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TELECOMMUNICATION ENGINEERING

MASTER THESIS

Communication Robustness Analysis and improvements in Leclanché BMS systems.

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El sotasignant, **Raul Aragonés Ortiz**, Professor de l'Escola Tècnica Superior d'Enginyeria (ETSE) de la Universitat Autònoma de Barcelona (UAB),

CERTIFICA:

Que el projecte presentat en aquesta memòria de Treball Final de Master ha estat realitzat sota la seva direcció per l'alumne David Gámez Baena,

I, perquè consti a tots els efectes, signa el present certificat.

Bellaterra, June 9, 2020

Raul Aragonés Ortiz **David Gámez Baena**

Communication Robustness Analysis and improvements in Leclanché BMS systems

David Gámez Baena

Keywords: Battery Management System (BMS), Battery Measurement Unit (BMU), Battery Control Unit (BCU), Communication robustness, RS-485, CAN, EMC, Baud rate, Bit Error Rate (BER)

Abstract

This master thesis have been done in the circumstance of an internship contract in a Swiss company called *Leclanché SA*. This company is develops, designs and manufactures complete battery storage solutions, covering the entire technology chain. From cells to pack solutions for Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs), as well as the Battery Management System which is the scope of this thesis.

Customers of the company have reported errors on the communication interface of the Battery Management System of the company, known as *G2 Leclanché BMS*. The purpose of the study done in this thesis is to find root causes of problems in the communication interface and its constraints.

To this end, faulty BMS samples returned by clients have been analysed and some special testing setups have been prepared in order to study communication constraints as baud rate, cable length, maximum number of nodes, etc.

Conclusions extracted from this robustness analysis of communication on *G2 Leclanché BMS* will be used for the next generation of BMS which is being developed by the company.

Acknowledgement

This master dissertation marked the end of a very important stage in my life. So, I would like to dedicate it and thank to each person that helped and supported me during this period.

Along these 6 years as student of Telecommunication Engineering, I had the chance to learn many things that aroused curiosity to me, at the same time that I was lucky to meet good, brilliant and smart people.

This last year has been special, since I could join the R&D department of *Leclanché SA* in order to do my master internship and dissertation. It has been extremely enriching for me since I could learn a lot of lithium battery field and electronic embedded systems related to it. At the same time, I could come back to the country where I was born and have a great first job experience in an international environment.

I would specially like to thank Aurelien, the hardware engineer of the company who supervised this project. Also Diego, my colleague from the master at the UAB, without whom I wouldn't have know IAESTE and I would probably not found this internship opportunity. And finally to Raúl Aragonés, my UAB professor that helped me to organise and coordinate this master thesis with the engineering school of the UAB.

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1 Introduction

1.1 Context

This master thesis report is done in the circumstances of an internship contract between the university (**Universitat Autònoma de Barcelona**), the company (**Leclanché SA**) and the student (**David Gámez Baena**).

The conditions for the placement to carry out the dissertation are as follows:

- The placement period is from 01.09.2019 until 31.12.2019, the timetable is 8 hours/day from Monday to Friday.
- The total numbers of hours for the external placement is 450. (subjects: Pràctiques profesionnals I II + MA dissertation).
- The placement takes place at Yverdon-les-Bains, Switzerland.

Leclanché SA is a world leading provider of high quality energy storage solutions, based on lithium-ion cell technologies, accelerating the progress towards a cleaner energy future. It is the only listed pure play, energy storage company in the world and is listed on the Swiss Stock Exchange.

The core technology of Leclanché SA expertise ranges from electrochemistry to energy management software. Leclanché develops, designs and manufactures complete, battery storage solutions, covering the entire technology chain from cells to pack solutions for Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs), as well as complete, energy storage solutions for multiple storage functions.

1.2 Cause

Leclanché offers multiple **Battery Management Systems (BMS)** technologies and a suite of Energy Management Systems software. BMS are an integral part of Leclanché's high voltage (e-Transport, Stationary) and low voltage systems solutions while the EMS software suite offers cutting-edge tools to manage large grid-connected Battery Energy Storage Systems.

Leclanché offers two high voltage BMS with 1000-V isolation: G2 for e-Transport solutions, and A1 for stationary solutions. Both have master-slave architecture and comply with design and industry safety standards. BMS offer pre-charge control, contactor control, and emergency stop and override control with system isolation fault monitoring.

The whole BMS architecture makes use of wired communication and work through **CAN** and **RS485** protocol. The purpose of this thesis is to provide a complete study of the **communication robustness** and propose some improvements in this matter of BMS systems.

1.3 Objectives

The expected outcomes of the study are:

- Make a status of current constraint into G2 BMS system related to communication.
- Propose solutions to mitigate communication issues in the field and to improve future Leclanché systems (impedance matching, shielding, casing, cabling groundings, EMC, etc.)
- Bring Academic knowledge to LSA on wired communications.
- Provides diagnostics techniques and tools for engineers.
- Analyse and diagnose faulty units returned by customers with problem on communication interfaces.
- Propose modifications on the BMS design for communication interface based on the analysis done in this dissertation.

1.4 Organisation of the report

This master thesis report is structured in four main paragraphs:

- **State of the art:** In this section the Battery Management System concept is introduced and the *G2 BMS from Leclanché SA* is presented. As the objective of this master thesis is to study communication robustness on the BMS of the company, a deep analysis of RS-485 communication hardware layer protocol is given since many problems have been detected on this communication interface in field application of the company. Also electromagnetic compatibility (EMC) and digital communication concepts are presented in this section for analysis purpose.

- **Setup preparation and preliminary tests:** in this paragraph the equipment used for testing and different setups prepared in order to test communication performance are described. Furthermore, some faulty BMS units returned by customers are diagnosed. Some problems on the communication interface have been detected for these units used on field application, and defects detected on them will be used to improve the design.

- **Study of the current G2 system performance:** This section presents different experiments done in the company laboratory in order to study communication interfaces performance and their results. Additionally, different problems related to communication issues along the BMS coming from customers are exposed. The battery management system is used for a large and wide set of customer that use it in different applications with disparate stress levels that can cause some trouble on communication interfaces. By making use of faulty BMS units coming from customer on field applications, an analysis of the root cause for communication issues will be done.

- **Improvement investigation:** After experimentation and investigation of communication robustness on the current G2 BMS, some improvements are proposed in order to reduce communication issues and improve communication performance.

2 State of the art

2.1 Introduction

As said in the introduction chapter, this master thesis report will provide a in depth analysis of the communication robustness of the actual Battery Management System used by Leclanché SA. The current system under study is denominated by the company as **G2 BMS system**.

Conclusions and improvement proposals extracted from the analysis carried out in this thesis will be taken into account for **G3 BMS system** that Leclanché SA is actually designing.

In order to have a clear idea about how the communication robustness analysis is going to be performed, this chapter presents an overview of the G2 Battery Management System describing its architecture, as well as hardware and software characteristics. Also, an exhaustive description of the communication standards used in the BMS system is done. Finally, some communication analysis concepts used along the study are explained.

Before all this, it is necessary to introduce what a **Battery Management System (BMS)** is.

2.2 BMS concept

Nowadays, most of the batteries on the market are based on Lithium ion cells technology which has two critical design issues:

- The cells can be damaged in case of overcharging, which can lead to overheating and even explosion or flame.
- Lithium ion cells can also be damaged if they're discharged below a certain threshold, approximately 5 percent of total capacity. If the cells are discharged below this threshold their capacity can become permanently reduced.

To avoid these issues, battery packs are equipped with a Battery Management System which can be considered as the "brain" of the system. This "brain" it is none other than an electronic system that will report crucial information to keep the battery operating inside its safe operating area.

2.3 Presentation of Leclanché SA BMS

G2 Battery Management System from *Leclanché SA* is the name the second generation of BMS used for mobility applications in the company. These applications include Marine, Road and Railway. Also, in some exceptional cases *G2 BMS* is also used in stationary applications. This generation of BMS are adapted to be compatible with M2 modules which is the name of the mechanical design for Lithium ion cells packs which are assembled to form a module.

Some important projects of the company make use of this BMS generation. Two examples are:

- **Ellen E-ferry**: inaugurated in august 2019, Ellen is the most powerful 100% electric-ferry in the world and is paving the way to a concrete transformation of maritime traffic.

  This project was co-financed by the European Union in cooperation with Danish islanders eager to achieve carbon neutrality. The Leclanché factory in Yverdon-les-Bains (Switzerland) was selected to power the ferry.

  For this purpose, the company developed a special solution: **The Marine Rack System (MRS)**. The Marine Rack System (MRS) is a modular and scalable Li-ion battery system for marine applications. Designed to be safe, the MRS has undergone numerous fire propagation tests and is DNV-GL certified. With redundant fire detection systems, hot gas extraction channels and the choice of two integrated fire suppression systems (foam or watermist based) the risk of fire propagation has been reduced to zero. The water mist system integrates easily with existing water based fire suppression systems. IP65 ingress protection allows the MRS to operate reliably in hostile marine environments.

Figure 1: Ellen E-Ferry

Figure 2: MRS

- **Graciosa Storage Power Plant**: Graciosa is an island of 4,500 inhabitants in the Atlantic Ocean that is part of the Portuguese Azores, 1,600 km away from the Portuguese mainland. In the past, 100 annual load was provided by diesel generators, requiring more than 3.3 million liters of diesel every year.

  Leclanché installed a 7.4 MW / 3.2 MWh Lithium Titanite Oxide (LTO) battery energy storage system (BESS) for a microgrid featuring a 4.5 MW wind farm, a 1 MW solar PV plant and a diesel generator plant. The BESS compensates for the highly variable renewable energy production, provides voltage and frequency control, and has grid-forming capability if needed.

Figure 3: Leclanché Storage Power Plant in Graciosa

As it can be seen, these are big projects providing a huge energy capacity. For example in Graciosa, Diesel generation is now used almost exclusively for backup power, decreasing overall diesel consumption by more than 65% and resulting in annual fuel savings of 1.9 million.

However, the installation cost of a Storage Power Plant like this can be really high. Then, it will be profitable only as long-term solution. Specifically, Leclanché's microgrid solution was provided on a turnkey basis and includes a 20-year lifetime performance warranty.

For that, Lithium Titanate Oxide (LTO) batteries must be perfectly monitored in order to operate in their safe operating area. Then, LTO technology guarantees optimal performance and minimises maintenance expenses over the lifetime of this key infrastructure asset. LTO cell technology is uniquely capable in this regard, retaining 80% of its nominal capacity after more than 20,000 cycles.

To provide a longer lifetime, a higher number of recharging cycles and secure operation is the main purpose of the lead of this thesis, the ***G2 Battery Management System*** from Leclanché SA.

2.4 Technical description of G2 BMS

The G2 BMS is a Battery Management System used for management of Lithium-Ion Batteries. The hardware design and some of the software layers of this system, come from previous supercapacitor management system. The design has been modified to make it compatible with Lithium-ion Batteries. The system now supports both LTO (Lithium Titanate Oxide) and G/NMC (Lithium Nickel Manganese Cobalt Oxide) cells.

The BMS hardware is divided in three main parts: BCU, BMU and the Switchbox Unit. This topology is illustrated in figure 5. It shows clearly a master/slave architecture where the BCU is the master and the BMU is the slave. This is a model of asymmetric communication or control where one device or process controls one or more other devices or processes and serves as their communication hub.

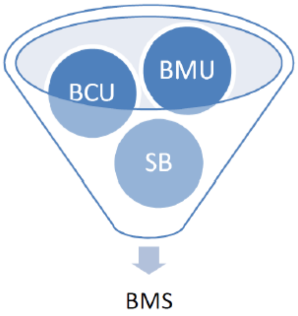


Figure 4: G2 BMS components

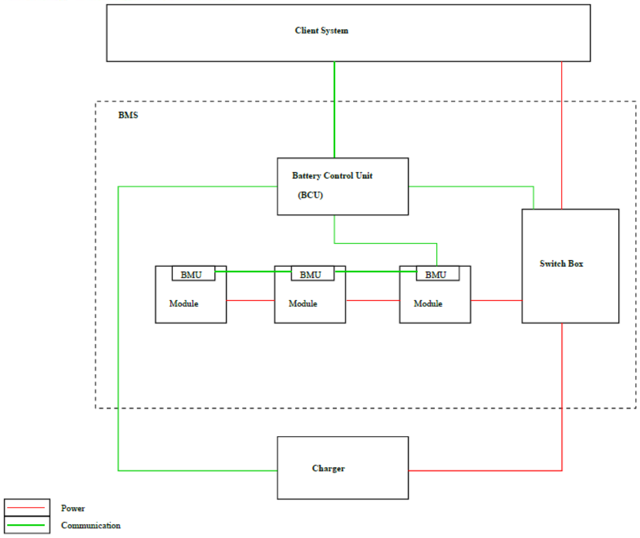


Figure 5: System Architecture

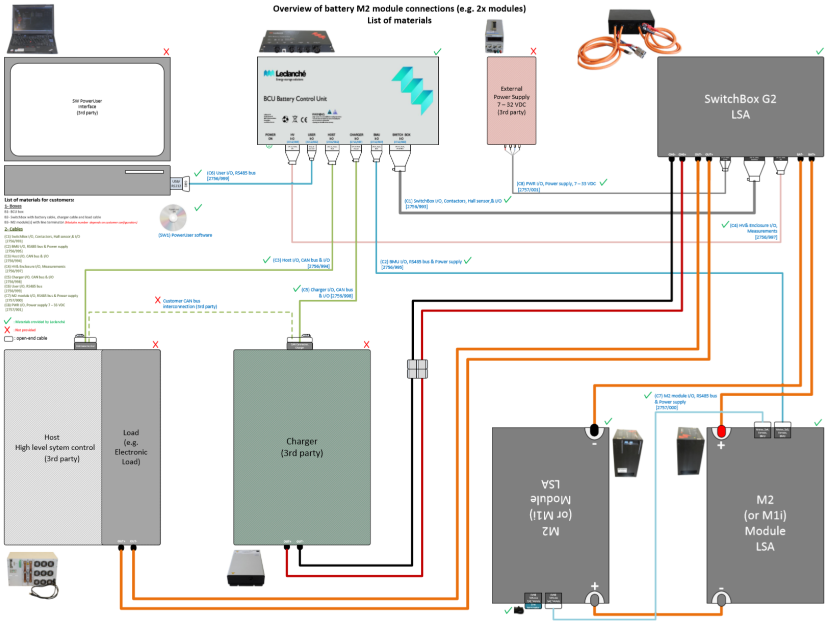


Figure 6: BMS G2

2.4.1 Battery Control Unit

The BCU (Battery Control Unit) is the main controller of the BMS. It contains the MCU (Microcontroller Unit) running the BMS code and has the interfaces to Host (Client) systems and other components of the BMS. This is often referred as the “Master” of the BMS.

