Decentralized Master-Slave Communication and Control Architecture of a Battery Swapping Station

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***Abstract*— The aim of this paper is to provide an overview of communication protocols that could be used to establish communication between different battery packs within energy management system of battery swapping station. In order to compare similarities and differences, the overview of communication within battery pack is also provided. For the choice of the most appropriate communications solution, it is of vital importance to consider energy management system operating conditions within the battery swapping station. For the time being, CAN protocol is widely accepted for the communication between battery packs and electric vehicle energy management system and it would be convenient to employ it also to the battery management system (BMS) because of its robustness to noise problem and compatibility with other hardware involved in BMS.**

Keywords—Battery Swapping Station, Electric Vehicles, Communication protocols, CAN bus, Battery Management System, Energy Management System

I. INTRODUCTION

There are several ways how to recharge electric vehicles (EV). The most usual way due to its simplicity and similarity with classical internal combustion engine (ICE) refueling is slow (home or work charging) or fast charging (charging stations) of electric vehicles. The major disadvantage of classical EV charging are long charging times. In order to solve mentioned problem there, the concept of battery swapping station (BSS) has been proposed. In BSS concept EVs do not charge their vehicles using chargers but they drive to the nearest BSS and they simply replace/swap the empty battery with the fully charged battery [1]. In other words, the BSS takes care for EV battery charging for EV owner. The Tesla company actually demonstrated that such concept is even faster than refueling an ICE vehicle. On demonstration battery swapping took about 90 seconds, while ICE refueling take at least double the time. Apart from Tesla demonstration BSS, a company called Better Place tried to build a network of BSS in Israel and Denmark but failed due to several reasons, lack of EVs in general and lack of EV battery pack standards were major ones [2]. With an increase of EVs, especially in commercial fleets where long waiting times mean that vehicle and driver are idle and not earning money, we believe that BSS can be valuable. For example, Tesla Semi truck would require very long charging times and BSS could just do the job. Another issue is battery standardization which is essential for BSS concept to work. One of the field which needs to be harmonized to operate BSS with large number of different battery packs are communication protocols. This paper will give an overview of different communication protocols used within the battery as well as between the battery and external equipment, Electric Vehicle Supply Equipment (EVSE) and EV Energy Management System (EV EMS). Also, it will propose the most promising standards to be used between battery packs in BSS and BSS Energy Management System (BSS EMS).

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II. BATTERY MANAGEMET SYSTEM

A. Lithium-ion batteries

Power in EVs is supplied by battery storage systems and the most commonly used technology is Lithium-ion batteries (LIB). LIB consist of two circuits: external electrical (e^- transfer) and internal ionic (Li^+ transfer) between electrodes. LIB batteries can be further divided based on materials used for electrode manufacturing [3]. The most common EV positive electrode nickel-cobalt based alloys (nickel-cobalt-aluminum or nickel-manganese-cobalt), manganese spinel or phosphates (iron or iron-manganese). The most common negative electrode technologies are graphite, while lithium titanate, hard carbon and graphene are in demo phase. Whatever the used technology is, they all resemble the same physical hierarchical architecture. The smallest part of a battery is called cell and it is composed of primary chemical components such as electrodes and electrolyte, primary electrical such as current collectors and terminals and mechanical such as metal framework or plastic gasket. LIB cell nominal voltages range from 2-4 V [4] and if higher voltages are required, such as in EVs, more cells should be connected in series. Capacity of LIB cells is also small, for example cylindrical 18650 cells capacity ranges from 2-4 Ah [5] and if higher capacity is required cells are connected in parallel.

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B. *Battery Management System Functions*

Battery management system (BMS) is the brain of a battery. It collects measurements from the components, computes control variables, sends commands to lower-level controllers and communicates with external devices. The goals of BMS can be seen as battery safeguarding in the real-time, maximizing its efficiency through optimal cycling and prolonging battery lifetime in the long run. Several crucial BMS functions can be listed:

- Battery monitoring: measurements (cell voltage, current and temperature) acquisition and processing.
- Battery protection: over/under voltage, over current and over/under temperature cut-offs. Usually done by cut-off FETs in charging/discharging circuits [6].
- Charging/discharging control: executing charging/discharging algorithms [7].
- Cell balancing: balanced cells increase stability, efficiency, and longevity of BPs [8].
- State-of-Charge (SOC) estimation: knowledge about the amount of energy stored in BPs [9], [10].
- State-of-Health (SOH) estimation: both calendar and cycling aging degrades battery through wide range of mechanisms [11], [12]. It is beneficial to know what is the maximum capacity storable in BP [13].
- Thermal management: maintaining working temperatures increase thermal stability, efficiency, and longevity of BPs [14], [15].
- Internal and external communications: BMS internally communicate with components externally with EV EMS or EVSE.

