early signs of component degradation or wiring failures, allowing predictive maintenance [15] and increasing vehicle availability.

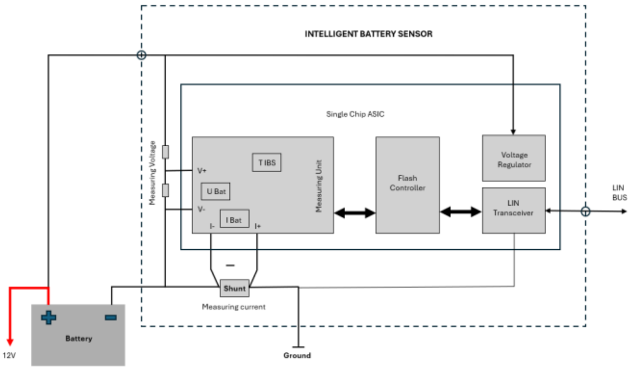

Figure 1. Hardware IBS.

IBS BENEFITS

Electrical and electronic architecture have evolved significantly over the years in the automotive industry. However, batteries have not kept pace with this progress at the same rate.

In this context, the IBS plays a vital role in the energy management system, contributing decisively to the balance between energy consumption and generation. This sensor ensures the availability of power for critical functions, such as engine start-up, making it a key component for the vehicle’s operational reliability. Its implementation represents a significant advancement in optimizing performance and preserving battery lifespan. The IBS’s main function is to perform real-time monitoring of fundamental parameters such as voltage, current, and temperature. These data are crucial for accurately determining the SOC and SOH of the battery.

This information is also essential for potential assessments of the vehicle's energy management system. Figure 2 shows the signals monitored by IBS.

The data presented in Figure 2 were collected from a test vehicle two weeks after the date shown in the graph, with the aim of illustrating the types of signals and information obtainable from an installed battery sensor. The sensor used was model 6PK 011.080-15, supplied by Hella. Figure 2 displays six distinct signal types: *batcpctyfull_cval*, *batcurr_cval_pnm*, *batsoh_cval*, *battemp_cval*, *batvolt_cval*, and *batcpctyrest_cval*.

- *batcpctyfull_cval* – Indicates the total capacity of the battery, which in this case is 180 Ah.

- *batcurr_cval_pnm* – Represents the current drawn by the electrical system from the battery.

- *batsoh_cval* – Indicates the SOH of the battery.

- *battemp_cval* – Reflects the internal temperature of the battery.

- *batvolt_cval* – Indicates the battery voltage.

- *batcpctyrest_cval* – Represents the remaining capacity of the battery.

It is also worth noting that the peaks in the signal correspond to the current draw during vehicle turn on, which is why the current values appear as negative.

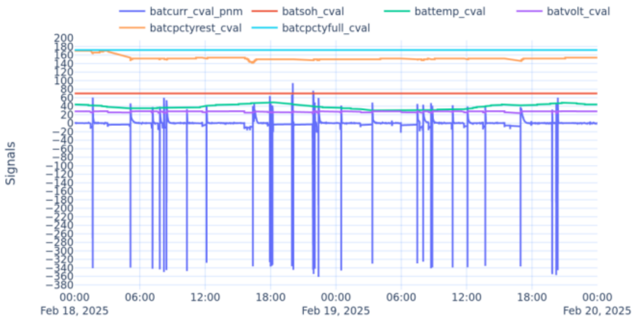

Figure 2. Signals monitoring through IBS.

Additionally, the sensor is capable of calculating the optimal charging voltage based on the battery’s temperature. This means that the voltage supplied by the alternator can be adjusted through the communication interface with the battery terminal [1], directly contributing to increased battery longevity. By optimizing the charge and discharge cycles, it helps prevent deep discharges, which negatively affect the battery's long-term performance.

IBS LIMITATIONS

While the IBS plays a crucial role in monitoring the battery state and optimizing energy management, its integration into vehicle systems comes with some limitations and challenges. These limitations must be carefully considered, particularly in cost-sensitive vehicle application and for improving user interface accessibility.