Figure 7: Battery Control Unit

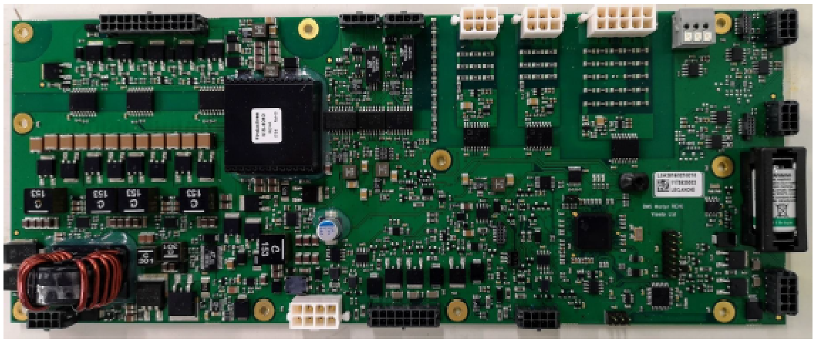


Figure 8: BCU PCB

Technical features

- Operating temperature -40C to 60C
- Operating range 8.32V, max 12A
- Power on 8-32V
- Charge sense, U higher than 7.4V

- Contactor control (x6)
- Contactor state feedback (x6)
- Battery stack voltage measurement up to 1000V
- DC Bus voltage measurement up to 1000V
- Insulation level measurement up to 1000V
- 2 current measurement channel for hall sensor, 0-5V
- CAN interface for charger control
- CAN interface for host connection
- RS485 interface towards PowerUSER
- RS485 interface towards BMU daisy chain
- BMU power on 20V
- Configurable digital input/output (x5)
- Emergency stop I/O (x2)
- Power on LED
- Real Time Clock with battery backup
- Watchdog Controller

2.4.2 Battery Measurement Unit

The BMU (Battery Measurement Unit) is a measurement card that is situated in the battery module (the M2 module). This card has connections to the cells for voltage measurement and balancing, and connections to temperature sensors in the module. It also has a RS-485 interface for communicating with the BCU. The BMU is the “Slave”-card of the BMS. However, it does have an MCU and is able to some more complex functions. Multiple BMUs can be daisy-chained for a maximum 1000VDC system voltage. The rate of the data update from BMU is 1 Hz.

There are two different variants for the BMU circuit:

1. BMU 12: for up to 12 cells management (2 Temperature sensors)
2. BMU 24: for up to 24 cells management (4 temperature sensors)

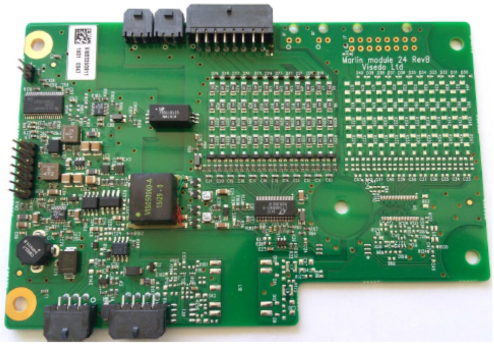


Figure 9: BMU PCB

Technical Features

- RS485 communication interface - outgoing
- RS485 communication interface - incoming
- Galvanic isolation
- Up to 4 temperature measurement
- 12 channels for cell voltage measurement, 0-5V, BMU 12 only
- 24 channels for cell voltage measurement, 0-5V, BMU 24 only
- Cell balancing (12 Ohm per channel)
- GPIOs x2

2.4.3 Switchbox Unit

Switchbox Unit is the component housing the physical contactors, fuses, HV connections and Hall sensor for current measurement. This component will be outside of scope of this thesis.

Figure 10: Switchbox Unit

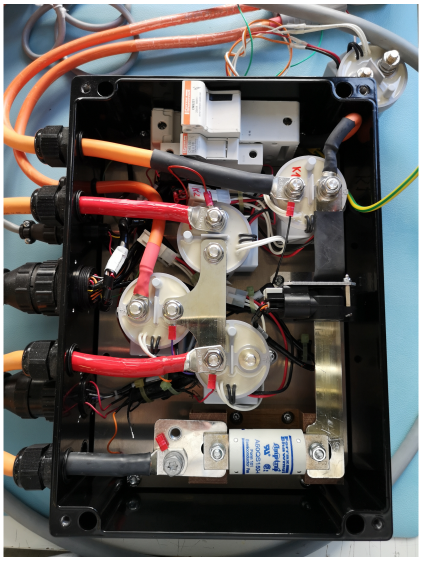


Figure 11: Switchbox Unit

2.4.4 Communication interfaces

The System has two CAN ports and two RS-485 ports. The CAN protocols are handled on application level and can be mapped to physical ports. They are used for Host and charger communication. The RS-485 communication is fixed to a physical port and it is used for BMU and PowerUser communication which is the scope of this project since many customers have reported error on these communication interfaces. The diagram below shows the BMS system communication interfaces.

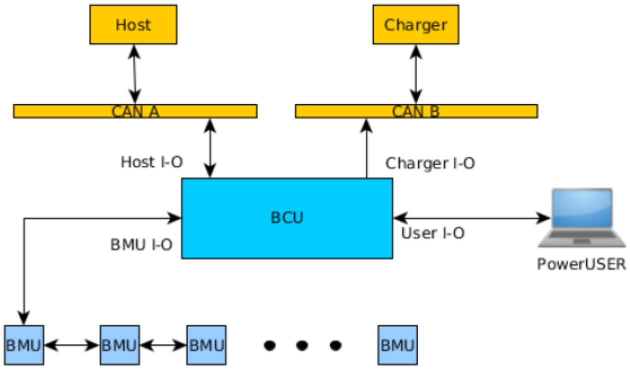


Figure 12: Communication interfaces

2.5 RS-485

2.5.1 Introduction

In 1983, the Electronics Industries Association (EIA) approved a new balanced transmission standard called RS-485. Finding widespread acceptance and usage in industrial, medical, and consumer applications, RS-485 has become the industry's interface workhorse.

This electrical-only standard, that defines the electrical characteristics of drivers and receivers for use in serial communication systems, is also known as TIA-485(-A) or EIA-485. It supports inexpensive local networks and multidrop communications links, using a differential signalling over twisted pair.

The key features of RS-485 that make it ideal for use in industrial and instrumentation communications applications are:

- Long distance links, up to 4000 feet.
- Bidirectional communications possible over a single pair of twisted cables.
- Differential transmission increases noise immunity and decreases noise emissions.
- Multiple drivers and receivers can be connected on the same bus. Up to 32 unit loads.
- Wide common-mode range allows for differences in ground potential between the driver and receiver.
- 10-Mbps maximum data rate (at 40 feet).

RS-485 Standard Specifications	
Mode of operation	Differential
Allow number of Tx and Rx	32 Tx 32 Rx
Maximum cable length	4000 ft
Maximum data rate	10 Mbps
Minimum driver output range	±1.5 V
Maximum driver output range	± 5V
Minimum drive capability	± 55 mA
Maximum driver short-circuit current	250 mA
Tx load impedance	54 Ω
Rx input sensitivity	±200 mV
Maximum Rx input resistance	12 KΩ
Rx input voltage range	-7 V to +12 V
Rx logic high	>200 mV
Rx logic low	<200 mV
Max common mode voltage	-7V to +12V

Table 1: RS-485 standard specifications

2.5.2 Network topology

The RS-485 standards suggests that its nodes be networked in a daisy-chain, also known as party line or bus topology. In this topology, the participating drivers, receivers, and transceivers connect to a main cable trunk via short network stubs.

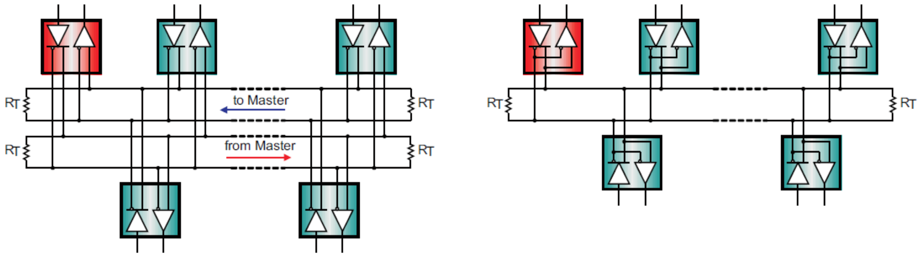


Figure 13: RS-485 Network topology

On the left side of figure 13, a full-duplex implementation is represented. It requires two signal pairs (4 wires) and full-duplex transceivers with separate bus access lines for transmitter and receiver. Full-duplex allows a node to simultaneously transmit data on one pair while receiving data on the other pair.

On the right side of figure 13, a half-duplex bus structure in RS-485 is represented. This is the bus structure implemented in the system and the spotlight of this communication robustness analysis. In half-duplex, only one signal pair is used, requiring the driving and receiving of data to occur at different times.

Both implementations necessitate the controlled operation of all nodes via direction control signals, such as Driver/Receiver Enable signals, to ensure that only one driver is active on the bus at any time.

Having more than one driver accessing the bus at the same time leads to bus contention, which, at all times, must be avoided through software control.

2.5.3 Signal characterisation

Differential data transmission signal in RS-485 can be characterised through four parameters: V_{OD}, V_{OS}, V_{GPD} and V_{CM}. Figures 14, 15 and 16 illustrates these parameters.

- V_{OD} represents the differential output voltage of the driver across the termination load. The RS-485 standard refers to this parameter as "termination voltage" (V_T), but V_{OD} is also commonly used. It can also be called V_{AB} since it's the differential voltage between bus A and B which is across the transmission line and not with respect to ground.

  RS-485 specifies that the receiver output state should be logic high for differential input voltages of $V_{OD} \geq +200$ mV and logic low for $V_{OD} \leq -200$ mV. That must be take into account in long cable runs since V_{OD} is attenuate due to the DC resistance. Also a possible very low impedance could lead to a out of range V_{OD} signal.

  For input voltages in between these limits, a receiver's output state is not defined and can randomly assume high or low.

  At the driver output, V_{OD} is 1.5V minimum. The IC manufacturer should guarantee this voltage under two test conditions: The first uses a simple differential load resistor. The second includes two 375Ω resistors connected to a common-mode supply. This test is difficult and is important, because it essentially guarantees the system's differential-noise margin under worst-case loading and common-mode conditions.

- V_{OS} represents the driver's offset voltage measured from the center point of the load with respect to the driver's ground reference. V_{OS} is also called "V_{OC}" for output common-mode voltage. This parameter is related to V_{CM}.

- V_{CM} represents the common-mode voltage for which RS-485 is famous. The limit is 7V to +12V. Common-mode voltage is defined as the algebraic mean of the two local-ground-referenced voltages applied to the referenced terminals (receiver input pins, for example).

- V_{GPD} represents the ground-potential difference that can exist between nodes in the system. RS-485 allows for a 7V shift in grounds. A shift of 7V below the negative (0V) power rail yields the 7V common mode limit, whereas 7V above the 5V positive power rail yields the other common-mode limit of 12V.

Understanding these parameters enables improved component selection, because some devices trade off certain parameters to gain others.

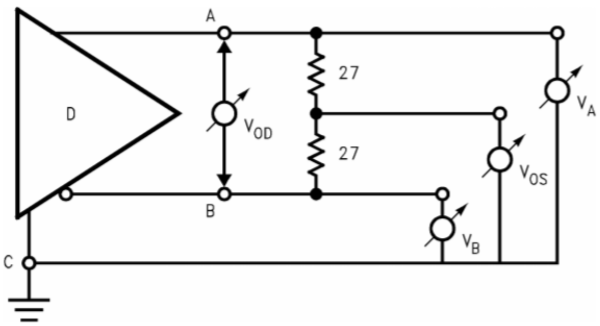


Figure 14: RS-485 signal parameters

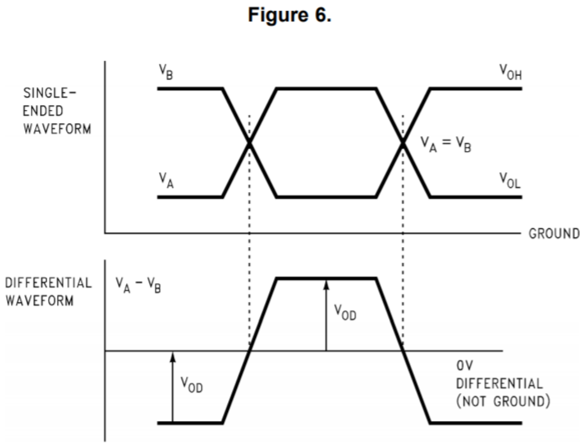


Figure 15: RS-485 signal parameters

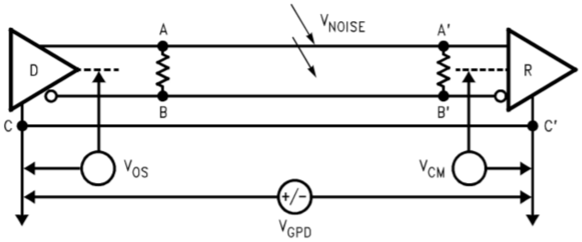


Figure 16: RS-485 signal parameters

Figure 17 shows the RS-485's noise-rejection capability. The plot includes the receiver's output signal. Note that the receiver clearly detects the correct signal state, despite the common-mode noise. Differential transmission offers this high noise rejection; a single-ended system would erroneously switch states several times under these test conditions.