C. *Battery Management System Architecture*

Different connections of cells form the battery packs for unique purpose. Very often, between cell and pack level there is a module level to cut the number of wires and pins and to distribute control functions. Therefore, we can name three main architecture types of battery management systems (BMS) [16]:

- Centralized: one central pack controller (Pack Management Unit or PMU) monitors, balances, and controllers all the cells. The most economical architecture but at the same time requires extensive wiring since measurements of each cell must reach PMU. Well suited for packs with fewer cells [17].

- Distributed: each cell has its own cell controller as a slave node connected through serial communication to PMU. Its very easily to implement but when number of cells is high the price of such BMS is high as well. Cells with own microcontrollers (Cell Management Units or CMU) are called smart cells and such application can be used if the number of cells in a pack is not constant. In other words, this architecture is exceptionally modular and implementable. Beside master-slave configuration there is also peer-to-peer configuration where smart cells communicate with each other and the there is no need for PMU [18], [19]

- Modular: each slave node (Module Management unit or MMU) monitors, balances and controls a group of battery cells within battery module. MMU node communicates with central PMU unit through serial interface. The modular architecture positions itself between centralized and distributed regarding cost, complexity, and modularity. Beside master-slave configuration there is also peer-to-peer where MMUs communicate with each other without PMU.

D. *Master-slave Battery Management System Topologies*

Master-slave architecture can be further divided to three different topologies [20]:

- Star topology: Slave nodes are connected in parallel to each other where master is in the middle. Communication is realized directly between each master-slave node.

- Bus topology: There is one main bus on which all the nodes, both master and slaves, are connected. The communication uses the same wiring and each of the nodes must have its specific address.

- Ring or daisy chain topology: Slave nodes are connected in series to each other and master node is at one end of communication chain. Communication is realized through slave nodes until it reaches master node.

- Hybrid topology: Combination of abovementioned three topologies. There are several daisy chained communication lines parallel to each other all connected to master or there are several star topologies connected to main bus etc.

Since the most common approach regarding EV battery packs is modular architecture with master-slave configuration, the rest of the paper will focus exclusively on such.

E. *Intra-battery communications*

Internally, PMU must communicate with components to collect measurements and to send control commands. Measurements within battery are cells' voltages and temperatures and series' currents. Each cell's temperature and voltage are measured, the analog measurements are amplified and multiplexed and send to MMU where signals are converted to digital form and forwarded to PMU. MMU uses those measurements to conduct cell balancing. The similar arrangements are made for series current measurements. Additional action is that current measurements are also sent to comparator within FET control to rapidly shut down charging/discharging if short circuit happens.

Digital measurements between MMU and PMU and control signals from PMU to other components are usually transmitted through serial communication bus protocols: SPI [21], [22] I2C [23], [24], [25], LIN or CAN [26], [27], [28], [29]. SPI and I2C are simpler and easier to implement but CAN is more robust and compatible with other system elements, therefore preferable for EV environment. Choosing the right protocol depends on the battery pack size and operation [30]