INCREASED VEHICLE COST - The addition of an IBS to a vehicle inevitably leads to an increase in the overall vehicle cost. The IBS is not a standalone component but requires an ECU for data processing and integration with the vehicle’s energy management system. This increase in hardware complexity adds to the bill of materials, which can be a significant concern, especially in entry-level vehicles and commercial fleets. Additionally, specialized components such as shunt resistors for current sensing, ADCs and microcontrollers add both material and design costs. Studies indicate that while advanced sensor systems provide valuable insights into battery health, they can also increase production costs by up to 10-15% for each vehicle [16, 17].

Moreover, maintaining such systems over the vehicle's lifetime can add costs in terms of diagnostic tools and possible repairs, particularly if the IBS components suffer from wear or failure under harsh environmental conditions, as is common in automotive applications [18].

COMPLEXITY IN SYSTEM INTEGRATION - Integrating the IBS with existing vehicle systems, particularly in legacy vehicle platforms, can introduce technical complexity. The system requires seamless communication between multiple components, such as the battery, alternator, and ECU with an energy management system. This integration may require substantial modifications to the existing wiring, communication protocols (such as LIN or CAN), and control strategies. In addition, optimizing energy management with real-time data from IBS requires a robust and sometimes costly software infrastructure [19].

LIMITED DIRECT FEEDBACK TO DRIVERS - Although the IBS collects a wealth of information, including battery voltage, current, and temperature, this data is generally not made accessible to the vehicle driver in real-time. Instead, the data is typically used internally by the Energy Management inside ECU to manage battery health and optimize performance without direct feedback to the driver. While the vehicle may alert the driver of critical issues, such as a low battery charge or failure, more detailed information (such as battery temperature or current values) is usually not available for everyday use. This can be a significant limitation, particularly for drivers who wish to monitor the health of their vehicle’s battery proactively [15, 19, 20].

Missing this feedback can also hinder the driver’s ability to take preventive measures in response to early signs of battery degradation. Ideally, more comprehensive Human-Machine Interfaces (HMI) could be implemented to display key metrics from the IBS, giving the driver better control and awareness of the vehicle’s electrical system. Some modern vehicle models are beginning to integrate such feedback systems, but it is still not universally available [21].

DISCUSSION

Due to the high energy demands of modern vehicles, the battery sensor plays a critical role in energy management. In addition to continuously monitoring parameters such as current, voltage, and temperature, it helps preserve engine start functionality by disabling electrical loads that could deplete the battery and compromise subsequent starts.

By leveraging engineering tools, the sensor enables real-time monitoring of alternator output, battery SOC, and battery SOH. This continuous oversight allows for the early detection of issues within the vehicle’s energy generation system, enabling preventive maintenance and reducing the risk of damage to system components.

Currently, not all data monitored by the IBS is made available to the driver in a way that facilitates timely intervention when immediate maintenance is required. Providing such information could help drivers better understand the actual condition of the energy management system, plan maintenance activities effectively, and prevent vehicle downtime - particularly in commercial applications - due to energy shortages.

It is also worth noting that the battery sensor requires an ECU to manage powernet data and make decisions, as the sensor alone does not possess this level of autonomy.

CONCLUSION

This paper aims to discuss the benefits and limitations of the IBS. The IBS is a key component in maintaining the balance between energy consumption and supply by monitoring current, voltage, and temperature. These parameters are crucial for the optimal operation of a vehicle's energy generation system.

One of the primary functions of the IBS is to preserve the minimum energy required for engine start-up by selectively disabling non-essential electrical consumers. In commercial vehicles, where vehicle availability is critical due to their use as work tools, a failure to start due to insufficient battery charge can result in significant disruptions and financial losses.

Furthermore, the IBS helps prevent deep battery discharges, which negatively impact performance and reduce battery lifespan. It can therefore be stated that the IBS contributes to extending battery life and supports the prognostics of potential failures in the vehicle’s energy generation system.

REFERENCES

[1] Schöllmann, Matthias, Marc Rosenmayr, and Joachim Olk. Battery monitoring with the intelligent battery sensor during service, standby and production. No. 2005-01-0561. SAE Technical Paper, 2005.