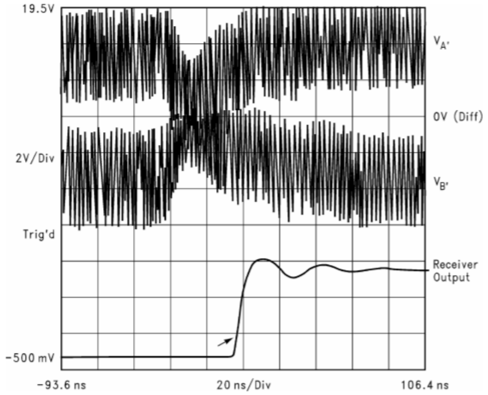


Figure 17: RS-485 response with large common-mode noise voltages

2.5.4 Cable type

RS-485 Applications benefit from differential signaling over twisted pair cable. This is because noise from external sources couples equally into both signal lines as common-mode noise, which is rejected by the differential receiver input.

Industrial RS-485 cables are of the sheathed, unshielded, twisted pair type (UTP) with a characteristic impedance of 120Ω and 22 AWG. Figure 18 shows the cross section of a single pair, UTP cable for half-duplex networks.

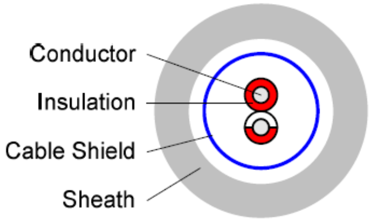


Figure 18: Example of RS-485 communication cable

2.5.5 Termination

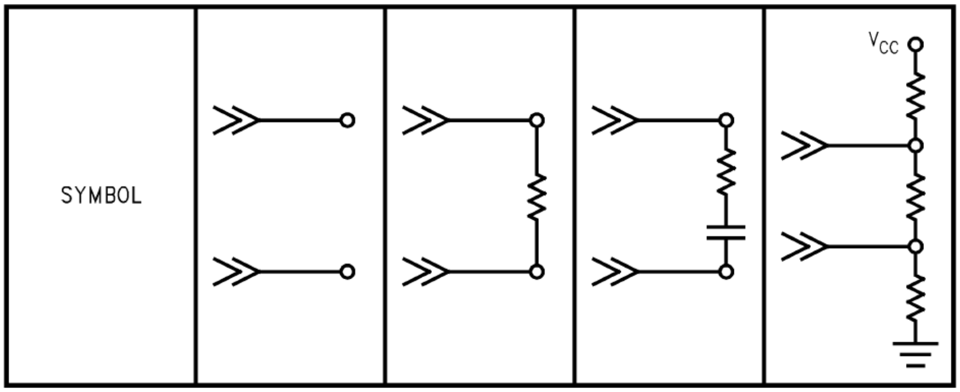
There are several options for terminating an RS-485 bus:

1. **No termination:** This option is feasible if the cable is short and if the data rate is low. Reflections occur, but they settle after about three round-trip delays. For a short-cable, the round-trip delay is short and, if the data rate is low, the unit interval is long. Under these conditions, the reflections settle out before sampling, which occurs at the middle of the bit interval.
2. **Parallel termination:** the most popular termination option is to connect a single resistor across the conductor pair at each end. The resistor value matches the cable's differential-mode characteristic impedance. If the bus is terminated in this way, no reflections occur, and the signal fidelity is excellent. The problem with this termination option is the power dissipated in the termination resistors.
3. **RC termination:** for minimising power dissipation, an RC termination may be the solution. In place of the single resistor, you use a resistor in series with a capacitor. The capacitor appears as a short circuit during transitions, and the resistor terminates the line. Once

the capacitor charges, it blocks the DC loop current and presents a light load to the driver. Lowpass effects limit use of the RC termination to lower data-rate applications.

4. **Failsafe termination:** another option is a modified parallel termination that also provides a fail-safe bias. A detailed discussion of fail-safe biasing occurs later in the state of art.

Figure 19 shows a compartation between these four termination methods. The main point to remember is that the termination should be located at both ends of the bus, as shown on figure 13 and not at every node.



TERMINATION NAME:	UNTERMINATED	PARALLEL	RC TERMINATION	FAILSAFE
DATA RATE:	LOW	HIGH	MEDIUM	HIGH
SIGNAL QUALITY:	LIMITED	EXCELLENT	LIMITED	EXCELLENT
POWER:	LOW	HIGH	LOW	HIGH

Figure 19: RS485 bus termination options

2.5.6 Unit Load concept

In a communication based on RS-485, the input impedance of the receiver is specified as larger than or equal to $12K\Omega$. This impedance is defined as one **Unit Load (UL)**. The standard RS-485 specification designates a capability to sustain up to 32 ULs. Exceeding 32-UL loads excessively limits the drivers and attenuates the differential signal, thus reducing the differential noise margin.

This maximum capability depends on the RS-485 transceivers model used in the communication system. The standard does not specify a maximum number of transceivers, but it does specify a maximum of 32 ULs. If a transceiver imposes one unit load, the maximum number of transceivers is also 32. Nowadays, transceivers with $\frac{1}{4}$ and slower ratings can be obtained, which allow 128 and more transceivers. However, these fractional-UL devices, with their high-impedance input stages, typically operate much more slowly than do single-UL devices. The lower speed is acceptable for buses operating in the low hundreds of kilobits per second, but it may not be acceptable for a 10 Mbps bus. Because of this reason, the input impedance of a transceiver is given by a value referred as a fraction of a Unit Load.

Table 2 shows the maximum number of nodes that can be connect in a RS-485 communication system depending in the transceiver input impedance.

Unit Load	**Max. number of nodes**	**Min. Receiver Input Impedance**
1	32	12 KΩ
1/2	64	24 KΩ
1/4	128	48 KΩ
1/8	256	96 KΩ
1/10	320	120 KΩ

Table 2: Unit Load transceiver input impedance

This node constraints comes from the RS-485 standard that specifies a maximum common-mode loading (or minimum common-mode resistance) of $R_{CM} = 375\ \Omega$.

RINEQ in figure 21 represents the equivalent input resistance lumped together to represent the common-mode input resistance of all transceivers connected to the bus. This resistance is given by 1, where n_{transc} is the number of transceivers connected to the network and UL_{transc} is the input impedance of these transceivers given as a fraction of a Unit Load.

$$R_{INEQ} = (n_{transc} \cdot \frac{1}{UL_{transc}^{-1} \cdot 12000})^{-1} \tag{1}$$

Table 3 shows the value of R_{INEQ}, depending on the number of transceivers connected. These values correspond to **SN65HVD1781** RS-485 transceivers, which is the model used in *G2 Leclanché BMS* system and its UL value is 1/10.

n_{transc}	R_{INEQ} (Ω)
1	120000
10	12000
100	1200
200	600
320	375

Table 3: Common mode loading vs number of transceivers

2.5.7 Fail-Safe operation

A receiver connected to a RS-485 bus must work under fail-safe operation. This means that it must be able to assume a determined output state in the absence of an input signal or when the differential signal is within the uncertainty range. The standard RS-485 uncertainty covers the range -200 mV to 200 mV.

There are three possible causes that can lead to the loss of an input signal:

- An **open circuit** caused by a wire break or the unintentional disconnection of a transceiver from the bus.
- A **short circuit** due to an insulation fault, connecting both conductors of a differential pair to one another.
- An **idle bus** when none of the bus transceivers are active. This particular condition is not a fault but occurs regularly when bus control is handed over from one driver to another to avoid bus contention.

Because the conditions above can cause conventional receivers to assume random output states when the input signal is zero, modern transceiver designs include biasing circuits for open-circuit, short-circuit, and idlebus fail-safe, that drive the receiver output to a determined state, when the input signal is within the uncertainty range.

The way to provide fail-safe operation requires only two additional resistors. At one end of the bus , a pullup and pulldown resistor are connected as shown in figure 20.

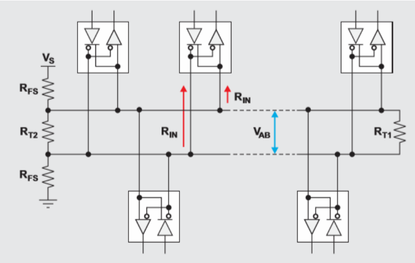


Figure 20: RS-485 Network with failsafe bias resistors

This arrangement provides a simple voltage divider on the bus when there are no active drivers that generates sufficient differential bus voltage, to drive the receiver output into a determined state.

Figure 21 shows the equivalent circuit with transceiver lumped together. Then, the differential bus voltage when a couple of failsafe biasing resistors are added is given by equation 2.

$$V_{AB} = \frac{V_S}{R_{FS}} \cdot \frac{1}{\frac{1}{R_{INEQ}} + \frac{1}{R_{FS}} + 2(\frac{1}{R_{T1}} + \frac{1}{R_{T2}})} \tag{2}$$

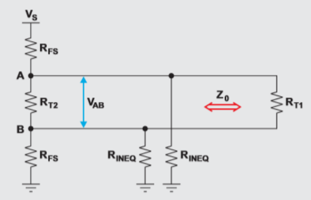


Figure 21: Equivalent circuit with transceiver resistance lumped together

2.5.8 ESD protection

In some applications, lightning strikes, power source fluctuations, inductive switching, and electrostatic discharge can cause damage to RS-485 transceivers by generating large transient voltages. The following ESD protection, EFT protection, and surge protection specifications are relevant to RS-485 applications:

- IEC 61000-4-2 ESD protection
- IEC 61000-4-4 EFT protection
- IEC 61000-4-5 surge protection

The level of protection can be further enhanced when using external clamping devices, such as TVS diodes. TVS diodes are normally used to protect silicon devices, like RS-485 transceivers, from transients. The protection is accomplished by clamping the voltage spike to a limit, by the low impedance avalanche breakdown of a PN junction. TVS diodes are ideally open-circuit devices. A TVS diode can be modeled as a large resistance in parallel with some capacitance while working below its breakdown voltage. When a transient is generated and the surge voltage is larger than the breakdown voltage of the TVS, the resistance of the TVS decreases to keep the clamping voltage constant. The TVS clamps the pulse to a level that does not damage the device that it is protecting. The transients are clamped instantaneously and the damaging current is diverted away from the protected device (see Figure 22).

The function of a TVS in RS-485 applications is to clamp the voltage on the bus to the common-mode voltage range of the RS-485 transceiver (7 V to +12 V). Some TVS devices have been specifically designed for RS-485 applications. For higher power transients, protection can be increased by adding Resistors RS (between 10 and 20) between the protected device and the input pin as shown in Figure 22 and Figure 23.

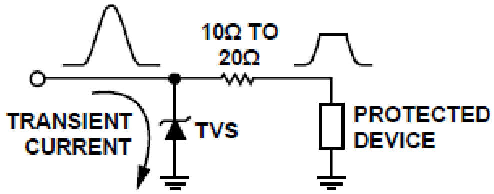


Figure 22: Transient Voltage Suppressor

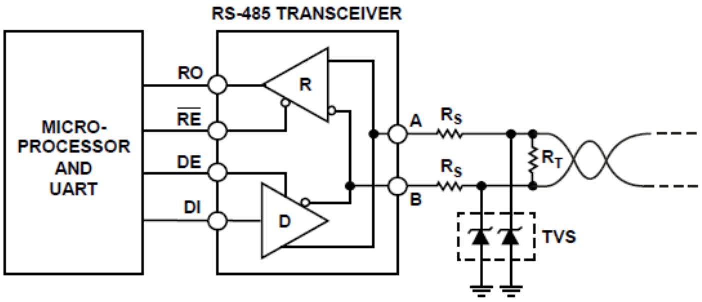


Figure 23: TVS Application Circuit

2.6 EMC: Shielding and grounding

2.6.1 Introduction

Despite the potential difference between the data-pair conductors determines the signal in RS-485 communication without officially involving ground, the bus needs a ground wire to provide a return path for induced common-mode noise and currents, such as the receiver's input current.

A typical mistake is to connect two nodes with only two wires. If you do this, the system may radiate high levels of electromagnetic interference (EMI), because the common-mode return current finds its way back to the source, regardless of where the loop takes it. An intentional ground provides a low-impedance path in a known location, thus reducing emissions.

Electromagnetic-compatibility and application requirements determine whether you need a shield. A shield both prevents the coupling of external noise to the bus and limits emissions from the bus. Generally, a shield connects to a solid ground (normally, the metal frame around the system or subsystem) with a low impedance at one end and a series RC network at the other. This arrangement prevents the flow of DC ground-loop currents in the shield. In this section, the shielding performance of different techniques is presented.

Later on this project some experimentation will evaluate the performance of the RS-485 communication concerning electromagnetic compatibility (EMC). So, some introductory concepts are explain down below.

2.6.2 Electromagnetic compatibility (EMC)

Electromagnetic compatibility (EMC) is the ability of electrical equipment and systems to function acceptably in their electromagnetic environment, by limiting the unintentional generation, propagation and reception of electromagnetic energy which may cause unwanted effects such as electromagnetic interference (EMI) or even physical damage in operational equipment. The goal of EMC is the correct operation of different equipment in a common electromagnetic environment. It is also the name given to the associated branch of electrical engineering.

EMC pursues three main classes of issue:

1. **Emission** is the generation of electromagnetic energy, whether deliberate or accidental, by some source and its release into the environment. EMC studies the unwanted emissions and the countermeasures which may be taken in order to reduce unwanted emissions.
2. **Susceptibility** is the tendency of electrical equipment, referred to as the victim, to malfunction or break down in the presence of unwanted emissions, which are known as Radio frequency interference (RFI). **Immunity** is the opposite of susceptibility, being the ability of equipment to function correctly in the presence of RFI, with the discipline of ”hardening” equipment being known equally as susceptibility or immunity.

3. **Coupling** which is the mechanism by which emitted interference reaches the victim.

Interference mitigation and hence electromagnetic compatibility may be achieved by addressing any or all of these issues which can be mitigated with engineering techniques such as shielding and grounding.

2.6.3 Shielding and ground loops

The purpose of shielding a cable is to reduce the coupling of external noise to the cable. At the same time, emission from this cable are also reduced. However, the manner in which the shield is terminated can significantly affect its effectiveness, as it shall see in this section.