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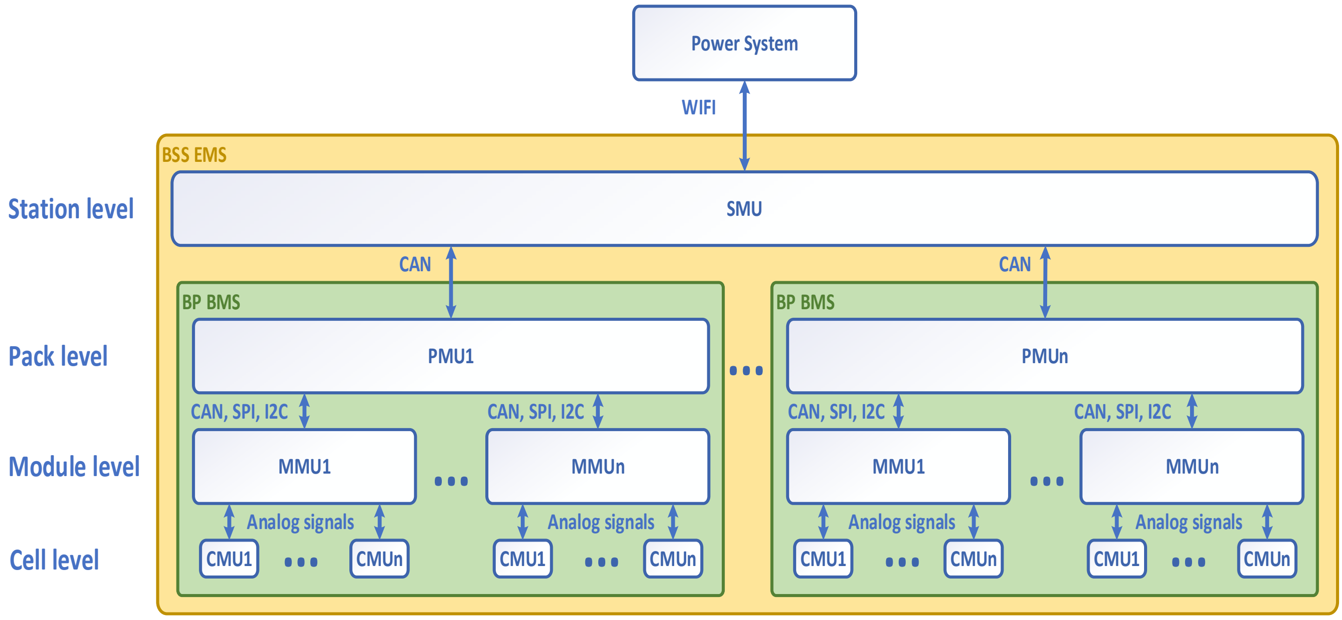

Figure 1 Communication between different nodes within battery packs and swapping station

III. Energy Managemet System

Battery swapping station is actually a large number of EV battery packs stacked at one place waiting to be charger or charging. If BSS is to be compared with battery pack architecture, additional level has been added above battery pack level. Each one of the BMS architectures could be implemented for BSS EMS, but due to modularity and easiness to control charging of variable number of packs, the decentralized approach with master-slave bus topology is the best choice. Figure 1 represents decentralized master-slave EMS architecture of BSS where BPs are using modular master-slave architecture. The EV battery pack communicates with various subsystems: with EVSE while charging, with EV EMS (EV traction system) while driving, with users mobile and EV fleet control applications. Communication with applications can be realized through wireless communications such as GPRS or UMTS [31], while the communication with EVSE and EMS must be realized through wired data exchange. For BSS EMS reasons, only the latter is important.

A. EV Battery Pack to EVSE Communication

Basic communication between an EV and EVSE is performed by means of the control pilot. EVSE has an internal voltage PWM source the signal from which is available on the EVSE output terminals. When an EV connects, the voltage measured by the EVSE on these terminals changes, thus indicating that the EV is connected. Change in voltage occurs because the EV contains voltage divider circuit with resistors. Furthermore, by varying resistance EV signals to EVSE whether it is ready for charging. On the other hand, by varying duty-cycle of the PWM signal EVSE provides information about the maximum available current to the EV. This communication is specified in [IEC 61851-1:2012]. Even if some high-level communication (HLC) is used between EV and EVSE, the control pilot is always used to initiate communication. Moreover, control pilot function may be used concurrently with the HLC, e.g. if HLC fails for some reason, basic communication over control pilot takes over. Details are prescribed in [ISO-15118-1:2015, ISO-15118-2:2016 ISO-15118-3:2016]. This pattern enables EV and EVSE to communicate even if both sides do not support HLC.

B. EV Battery Pack to EV EMS Communication

EV BMS must be able to communicate with EV EMS in order to efficiently supply power and energy for EV drivetrain. Conversely, the drivetrain can supply the energy to EV battery by regenerative braking. If EV is a hybrid vehicle then it can also have ultracapacitor for power peaks or range extender for additional energy supply. Except drivetrain, modern vehicles also have numerous electric loads which discharge battery (infotainment, HVAC systems, sensors, automatic locking…). All these systems must communicate between themselves and must be able to send data to On-Board-Diagnostics connector (OBD-II) if required.