[2] Olarte, Javier, et al. "A battery management system with EIS monitoring of life expectancy for lead–acid batteries." Electronics 10.11 (2021): 1228.

[3] Wang, Pengcheng, and Changqing Zhu. "Summary of lead-acid battery management system." IOP Conference Series: Earth and Environmental Science. Vol. 440. No. 2. IOP Publishing, 2020.

[4] Vaish, Shivam Anand, Naqqash Ghaffar Abbassi, and Thomas Zimmermann. "A high precision current measurement device for Battery Management Systems (BMS)." *23. DESIGN&ELEKTRONIK*. 2016.

[5] F. Sun, X. Hu, Y. Zou, and S. Li, “A Review on State-of-Charge Estimation for Lithium-Ion Batteries,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1461–1471, Apr. 2013.

[6] Saha, Arijit, et al. "An Improved PMOS-Based Low Dropout Regulator Design for Large Loads." *arXiv preprint arXiv:2209.12726* (2022).

[7] Kim, Seung-Han, et al. "A gateway system for an automotive system: LIN, CAN, and FlexRay." 2008 6th IEEE International Conference on Industrial Informatics. IEEE, 2008.

[8] Li, Zixuan, et al. "RC-Oscillator-Based Battery-Less Wireless Sensing System Using RF Resonant Electromagnetic Coupling." IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences 107.5 (2024): 727-740.

[9] Heim, Andreas, and Tilo Streibl. The intelligent battery sensor: key component for a scaleable motor-vehicle-independent energy management system. No. 2006-21-0001. SAE Technical Paper, 2006.

[10] Çadırcı, Y., and Y. Özkazanç. "Microcontroller-based on-line state-of-charge estimator for sealed lead–acid batteries." Journal of Power Sources 129.2 (2004): 330-342.

[11] R. Bosch GmbH, *Automotive Electrics and Electronics: Systems and Components, Networking and Hybrid Drive*, 5th ed., Springer Vieweg, 2014.

[12] H. He, R. Xiong, and J. Fan, “Evaluation of Lithium-Ion Battery Equivalent Circuit Models for State of Charge Estimation by an Experimental Approach,” *Energies*, vol. 4, no. 4, pp. 582–598, 2011.

[13] Wang, Yuefei, et al. "Real-time vehicle energy management system based on optimized distribution of electrical load power." *Applied Sciences* 6.10 (2016): 285.

[14] Jackey, R., "A Simple, Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection," SAE Technical Paper 2007-01-0778, 2007

[15] Karden, Eckhard, et al. "Energy storage devices for future hybrid electric vehicles." Journal of Power Sources 168.1 (2007): 2-11.

[16] C. Lohmeier and T. Veik, “Battery Management With an Intelligent Battery Sensor Is Vital to the Success of Future Automotive Designs,” *Battery Power Online*, Oct. 8, 2014. https://www.batterypoweronline.com visited on 14.05.2025.

[17] C. C. Chan, “The state of the art of electric, hybrid, and fuel cell vehicles,” *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704–718, Apr. 2007.

[18] S. N. P. R. Singh and K. B. S. R. Anjaneyulu, “Design of Intelligent Battery Management System for Electric Vehicles,” in *2013 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Bangalore, India, 2013, pp. 1–6.

[19] Ostadian, Reihaneh, et al. "Intelligent energy management systems for electrified vehicles: Current status, challenges, and emerging trends." *IEEE Open Journal of Vehicular Technology* 1 (2020): 279-295.

[20] Fors, Carina, Katja Kircher, and Christer Ahlström. "Interface design of eco-driving support systems–Truck drivers’ preferences and behavioural compliance." *Transportation Research Part C: Emerging Technologies* 58 (2015): 706-720.

[21] Leong, Wai Yie, Yuan Zhi Leong, and Wai San Leong. "Human-Machine Interaction in the Electric Vehicle Battery Industry." *2024 10th International Conference on Applied System Innovation (ICASI)*. IEEE, 2024.