A shielded cable which is not in contact with a ground plane anywhere except possibly at the ends can be modelled as a physical environment as shown in figure 24

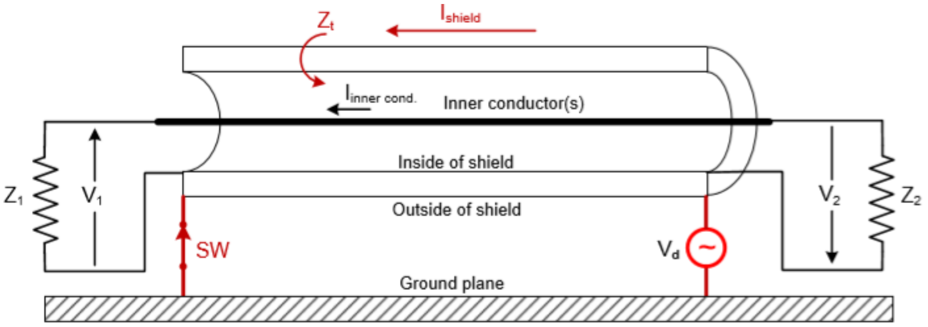


Figure 24: Model of the physical environment including termination

A transmission line is formed by whatever ground plane exists and the outside of the shield. Likewise the inside of the shield and the conductors enclosed also form a transmission line. Thus what we have is two transmission lines coupled by the leakage through the shield. The coupling of the inner and outer transmission lines is characterised by a mechanism called surface transfer impedance, Z_t.

In most installations the shield of the conductors is shorted to ground either at both ends or one end. This shown schematically in figure 24 by the switch SW.

- **Shield terminated at both ends.** In this condition, current can flow along the outside of the shield. This current can be due either to ground loops caused by the grounds at the ends of the cable being at different potentials (V_d), or it can be due to induction from external fields, or both. In either case the external shield current is coupled into the inner circuits via the surface transfer impedance, Z_t.
- **Shield terminated at only one end**. If the shield is terminated at only one end, the ground loop is broken. Current is limited to that which is induced to flow through the distributed capacitance between the outside of the shield and the ground plane, see figure 25.

  The induced current may be small, in which case the important quantity is the voltage distribution along the cable. The voltage is zero where the cable is terminated, but can be high at the open end for frequencies where the cable exceeds one-tenth of a wavelength, because at that point it becomes a very efficient antenna.

  At the open end, there is capacitive coupling between the shield and the conductors of the cable due to the fringing capacitance C_f. As the voltage across this capacitance can be high, a significant current can be coupled into the conductors of the cable through the fringing capacitance.

  Because a capacitance exists between the end of the shield and the cable conductors, electrical interference can be injected directly into the cable loads. The magnitude of this capacitance depends a lot on the installation, so it can't really be calculated. The capacitive coupling is greatest at high frequencies, where the capacitive reactance is the lowest.

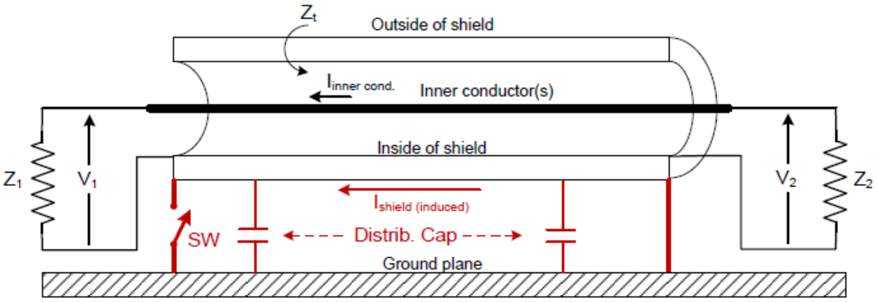


Figure 25: Electrical model of a shielded cable terminated at only one end

The theory of shielding gives a general understanding of what can be expected of shield performance, but the manner in which the shield is terminated also has a significant impact on the effectiveness of the shield.

An important factor to consider is whether or not the grounds at opposite ends of the cable are at close to the same potential. If they are, ground-loop currents will be minimal. In this case grounding both ends of the shield is likely to give the best shielding performance. If the grounds are at substantially different potentials, ground loop currents could be a problem, and in this case leaving one end of the shield unterminated may give the best overall shielding performance, providing that shielding against high frequencies is not an issue.

The decision to terminate or not terminate depends on the application. Unfortunately there is no rule that applies to all situations, and an experiment is often required to determine the best way to terminate the shield. This experimentation has been done for shielded cable used in *G2 Leclanché BMS* for communication between BMUs and BCU.

2.6.4 Wire routing for optimal shielding and EMC

EMC it's not that difficult to achieve. Sometimes following some simple rules on wire routing can avoid many issues. As it is explain in [1], five rules must be followed when installing wires of the system are:

1. **Return conductors must be nearby:** this will avoid big loops and will limit common impedance coupling.
2. **Wired connections must be push against equipotential structures:** mass loop surface reduction, common mode diaphony coupling reduction.
3. **Connect free wires to the chassis mass:** this will avoid big loops and will limit common mode impedance coupling.
4. **Use shielding for noisy and sensitive wires:** A shield connected to the mass in both termination is a really effective HF protection.
5. **Do NOT move away signal wires from supply wires:** 10 to 30 cm are enough to avoid diaphony issues. However, a big distance between supply wires and signal wires will increase the loop surface. Then, magnetic field collection is increased and some troubles can result.

2.7 Communication analysis concepts

In this section some elementary concepts for digital communication analysis are introduced.

2.7.1 Bit Error Rate

In digital transmission, the number of bit errors is the number of received bits of a data stream over a communication channel that have been altered due to noise, interference, distortion or bit synchronisation errors.

The bit error rate (BER) is the number of bit errors per unit time. The bit error ratio (also BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. Bit error ratio is a unitless performance measure, often expressed as a percentage.

2.7.2 Eye diagram

he eye diagram is a useful tool for the qualitative analysis of signal used in digital transmission. It provides at-a-glance evaluation of system performance and can offer insight into the nature of channel imperfections. Careful analysis of this visual display can give the user a first-order approximation of signal-to-noise, clock timing jitter and skew.

The eye diagram is an oscilloscope display of a digital signal, repetitively sampled to get a good representation of its behavior.

The eye diagram can also be used to examine signal integrity in a purely digital system, such as fiber optic transmission, network cables or on a circuit board.

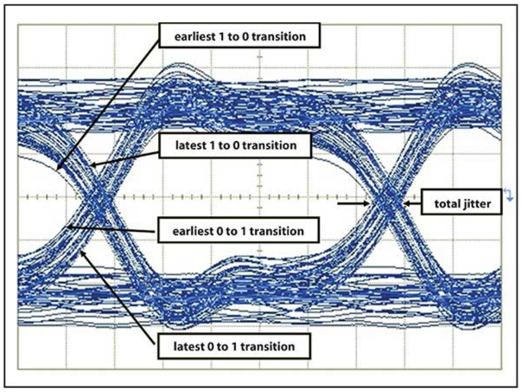


Figure 26: Eye pattern

2.7.3 Jitter

Jitter is the time deviation from the ideal timing of a data-bit event and it is perhaps one of the most important characteristics of a high speed digital data signal. To compute jitter, the time deviations of the transitions of the rising and falling edges of an eye diagram at the crossing point are measured. Fluctuations can be random and/or deterministic.

2.7.4 PRBS stress test

PRBS stress test is a commonly used tool for testing serial digital interface, [2] is an example of study based on this stress test. A **Pseudo-Random Binary Sequence (PRBS)** is a series of digital 1's and 0's that is statistically random within the sequence length. This type of sequence shows no correlation between adjacent bits and as such can be considered a "worst case" stress test signal for testing serial digital interfaces.

Mathematically, a binary sequence (3) of $\boldsymbol{N}$ bits is defined as PRBS if its autocorrelation function (4) has only two values. These values are defined by (5).

$$a_j \in \{0,1\} \;\; for \;\; j = 0,1,...,N-1 \tag{3}$$

$$C(v) = \sum_{j=0}^{N-1} a_j \;\; a_{j+v} \tag{4}$$

$$C(v) = \begin{cases} m & \text{if } v = 0 \text{ (modN)} \\ mc & \text{otherwise} \end{cases} \tag{5}$$

If the interface can handle a "noisy" random sequence of bits without generating bit-errors, then we can be confident that it will be able to handle "clean" non-random sequences.

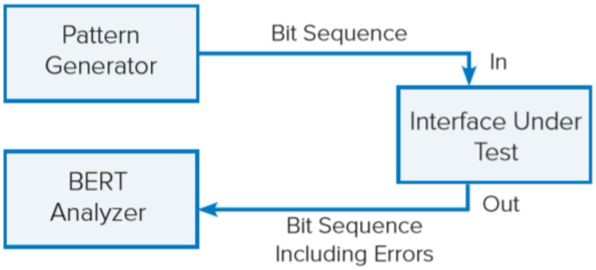


Figure 27: Serial interface stress testing

This test is also suitable for eye diagram testing. As it was described in the previous section, a properly constructed eye diagram consists of all possible combinations of 1's and 0's including isolated 0's and 1's after long runs of successive 1's and 0's. Any deviation from such a signal type will give different results for both vertical and horizontal Eye opening.

PRBS patterns are a suitable source of such pseudo-random combinations of 1's and 0's for eye diagram testing.

3 Setup preparation and preliminary tests

3.1 Introduction

In this section, the equipment used for testing during the communication robustness analysis is described. Also, some special setups replicating communication on *G2 Leclanché BMS* are implemented in order to have additional features to evaluate communication performance. Finally, some preliminary test are done on faulty BMS units returned by customers where communication is failing.

3.2 Equipment for testing

3.2.1 RIGOL DSA 815

RIGOL DSA 815 is a spectrum analyser designed for starters. It can be widely used in various fields, such as education, company research and development as well as industrial manufacture. Main features of this model are:

- Frequency range operation: 9 KHz - 1.5 GHz
- Minimum resolution bandwidth: 10 Hz
- EMI filter and Quasi-Peak Detector Kit

This tool will be used in the study of the shielding performance corresponding to paragraph *4.4*. Tracking generator feature will be used to inject some currents on the communication cable for different shielding and grounding configurations and the electromagnetic response of the cable will be measure with the spectrum analyser input.

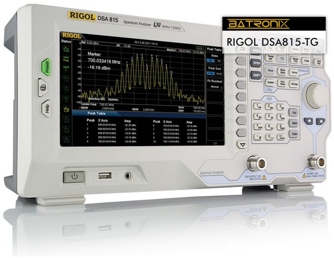


Figure 28: TBCP1-150

3.2.2 TBCP1-150

This is a RF current monitoring probe from Tekbox which is used as EMC pre-compliance test equipment.

The probe has a 3 dB bandwidth of approximately 150 MHz and is characterized and usable over the frequency range from 10kHz to 250 MHz.

Figure 29: TBCP1-150

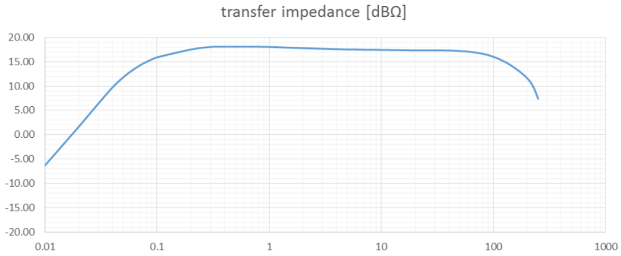


Figure 30: Transfer impedance of TBCP1-150

This tool is connected to he spectrum analyser input which will show a voltage measurement. The transfer impedance in dB subtracted from the analyser reading in dBV gives the corrected reading in dBA.

DIY current probe

For shielding performance study purposes, a second current probe is needed. Since buying a second current probe would suppose an extra cost for the company and would take an unavailable time, a DIY (Do-It-Yourself) current probe has been built with some already available components in the company.

Current probe: theory of operation

Currents probes are essentially RF current transformers. When the probe is clamped over the conductor or cable in which current is to be measured, the conductor forms the primary winding and the probe's windings are the secondary. This is essentially a broadband high-frequency transformer, as shown in figure 31.

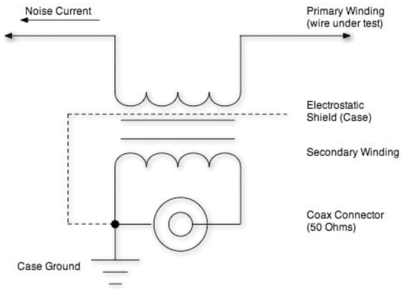


Figure 31: The basic current probe (high-frequency current transformer)

Current measurements are made by having the current carrying conductor pass through the aperture of the probe and the probe's output voltage is measured using a spectrum analyzer (or field intensity meter).

It is the magnetic flux generated by the varying RF current in the cable that are picked up by the current probe through the mutual coupling inductance. Figure 32 shows 2 DIY probes based on this principle. To do them, a couple sample Steward chokes – a round one (model 28A3851-0A2) and a square one (model 28A2024-0A2) are used. They each had 7 turns of Teflon-insulated wire wound around one-half and glued down on the inside to hold the windings. A BNC connector is used to connect the probe and the spectrum analyzer.

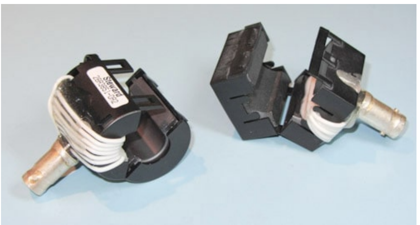


Figure 32: Examples of DIY probes based on clamp-on ferrite chokes.

A better performance in high frequencies is obtained with a DIY current probe based on a large toroid core, as shown in figure 33. Keeping the turns as far apart as possible will reduce inter-winding capacitance and yield better results at the higher frequencies. This is one of the largest drawbacks in performance of the clamp-on ferrites (as in figure 32).

Figure 33: Examples of DIY probes based on a large toroid core

The Common Mode currents measured by these probes in the conductor under test is determined from the reading of the current probe output (V) in microvolts divided by the current probe transfer impedance (Z_T). In dB, this relation is given by equation 6.

$$I(dB\mu A) = V(dB\mu V) - Z_T(dB\Omega) \tag{6}$$

The typical transfer impedance of the current probe throughout the frequency range is determined by passing a known RF current (Ic) through the primary test conductor and noting the voltage (V) developed across a 50-Ohm load. Then,

$$Z_T(dB\Omega) = V(dB\mu V) - Ic(dB\mu A) \tag{7}$$

On figure 36, the Tracking Generator (special feature of the spectrum analyser DSA815 to generate an output signal) has been set to an output voltage of 107 $db\mu V$ through a resistance of 50 Ω. This is equivalent to a 73 $dB\mu A$ current. This current pass through the DIY probe and the measured voltage is used to characterise the probe transfer impedance given by 7.