There are several usual communication protocols used in automotive industry: MOST, FlexRay, Ethernet, CAN, LIN [32], [33], [34], [35]. Very often, different protocols are used in the same vehicle because they differ in transmission speed and other characteristics required for specific application. CAN is de facto standard for in-vehicle networks: It is used as the backbone network as well as for powertrain, chassis, and body systems. LIN is simplified CAN protocol with single master and up to 15 slaves. It is slower then CAN and usually used for low bit rate vehicle body control applications such as door control, light control, door mirror control etc. LIN is used as link between intelligent control unit and remote sensors/actuators. LIN master node is often connection to CAN network where it acts as a slave node. Ethernet is used today as an interface for diagnostics to connect external computer that runs diagnostics software, but in future it will be more used for driver assist (cameras) and infotainment (video) as well [36]. FlexRay is high speed, flexibility and reliability protocol used for active technology such as next generation x-by-wire applications (e.g. brake-by-wire system) [37]. MOST is a standard for vehicle multimedia networks (high quality audio, video and data).

Since EV BMS to EV EMS data transfer do not require high-quality data nor high speed transmission expensive networks (MOST, FlexRay, Ethernet) are not viable. On the other hand, it must be connected to main EV network (CAN) not on LIN auxiliary networks. CAN protocol is robust, disturbance resilient [38] and it was wildly excepted in automotive industry [39], [40]. Almost all PMU in EV battery packs use or can use CAN to transmit or receive messages to SMU. The minimum changes are required if CAN is adopted as the main communication protocol within BSS. The only issue is that each EV producer has it own CAN data coding, so decoder is necessary.

C. Controller Area Network

Nowadays the CAN protocol is a standard for vehicles on-board communications and many other industrial applications. Several papers analyze Battery Management System (BMS) based on CAN communication. In [41], authors developed the BMS platform based on digital signal processing platform which is a Master-Slave structure and adopted CAN communication technology between Master and Slave. In [42], authors developed a new method allowing data exchanges between a BMS and the application’s Energy Management System (EMS). The developed solution is based on the Power Line Communication (PLC) technology that uses versatility of the well-known CAN protocol. In [43], authors designed a BMS, that is based on the CAN-bus, for the Li-ion battery pack which consisted of many series-connected battery cells and was distributed dispersedly on the electric vehicle (EV). The developed BMS used two individual CAN-buses for the sake of avoiding the data disturbance. The first CAN-bus named ‘’inner-CAN’’ is used for communication within the BMS, while the second CAN-bus named ‘’outer-CAN’’ is used for the communication with the EMS. The authors in [44] analysed how to enhance and protect the reliability and robustness of the CAN-bus based communication in BMS to maintain safe operation of the battery stack for data transmission from high voltage battery to low voltage electronics elsewhere in the EV. Additionally, the advantages of the CAN-bus based communications within the BMS were also emphasized in [45].

Initially, the CAN bus was developed by BOSCH as a multi-master, message broadcast system that specifies a maximum signaling rate of 1 megabit per second and compared with traditional networks such as USB or Ethernet, CAN does not send large blocks of data point-to-point from node A to node B under the supervision of a central bus master. In CAN based network a lot of short messages are broadcast to the entire network, which provides data consistency in every node of the system. CAN is an International Standardization Organization (ISO) defined serial bus communications bus. The main reason for the development of CAN is to replace the complex wiring harness in vehicles with a two-wire bus. Additionally, CAN Standard specification required high immunity to electrical interference and the ability to self-diagnose and repair data errors. The CAN communication protocol is defined by the ISO-11898 standard [46]. This standard describes how information is passed between devices on the network and corresponds to the Open System Interconnection (OSI) model that is defined in terms of communication layers. According to the OSI reference model the CAN architecture represents physical layer and data link layer [47]. The ISO 11898 architecture is presented in Figure 2.