Voltage measurement of this DIY toroid probe is shown in figure 35 and probe transfer impedance in figure 36 which is computed using 7.

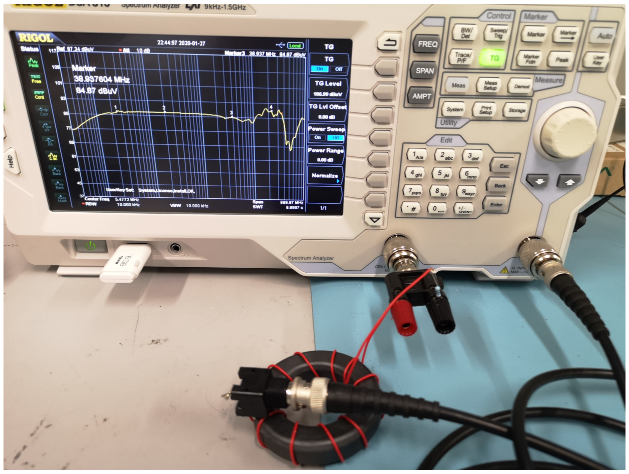
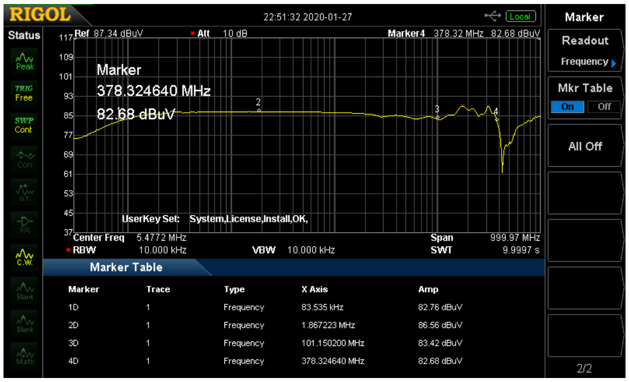


Figure 34: Setup for probe transfer impedance characterisation



22:51:32 2020-01-27

Ref 87.34 dBuV Att 10 dB Marker4 378.32 MHz 82.68 dBuV

Marker
378.324640 MHz
82.68 dBuV

UserKey Set: System,License,Install,OK,

Center Freq 5.4772 MHz Span 999.97 MHz
RBW 10.000 kHz VBW 10.000 kHz SWT 9.9997 s

Marker Table

Marker	Trace	Type	X Axis	Amp
1D	1	Frequency	83.535 kHz	82.76 dBuV
2D	1	Frequency	1.867223 MHz	86.56 dBuV
3D	1	Frequency	101.150200 MHz	83.42 dBuV
4D	1	Frequency	378.324640 MHz	82.68 dBuV

Figure 35: DIY toroid probe voltage measurement for 107 $dB\mu V$ TG output

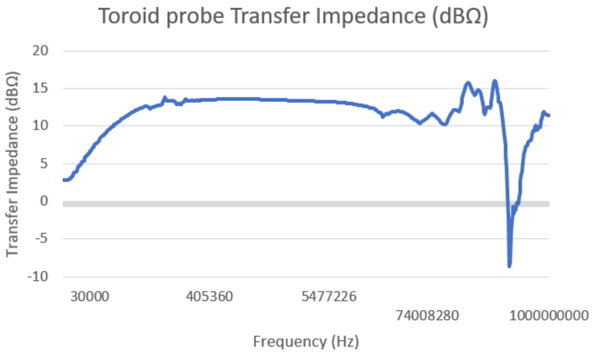


Figure 36: DIY toroid probe transfer impedance

3.2.3 TB0H01 5uH LISN

It is a device required to setup conducted noise measurements of DC-powered devices. It is designed to be used for EMC pre-testing in the frequency range of 150kHz to 110 MHz according to the CISPR-25 standard, ISO 7637-2, ISO11452-2/4/5 and with constraints DO-160/ED-14G.

Figure 37: DIY toroid probe transfer impedance

3.2.4 Oscilloscope TECKTRONIX 2024B

Oscilloscope to display the change of an electrical signal over time, with voltage and time as the Y- and X-axes, respectively, on a calibrated scale. The waveform can then be analyzed for properties such as amplitude, frequency, rise time, time interval, distortion, and others.

Figure 38: Oscilloscope TECKTRONIX 2024B

3.2.5 Differential probe: MODEL SI-9001

This differential probe is used to display in the oscilloscope differential signal on RS-485 interface.

Figure 39: Differential probe

3.3 RS-485 communication setup

The purpose of this study is to analyse robustness of communication on RS-485 interfaces which are used in the BMS for communication between BCU and BMU, and also for user communication to interact with BCU. For this, a special setup replicating communication on *G2 Leclanché BMS* has been developed with some special extra features in order to study communication performance.

3.3.1 Hardware

To replicate a communication scenario on *G2 Leclanché BMS*, the following hardware components are needed:

- 2 Battery Measurement Units (BMU).
- 2 potentiometers: added between bus B and ground of RS-485 transceiver, and also between bus A and transceiver voltage supply, in order to replicate failsafe biasing resistors.
- Termination resistor at both end of the RS-485 bus.
- RS-485 cables with different length.

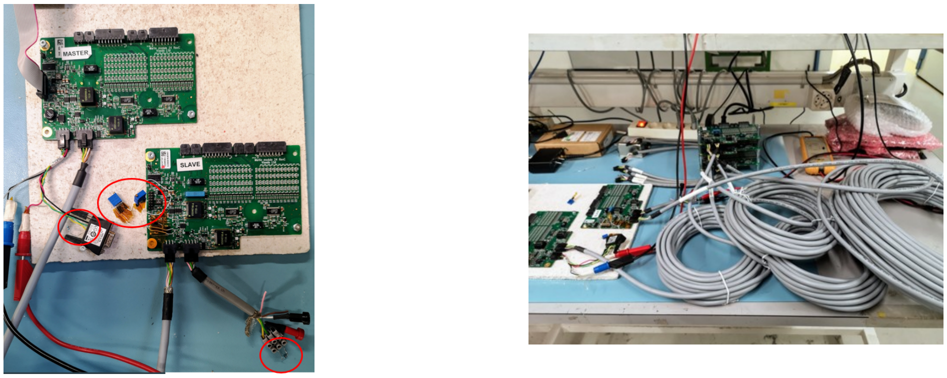


Figure 40: Hardware Testing setup

3.3.2 Software

In order to be able to evaluate communication performance and its constraints, a special code has been developed and flashed on BMUs. This software will allow to compute the bit error ratio (BER) of the communication.

Description of the testing code:

For the Battery Measurement Unit (BMU), a microcontroller from *Texas Instrument* is used for communication through an RS-485 transceiver. Specifically, this microcontroller belongs to *TMS320F2802x* and allow to communicate with 8 bits messages. These bits forming the message can be modified as desired. Baud rate of the microcontroller is limited to 925 Kbits/sec.

Figure 41 shows the UML diagram of the testing code developed. There are two testing codes: one is named as *"slave behaviour"* and the other as *"master behaviour"*. Both BMUs used for testing are flashed with these codes and can communicate each other through an RS-485 interface as described in the previous section.

The *"master BMU"* is set to send an 8 bits message to the *"slave BMU"*. This message can be predetermined or it can be a Pseudo-Random Binary Sequence (PRBS) generated by a special function as described on *section 2.7.4*. After receiving this message, the *"slave BMU"* has to echoback it to *"master BMU"*. For this, it has to save the received bit sequence through the RS-485 interface and send it back. To compute the BER of the communication the *"master BMU"* compares the original sent message and its echoback bit per bit.

The idea is to repeat this operation sending a PRBS message thousands of times to have a representative value of the bit error ratio of the communication. Then, some hardware and software configurations variables (Baud rate, cable length, etc.) will be changed in order to test constraints of the RS-485 interface. Outcomes of this experimentation will be exposed later on this thesis report.

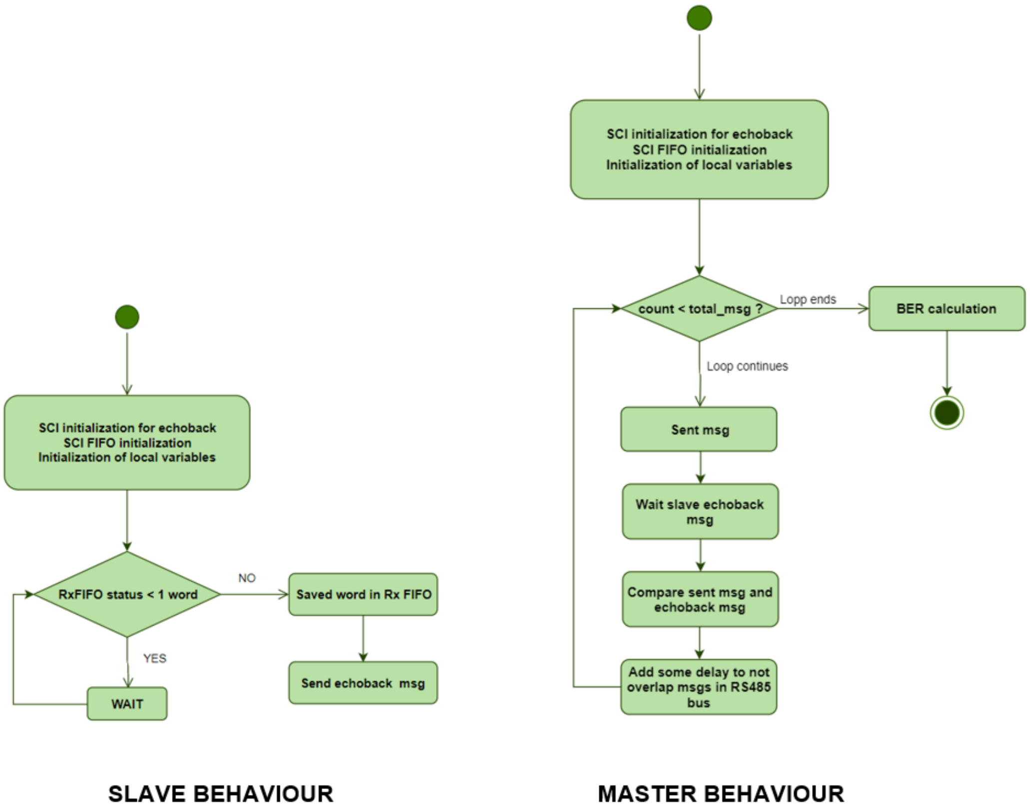


Figure 41: UML diagram, testing code

3.4 Analysis of faulty units from field applications

In this section some faulty units turned back to the company after field application are analysed. Customers have detected communication issues on them, so conclusions extracted from these samples will be take into account for the study of communication performance.

3.4.1 Faulty BMU from Škoda Auto

To understand the problem detected in this case it is necessary to introduce how a Battery Measurement Unit (BMU) establishes communication wit the Battery Control Unit (BCU).

BCU and BMU are connected forming a daisy chain as shown in figure 42. It is convenient to remember that both of them form the *G2 Leclanché BMS* which is structured on a master slave architecture. The master is the BCU which is in charge to process all the information coming from BMUs and take the corresponding actions.

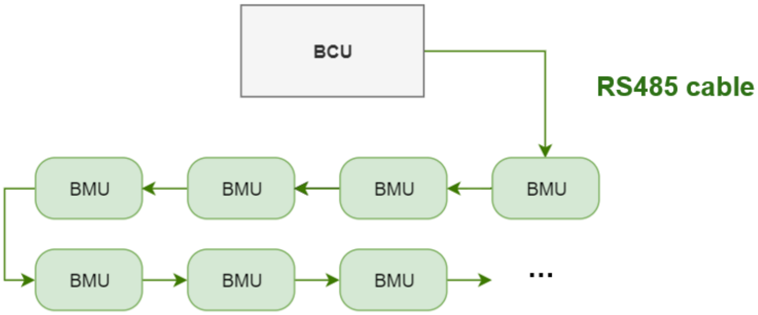


Figure 42: Daisy chain BCU and BMUs

For a proper working of the BMS, the number of BMUs in the system must be set on the BCU's setting parameters. Then, the BCU will send a boot signal to each of the BMUs in order to establish communication. Figure 43 show the input and output connectors for RS-485 interface on a BMU. The first BMU will be connected to the BCU, the second BMU is connected to the first BMU, the third to the second, ... forming a daisy chain. As it is shown on the picture the RS-485 interface is also used to power BMUs and transmit the boot signal to establish communication.

On figure 43, the boot signal to establish communication is received by the corresponding BMU through *"BOOT_IN"* and transmitted to the following BMU through *"BOOT_OUT"*. From a hardware point of view, this boot output signal is implemented with a transistor as shown in figure 44.

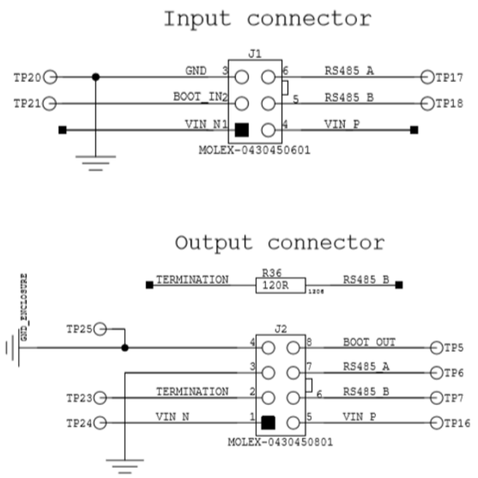
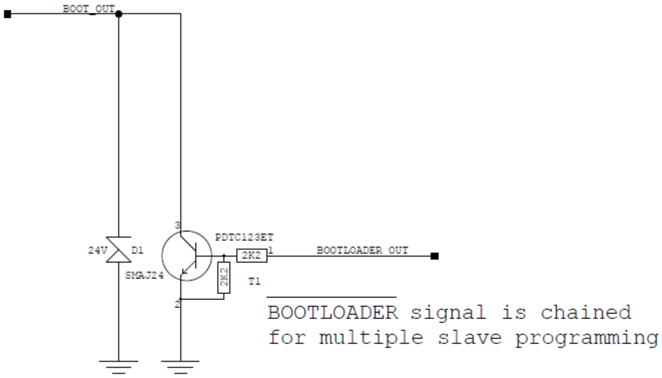


Figure 43: Input and output connector on BMU RS-485 interface



BOOTLOADER signal is chained
for multiple slave programming

Figure 44: Hardware implementation of boot output signal

The faulty BMU unit received from *Škoda Auto* was tested standalone with a BCU and was working properly. However, when this BMU is connected with a daisy chain of BMU, the BCU is not able this to establish communication properly with the string of BMUs.

After checking the PCB of the BMU received from the customer, it was detected that the boot out transistor from figure 44 which is shown on figure 45 was damaged. The source and drain were shorted, then the *BOOT_OUT* signal was permanently pulled down to ground.

Normally, *BOOT_OUT* signal is pulled up to *"VIN_P"* by default and pulled down to *"VIN_N"* for transmitting the boot signal to the following BMU. Since this signal is permanently pulled down in the faulty unit returned by *Škoda Auto*, this fact is leading to problem with the communication protocol and BCU is not able to establish communication with BMUs located after the faulty BMU.

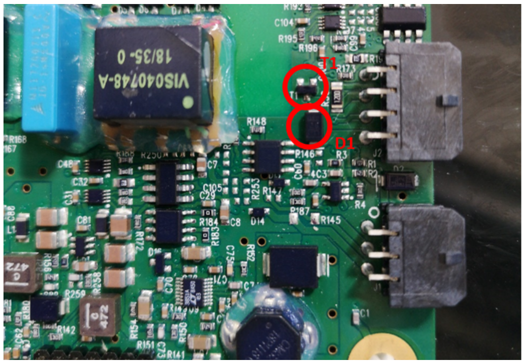


Figure 45: Boot Out transistor and TVS diode on BMU PCB

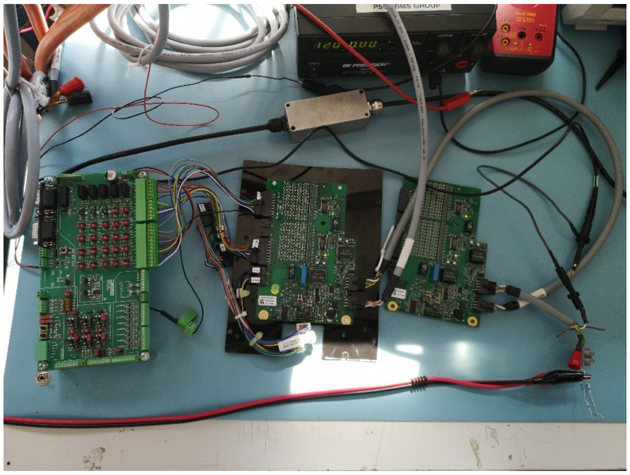


Figure 46: Setup for faulty BMU testing

3.4.2 Faulty BCU unit from Sun Mobility

Another customer that reported errors on communication for the *G2 Leclanché BMS* is *Sun Mobility* which is an Indian company that make use of the BMS for their electric bus.

In this case, the problem was detected in the Battery Control Unit (BCU) for communication with the user interface software *PowerUser* which is also implemented on RS-485 hardware layer protocol.

Figure 47 shows the schematic and hardware components composing the RS-485 interface on the BCU side. Some RS485 design rules explained in the *State of art* can be observed in the schematic.

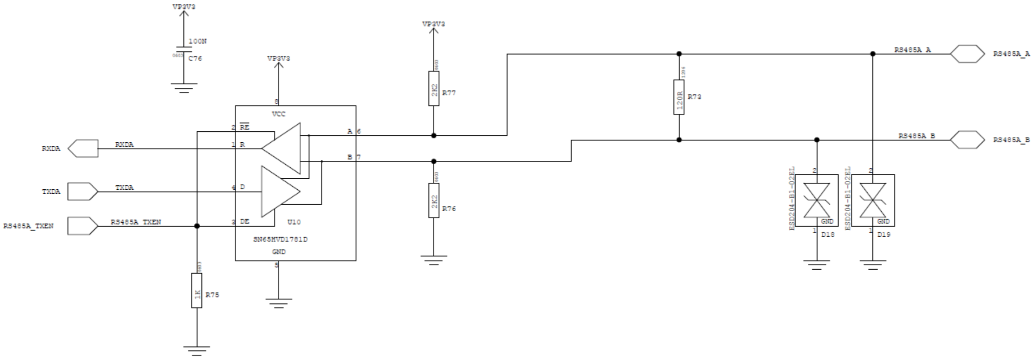


Figure 47: RS-485 schematic on BCU

After some testing and taking measurements directly in the BCU's PCB, it was detected that bus B from the RS-485 transceiver is shorted to ground. Looking at the schematic, that there are three root possible causes for this problem:

1. **SN65HVD1781D RS485 transceiver** is internally broken.
2. **R76 2.2$K\Omega$** is damaged to short.
3. **ESD204-B1-02EL TVS diode D18** is damaged and shorted.

Finally, the root cause was detected on *D18* which was shorting bus B and GND, so the communication signal could not be propagated properly and BMU RS-485 transceiver were not able to interpret the signal coming from BCU. After removing this diode from the board, which has surge voltage protection purpose, communication was working properly. Location of this diode on the BCU board is shown on figure 48.

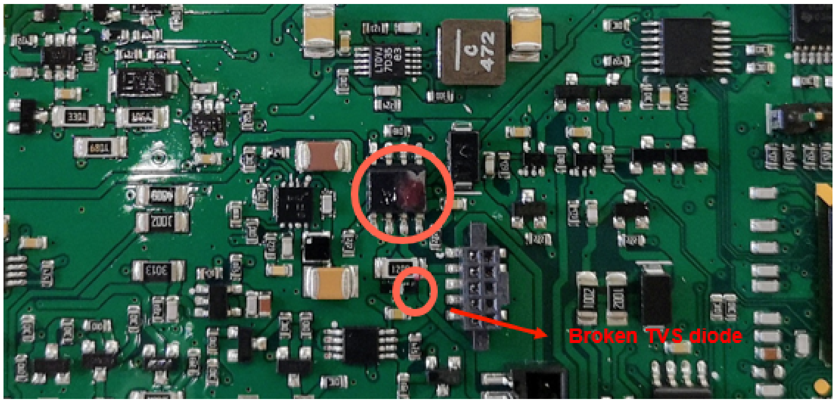


Figure 48: D18 on BCU PCB

To avoid this issue to be repeated, it was recommended to the client to use an RS-485 isolator between the HOST or computer and the BCU to reduce spike voltage created by a potential di/dt (contactor opening under current for instance) or in case that common mode voltage exceeds specifications during operation.

4 Study of the current G2 system performance

4.1 Introduction

In this section, performance of the current *G2 BMS system of Leclanché SA* is going to be evaluated in term of communication robustness.

During the time that this version of Leclanché's BMS system has been on the market, some customers have found problems with the communication either on PowerUser or BMU RS-485 interface. As background for this study, some faulty units returned by the clients have been recovered to be diagnosed.

On the other hand, some applications of the company require high energy storage capacity. To achieve this, it is necessary to connect many battery modules in series. All these modules have to be managed by the Battery Control Unit (BCU) that receives the information of the Battery Measurement Unit (BMU) which is located in each module. This architecture, which was explained with more details in the state of art chapter, leads to considerable cable lengths to allow the communication of all BMUs with the BCU. This chapter presents a special test setup and experiment that have been done in order to check the robustness of the communication depending on this factor, the cable length. Also other design variables on the communication interface as Baud rate, termination, etc. will be changed to check their influence.

Moreover, depending on the application, the company is actually using different configurations of shielding and grounding on RS-485 cables. *Subsection 4.4* presents a study of the electromagnetic compatibility depending on the shielding and grounding configuration of the cable used for RS-485 communication. The objective is to study noise immunity and radiated noise depending on this factor and select the optimal configuration with the performance in Leclanché BMS system.

4.2 Survey of current RS-485 interface implementation

Figures 49 and 50 show the implementation of the RS-485 communication interface on BCU and BMU in *G2 Leclanché BMS* respectively. It makes use of the following components:

- **SN65HVD1781D:** this is the RS-485 transceiver which is in charge to compute and interpret the received signal on the differential bus. And also to create the differential signal corresponding to send messages.
- **R76 and R76:** these are failsafe biasing resistors. The function of this design feature was explained in section *2.5.8* and its effect will be examined in this section.
- **R73:** it is the termination resistor located on the BCU side. Another one must be connected in the last BMU of the BMS system to avoid reflection on the RS-485 bus lines. Theoretical background of this design feature is explained in section *2.5.6*.
- **D18 and D19:** ESD204-B1-02EL. These are ESD/transient protection diodes according to: IEC61000-4-2 (ESD): ±20 kV (air/contact discharge) and IEC61000-4-4 (EFT): 40A (5/50 ns).
- **D13 and D14:** CDSOD323-T36SC. These are ESD/transient protection diodes according to IEC 61000-4-2 (ESD), IEC 61000-4-4 (EFT) and IEC 61000-4-5 (Surge) requirements.

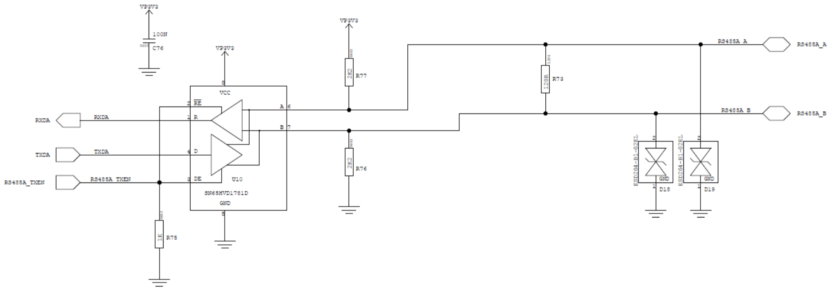


Figure 49: BCU RS-485 interface schematic

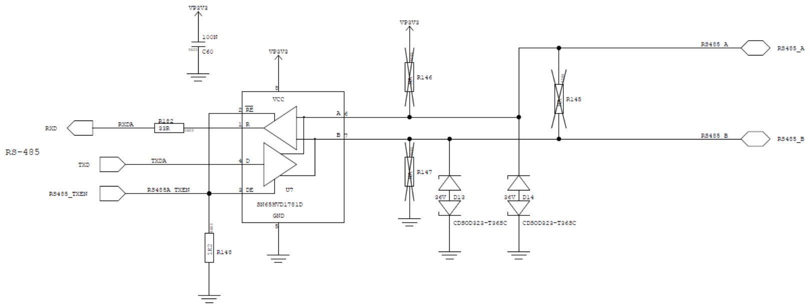


Figure 50: BMU RS-485 interface schematic

As it can be seen, both RS-485 interface are quite similar and TVS diode protection counts with the same features for BCU and BMU. Hence, to simplify the testing setup, two BMUs are used to replicate communication on *G2 Leclanché BMS* as it was explained on *section 3.3.1*.

4.3 Experimentation to test RS-485 communication constraints

In this section the testing setup presented previously in *section 3*, is used to test and evaluate some constraints regarding communication in *G2 Leclanché BMS*. Limiting factors related to RS-485 interface carried on this study are:

- Cable length
- Termination
- Baud rate
- Number of nodes

4.3.1 Cable length vs Termination vs Baud Rate

For this test, setup shown on figures below is used. Some different length cable are available in order to communicate between both BMUs that will interact each other with the software explained in *section 3.3.2*. Maximum available length is 80m. This is enough since real application of the company do not overpass 50m cable length. Also, a programmer is used in order to change the baud rate of the microcontroller sending the messages through the RS-485 interface. And finally a 120Ω resistor is connected and disconnected to the end of the differential line to see effect of reflection on the bit error ratio.