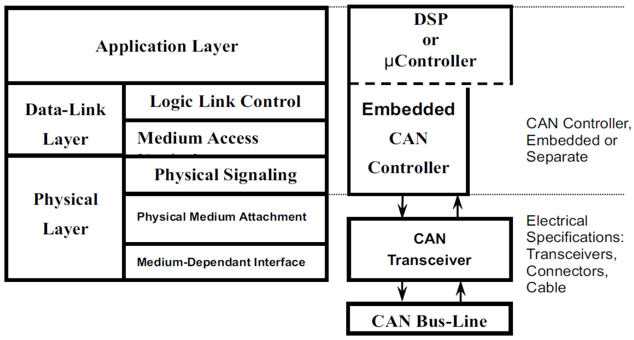

Figure 2 The Layered ISO 11898 Standard Architecture

D. EV battery pack to BSS communication

When talking about battery swapping station, the above described EV-EVSE communication pattern may be used for connecting each individual battery to a battery charging point (BCP). However, HLC must be used in order to provide information about the battery status to the BSS central controller or station management unit (SMU). SMU manages multiple charging points at the same time by performing energy management, i.e. it decides how to distribute the available energy (and power) between the batteries. HLC must also be used between the SMU and the individual BCP. Since almost all batteries in EVs use CAN protocol for communication with EV EMS, the best option for HLC is CAN bus. Battery management system governs the battery and it is also in charge for communication with the SMU (via BCP). The information sent from each individual battery (its BMS) to the SMU are:

- maximum charging current – for (CC-CV) charging,
- charging voltage – for CC-CV charging,
- state of charge (SOC),
- state of health (SOH) – optional.

Based on the received information from all the batteries, SMU sends to each BCP:

- charging current setpoint,
- charging voltage setpoint,
- switch ON/OFF command – for physically connecting battery to the charger

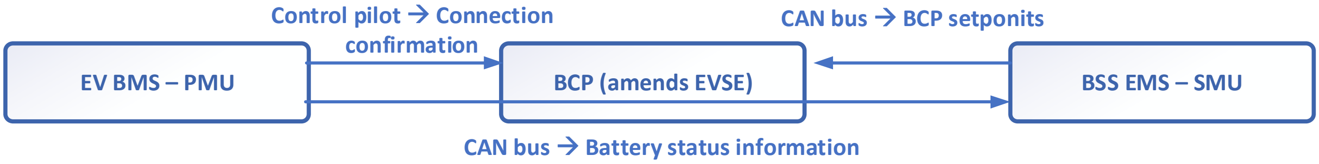

Figure 3 EV BMS to BSS communication

SMU is the brain of the BSS and it must calculate battery charging schedules based on all the available information. If batteries are soon to be swapped, they should be charged with maximum allowed current. If there is no rush to charge the batteries (e.g. overnight) the batteries are charged with lower currents which is beneficial for both the batteries and the peak grid load. When battery reaches 100% SOC, charging terminates, i.e. setpoints for charging current and voltage are set to zero, while switch is set to OFF. In some situations, and if SOH information is available, SMU may decide to apply lower charging currents to batteries with lower SOH, as this reduces stress on the battery cells.

The link between EV BSS and reused EV batteries stationary storage can be made. Reused EV batteries, i.e. batteries with SOH less than 80%, cannot be used in EVs anymore but can still be used as part of larger stationary storage for grid purposes. In general, stationary storage with reused batteries is similar to BSS since it must connect different battery types to one central charging station management unit. The only difference is that in BSS the batteries' SOH is higher than 80%. In paper [48], the authors describe communication protocols for such stationary storage. They also consider CAN protocol as the most prominent for high level communication between battery and the EMS system of stationary storage. Interesting observation is that additional decodification equipment must be added if CAN protocol will be used. The reason is that each EV producer codifies its protocol in its own way.

IV. Conclusion

It is very important to choose both the appropriate EMS architecture and communication protocols for battery swapping station. A bad choice could lead to high investment cost of BSS but also could make severe problems in BSS operation. Due to high voltage of battery packs and large number of switching equipment, electromagnetic interferences could appear. Also due to communication failures battery packs could end up semi charged and supplied to the customer which can lead to unsatisfied BSS customers. This paper discussed different communications protocols within battery pack and within BSS. Also, the choice of data to transmit between different elements in BSS has been mentioned discussed. As a final remark, it can be pointed out that the same control pilot signals used in todays communication between battery and EVSE can be used in BSS as well. Also, the same HLC protocols used in battery and EV EMS communication used todays EVs can be used for detail information exchange between EV and BSS. The most prominent HLC in auto-industry is by far CAN bus protocol with additional decodification equipment to be able to read data from different EV manufactures.

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