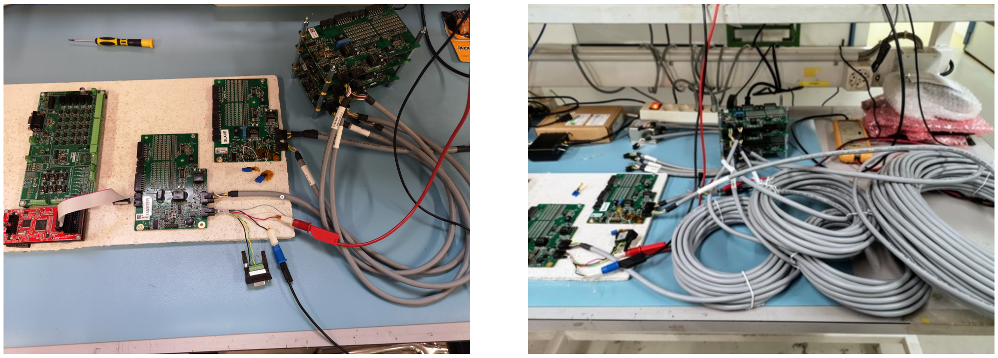
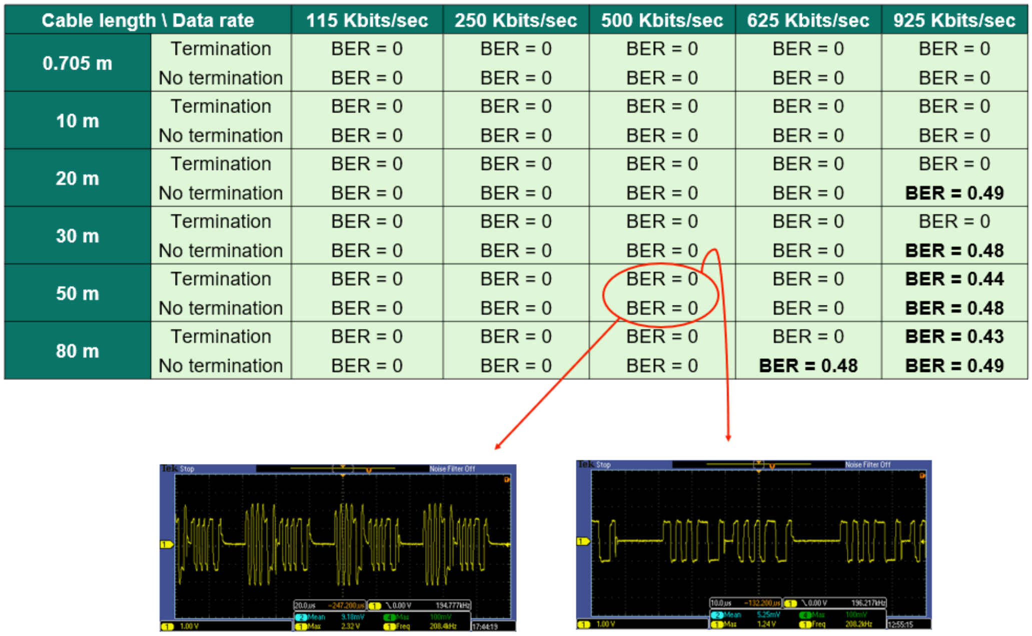


Figure 51: Testing setup



Cable length \ Data rate		115 Kbits/sec	250 Kbits/sec	500 Kbits/sec	625 Kbits/sec	925 Kbits/sec
0.705 m	Termination	BER = 0	BER = 0	BER = 0	BER = 0	BER = 0
	No termination	BER = 0	BER = 0	BER = 0	BER = 0	BER = 0
10 m	Termination	BER = 0	BER = 0	BER = 0	BER = 0	BER = 0
	No termination	BER = 0	BER = 0	BER = 0	BER = 0	BER = 0
20 m	Termination	BER = 0	BER = 0	BER = 0	BER = 0	BER = 0
	No termination	BER = 0	BER = 0	BER = 0	BER = 0	**BER = 0.49**
30 m	Termination	BER = 0	BER = 0	BER = 0	BER = 0	BER = 0
	No termination	BER = 0	BER = 0	BER = 0	BER = 0	**BER = 0.48**
50 m	Termination	BER = 0	BER = 0	BER = 0	BER = 0	**BER = 0.44**
	No termination	BER = 0	BER = 0	BER = 0	BER = 0	**BER = 0.48**
80 m	Termination	BER = 0	BER = 0	BER = 0	BER = 0	**BER = 0.43**
	No termination	BER = 0	BER = 0	BER = 0	**BER = 0.48**	**BER = 0.49**

Figure 52: Test results

Results obtained for this test are shown on figure 52. For a slow baud rates, cable length and RS-485 bus termination is not a limiting factor, but for higher baud rates it can be seen that a proper termination of the bus can be a critical factor. This termination will avoid reflections in the cable that are happening when the signal wave length propagating in the cable is closer to the cable length.

When reflections occurred, the communication signal is distorted and reflection are superposed to the original signal. This lead to BER different than 0. However, even when the communication has not errors, the termination has a positive impact as it is shown on oscilloscope screenshots from figure 52.

4.3.2 Number of nodes

The maximum number of nodes for RS-485 bus is determined by the *Maximum common-mode load* stated in the *Standard RS-485 specification* which is **375Ω**.

Each transceiver connected to the RS-485 bus represents a load for the differential line that is represented by R_{INEQ} on figure 53. The value of this equivalent resistance associated to all transceivers connected to the bus is given by 1 from the *section 2.5.7*.

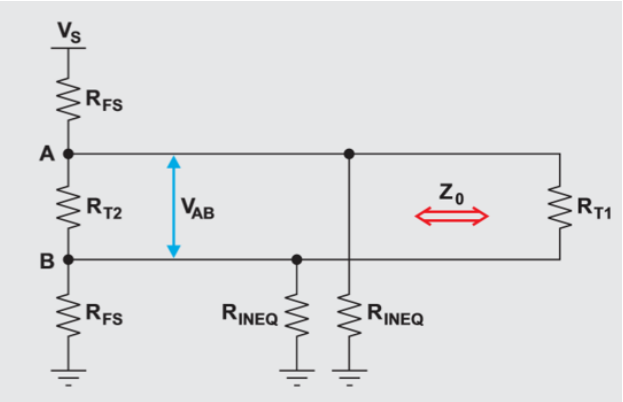


Figure 53: Loads connected to RS-485 differential line

SN65HVD1781D is the model of RS-485 transceiver used in *G2 Leclanché BMS*. Its unit load is 1/10. So, attending to table 2 the maximum number of nodes that could be connected on a RS-485 bus is 320.

However, the failsafe biasing resistors (R_{FS}) implemented in *G2 Leclanché BMS* also affect to the maximum common mode load, as they are connected on parallel with R_{INEQ}. Then:

$$R_{FS} \parallel R_{INEQ} \geq 375\Omega \tag{8}$$

$$R_{INEQ} = (n_{transceivers} \cdot \frac{1}{\frac{1}{10}^{-1} \cdot 12000})^{-1}\Omega \tag{9}$$

To fulfil equations 8 and 9, the maximum number of transceiver connect to the RS-485 bus must be:

$$n_{transceivers} \leq 265$$

So, the failsafe biasing resistors are limiting *G2 Leclanché BMS* for a maximum of 265 BMUs connected to it.

4.4 Electromagnetic compatibility testing

In this section, possible electromagnetic interference signals caused by the communication interface of the Battery Management System are going to be studied. Making use of the EMC equipment presented in *section 3*, interference radiated by different cable configurations used for communication between BCU and BMUs will be measured.

Purpose of this part of the study is to check which cable shielding configuration is performing the best, since actually the company is using different cables depending on the application. Later on this section, based on theory explained in *section 2.6.3* which exposes the relation between EMI and cable shielding configuration, the optimal solution in terms of radiated emission for the communication cable is selected.

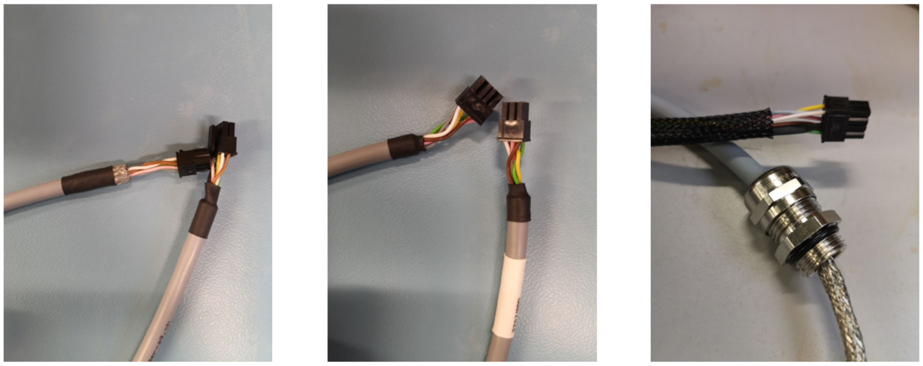


Figure 54: Cables used for RS-485 communication interface

4.4.1 No shielded cable

This is one of the possible configuration for the cable connecting RS-485 interfaces for the communication between BCU and BMUs. It corresponds to the photo in the middle on figure 54.

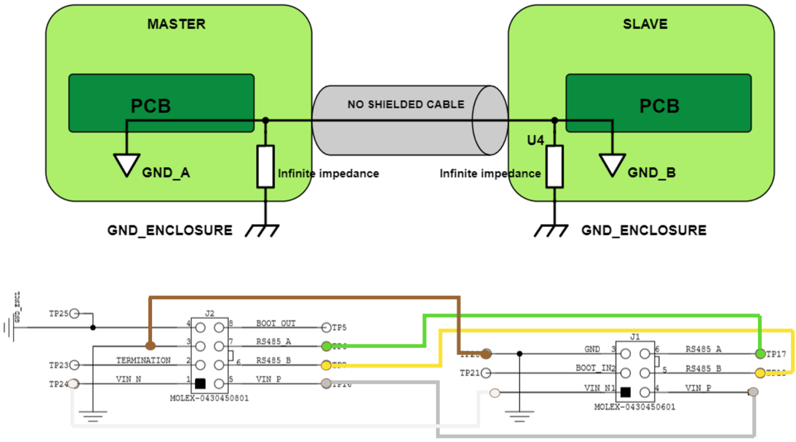


Figure 55: No shielded cable

It is not shielded. Ground connections between PCBs and enclosures are linked as shown schematically on figure 55 when this cable is used to connect two BMUs. In this schematic "*GND_ENCLOSURE*" represents the module chasis where the BMU'PCB is placed in, which can be used as ground reference.

4.4.2 Confectronix cable

This cable is shielded and it corresponds to the left photo on figure 54. Its grounding configuration is schematically represented on figure 30. Shielding is linked to the module enclosure ground reference on one side.

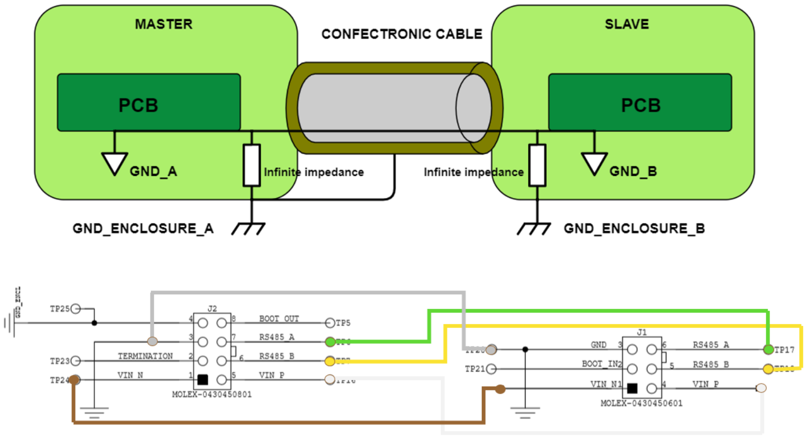
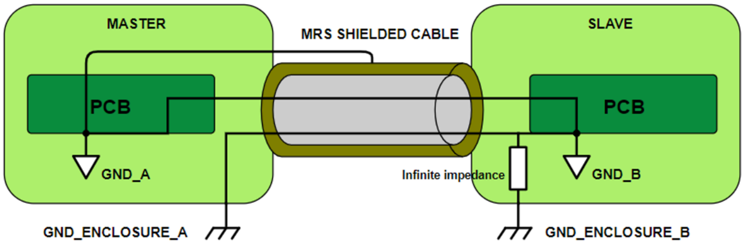
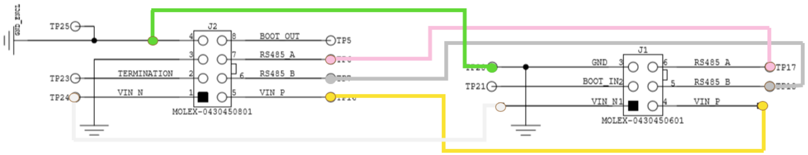


Figure 56: Confectronix cable

4.4.3 MRS cable

This cable configuration corresponds to the right photo from figure 54. It is also shielded but this time the shielding of the cable is linked to a ground which is common for both extremes of the cable.





4.4.4 Testing setup

In order to test which of the previous cables has a better EMC performance, the setup shown on figure 57 has been prepared. Two aluminium box are replicating the module enclosure where the BMU is placed.

The spectrum analyser *Rigol DSA815* is used to inject noise to the cable through the tracking generator which is able to output a 107 dBuV signal. With another current probe the electromagnetic emissions radiated by the cable (while it is communicating and being perturbed by an electromagnetic interference) are measured. These measures will be smaller for the cable with a better shielding performance since the cable will be less susceptible to emission coming from the tracking generator and will also radiate a less powerful electromagnetic interference.

Following this procedure, electromagnetic emissions measured for each cable configuration are shown in figure 58. As expected, the MRS cable has a better shielding performance since the shield is grounded at both ends of the cable and both grounds are equipotential.

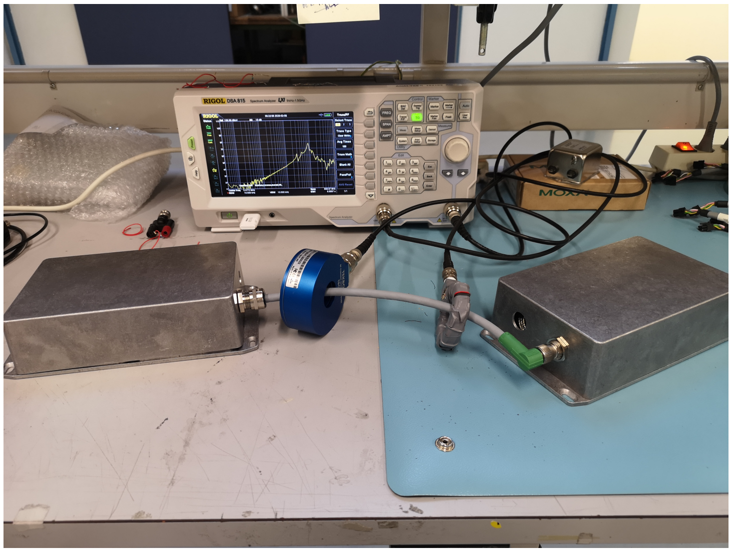


Figure 57: EMC testing setup

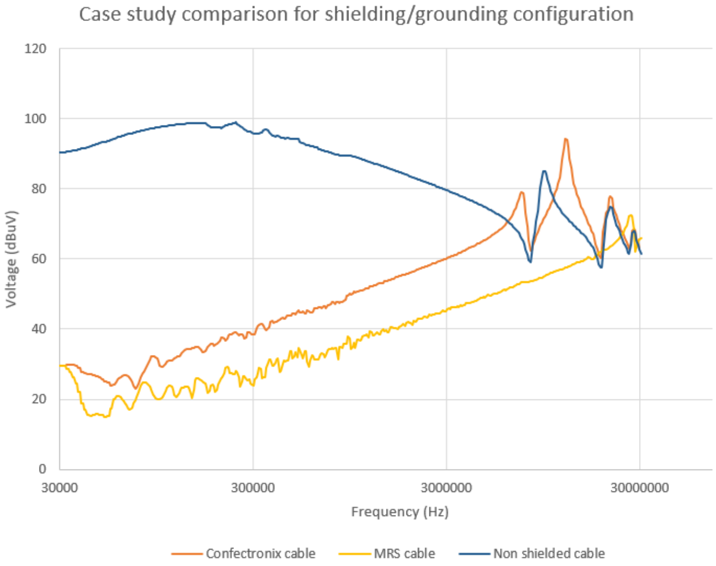


Figure 58: EMC test: electromagnetic emission measurement

5 Improvement proposals

In this section some changes on the communication interface design are proposed in order to solve issues and improve constraints detected during this analysis. Another problem for the company was to find the root cause for communication issue on large systems. So, a small description of how to detect the problem root cause is given as tool for diagnostic on field.

5.1 Diagnostic tools for communication issues on field

Figure 59 show a real Marine Rack System (MRS) that makes use of *G2 Leclanché BMS* that was being prepared in the lab of the company to be sent to a client. During testing a problem on communication was detected. The MRS is composed of 52 battery modules which their corresponding 52 Battery Measurements Units. However, the Battery Control Unit was not able to establish communication with all of them.

Figure 59: Marine Rack System (MRS)

The best way to find the root cause is to directly check the differential signal on the RS-485 bus which can be read with a differential probe and an oscilloscope. When the communication signal is working properly, it looks like in left side of figure 61.

However, in this case with 52 battery modules connected, the differential signal on RS-485 bus was distorted as shown on the right photo of figure 61. This was caused by a faulty BMU placed in one of the 52 modules.

To locate the BMU perturbing the signal, the best strategy is to disconnect the communication cable for the second half of the modules and then check the communication signal again. If this time the signal looks well, it is known that the problem root cause is one of the last 26 BMUs. Once this faulty unit is located, the BMU in the module must be changed.

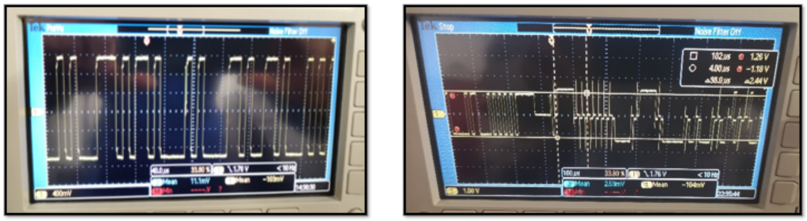


Figure 60: RS-485 differential signal

5.2 Design improvements

5.2.1 Changes on the communication interface components

- **Transient Voltage Suppression diode**

  As it was reviewed previously, the RS-485 differential bus on *G2 Leclanché BMS* is protected against electrostatic discharge event with some TVS diodes.

  Based on faulty units of the BMS returned by clients, it has been detected that these diodes protecting bus A and B of the RS-485 transceiver on BMU and BCU, are frequently damaged to short-circuit. An example was explained in *section 3.4.2*.

  If this happen in any bus, it will lead to ground the differential line and the communication signal will be offset as in figure **??**. In this condition, RS-485 transceivers connected to the line will not interpret correctly every bit send on the line and the communication can not be establish.

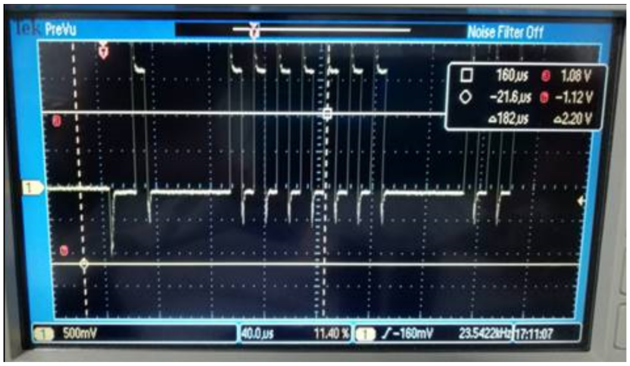


Figure 61: Offset RS-485 differential signal

Normally, these TVS diodes get broken when they are frequently under over stress conditions. When avalanche breakdown occurs, the silicon p-n junction device conducts a large amount of current (I_{PP}) to ground in front of the protected load for a short duration transient that is typically 1 ms or less. During this short event, the TVS device clamps the voltage to a safe level (V_C). This also results in significant power (P_{PP}) and heating at the p-n junction. This can repeat itself for random recurring transient events indefinitely within the rating of the TVS, but only if there is sufficient time for the device to cool before the next event occurs. Rapid repetitive surges that would cause cumulative heating effects are not part of the normal rating of a TVS.

When individual excessive surges occur beyond the rating of the TVS, these devices can fail just like any other semiconductor component when exceeding their ratings. In the vast majority of cases, a TVS will fail in a shorted or severely degraded mode when overstressed. Another possibility is that TVS break in an electrical open. This is neither a desirable failure mode for a TVS in its shunt protective position in the circuit, because that would expose the remaining sensitive load to subsequent transient threats. An electrical open of the TVS location can also make it difficult to verify whether anything is wrong until a subsequent surge occurs that may damage the remaining circuit requiring protection.

To solve this issue, it is proposed for future design on *Leclanché BMS* to add a redundant ESD protection circuit on the communication line. For this, TVSs may be applied in such a manner where any single component failure will not significantly affect the application. For example, two TVS devices may be placed in series where twice the clamping voltage (V_C) of any one TVS device is still adequate to protect the sensitive load behind the TVS and the working standoff voltage (V_{WM}) of one device. If any one TVS device in series becomes electrically shorted or severely degraded, the remaining device in series still provides protection.

In those cases where an unusual electrical open of any one TVS device may be of concern, two such legs of TVSs are provided in parallel, representing a total of four TVS devices. These redundant protection configuration are shown on figure 62.

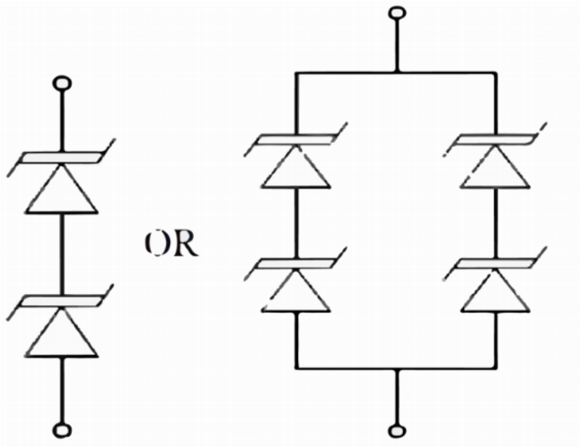


Figure 62: Redundant TVS Circuit Design

- **RS-485 transceiver update**

  In *section 2.5.7*, the failsafe design feature on RS-485 communication interface was explained and its implementation on *G2 Leclanché BMS* was reviewed in *section 4.2*.

  Later on *section 4.3.2* it was seen that this feature has an associated constraint regarding the maximum number of nodes (transceivers) that can be connected to the RS-485 differential bus.

The failsafe biasing resistors were implemented on the BMS communication interface in order to do not have random signal on the differential bus in case of idle bus, shorted bus or open bus conditions.

In those cases the differential signal on the bus is a 0V signal which is the uncertainty range of the RS-485 standard (-200 mV, 200 mV). Then, it is necessary to implement a failsafe biasing circuit to push the differential signal to a know state, for example V_{CC}.

However, there are some RS-485 transceivers that accomplish failsafe by offsetting the receiver thresholds such that the "input indeterminate" range does not include zero volts differential.

Figure 63 shows voltage threshold for SN65HVD178x familiy of RS-485 transceivers. These voltage thresholds sill comply with the RS-422 and RS-485 standards, the receiver output output a High when the differential input V_{ID} is more positive than +200 mV, and output a Low when the differential input V_{ID} is more negative than –200 mV.

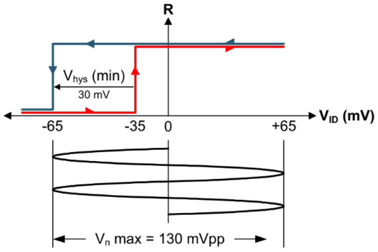


Figure 63: SN65HVD178x thresholds

Then, failsafe biasing resistors are not needed to be connected on the RS-485 differential line and **maximum number of nodes connected to the BMS can be increased from 265 to 320 transceivers**.

5.3 RS-485 vs CAN protocol

RS-485 and controller area network (CAN) interface protocols were implemented on the mid-1980s, when they were introduced as communication standards. RS-485 was an evolutionary step from previous transceiver (physical layer) standards like RS-423, RS-422, and RS-232. RS-485 enabled systems to have multiple master nodes in a single system. Around the same time as these commonly used interfaces were being used in applications such as computer keyboards and mice, printers, and industrial automation equipment, the CANbus interface was being developed as an automotive communication platform (by Robert Bosch GmbH) to reduce cost in automobile manufacturing. It was considered an alternative to the conventional, large multi-wire looms needed in automobiles, simplifying cabling and taking advantage of multi-node buses.

The two standards, the ISO-11898-2 (CAN) and TIA/EIA-485 (RS-485) define the electrical components of the transceivers and are represented in figure 64.

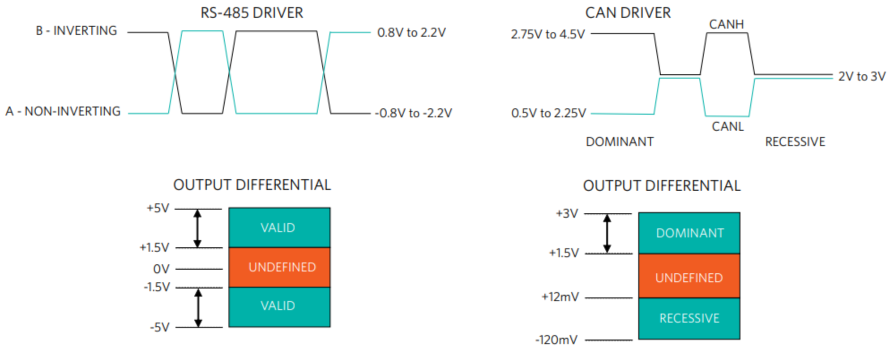


Figure 64: CAN vs RS-485

Despite both standard count with transceivers with similar electrical features (protection fault, maximum common-mode range, etc.) CAN shows an ever-increasing adoption on current markets, even replacing the RS-485 in traditional industrial applications.

One of the major reasons for industrial applications to design in CAN versus RS-485 transceivers is how messages are handled on the bus. In a RS-485 system with many nodes communicating to the microprocessor, there may be instances where there are several messages sent out from multiple nodes onto a bus simultaneously that may result in a collision of messages, otherwise known as contention. When this happens, the bus state could possibly be invalid or indeterminate, causing data errors. Furthermore, contention could damage or degrade the signal performance when multiple RS-485 transceivers on the bus are in one state and one single transceiver is in the opposite state. In such a condition, the lone RS-485 would cause significant current draw that would likely cause thermal shutdown of the IC or permanent damage to the system This is where CANbus has a big advantage over the RS-485 protocol. With CANbus, there is a way to resolve multiple messages on the line by way of ranking each message. Prior to bringing the system up, different faults are assigned different priorities by the system engineer.

Due to CAN features such as arbitration, error-message checking, improved bandwidth, and a larger data field, it is easy to understand the appeal of CANbus in the industrial market. CAN is suitable for applications that require robust communications and reliability in harsh environments. CAN systems are able to prioritize the importance of frame messages and treat critical ones appropriately. Many different systems can be exposed to either electrically noisy sources or a local service personnel that may accidentally short to local supply rails. CAN transceivers are known for their robust serial interface, with class-leading ESD performance and high level of fault protection.

This communication robustness analysis was done for the communication between BCU and BMUs of Leclanché Battery Management System, which is implemented on the hardware layer protocol RS-485 in the current *G2 Lecanché BMS*, but CAN will be consider to be used also for communication between BCU and BMU in the next BMS generation.

6 Conclusions

A robustness analysis for communication on *G2 Leclanché BMS* has been performed in this thesis. The RS-485 communication interface design has been reviewed and tested to find its constraints.

Regarding the study done on faulty BMS units returned by customers after field application, it was concluded that the actual electrostatic discharge (ESD) protection on the RS-485 differential bus was a root cause of problems for communication in *G2 Leclanché BMS*. The current implementation with a single TVS diode on each line is not robust enough to customers stress environment. A change in the hardware design has been proposed as solution in *section 5.2.1*, this redundant TVS circuit is more robust against ESD events.

By another hand, the company was wondering for some configuration variables as baud rate for BCU-BMU communication, cable shielding or maximum number of nodes connected or to the BMS. These previously unknown variables where solved in *section 4*.

As the BMU default design does not count with a 120 Ohms termination resistor, the company was wondering in which of their system they should add this termination to match the RS-485 differential as shown in figure 65. From *section 4*, it can be concluded that this termination will only be needed in large systems as the MRS where the cable length is longer and the Baud rate must be higher to synchronise many BMUs.

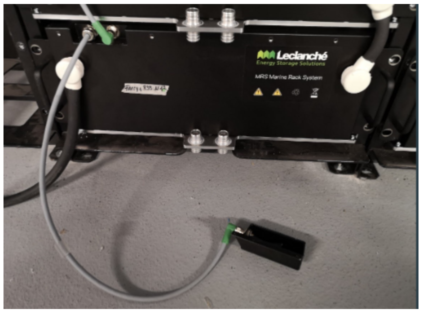


Figure 65: 120Ω termination

Concerning electromagnetic compatibility, it was proved that MRS cable configuration has a better EMC performance and must be used in noisy and harsh environments. Also in larger systems as the Marine Rack System to avoid interference emissions.

As final conclusions it can be said that, after this robustness analysis for communication on *G2 Leclanché BMS*, constraints related to the RS-485 communication interface are not limiting the company application since they cover minimum requirement for their systems in therms of cable length, maximum number of nodes and baud rate. However some changed must be done on the hardware design in order to have a bigger robustness to ESD events. Also, migrate to a CAN interface should be consider due to its robustness in harsh electrical environments, fault protection capabilities, and unique message handling.

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