Considerations for a power line communication system for traction batteries

A. Pake Talei¹, W. A. Pribyl, G. Hofer

Electric vehicles (EVs) are without a doubt one of the hottest topics of our time because of their advantages over combustion engine vehicles. This has persuaded many developers to try improving EVs so they will be more reliable and cheaper and as a result suitable for a broader range of consumers.

In this paper we dive into the proper way of measuring and understanding the impedance of one prismatic cell from 100 kHz up to 1 GHz. Some common measurement mistakes and important points to notice are also explained. The effect of a power bar is shown as well. In order to make sure of the accuracy and the consistency of the measurements, they are compared with finite element simulations as well as with mathematical calculations.

Investigations of conducted emissions are also of key importance since it has a direct influence on selecting a suitable frequency range. Accordingly, a thorough lab measurement is conducted to see the distortion harmonics and their influence on the carrier frequency. This knowledge can then be used to implement the power line communication (PLC) method.

The PLC technique helps us to reduce the wire harness of a battery pack by using the existing high-voltage lines of the vehicle as the main transmission channel. This leads to cheaper battery packs by reducing the amount of used material for the wire harness and production time as well as assembly complexity.

Keywords: power line communication; battery management system; electric vehicle; impedance measurement; conducted emissions; finite element method

Betrachtungen für ein Powerline-Kommunikationssystem für Antriebsbatterien.

Elektrofahrzeuge (EV) sind zweifellos eines der hochaktuellsten Themen unserer Zeit aufgrund ihrer Vorteile gegenüber Fahrzeugen mit Verbrennungsmotoren. Dies hat viele Entwickler dazu bewogen zu versuchen, EVs so zu verbessern, dass sie zuverlässiger und billiger und damit für ein breiteres Spektrum von Verbrauchern geeignet sind.

In der folgenden Arbeit beschäftigen wir uns mit der Behandlung der richtigen Art und Weise, die Impedanz einer prismatischen Zelle von 100 kHz bis 1 GHz zu messen und zu verstehen. Einige häufige Messfehler und wichtige Punkte, die zu beachten sind, werden ebenfalls erläutert. Die Effekte der Zellenverbindung im Leistungskreis wird ebenfalls gezeigt. Um die Genauigkeit und die Beständigkeit der Messungen zu gewährleisten, werden sie mithilfe von Finite-Elemente-Simulationen sowie mathematischen Berechnungen verglichen.

Von zentraler Bedeutung sind auch Untersuchungen der leitungsgebundenen Emissionen, da diese einen direkten Einfluss auf die Auswahl eines geeigneten Frequenzbereichs haben. Folglich wird eine gründliche Labormessung durchgeführt, um die harmonischen Verzerrungen und ihren Einfluss auf die Trägerfrequenz zu erkennen. Dieses Wissen kann dann verwendet werden, um die Methode der Powerline Communication (PLC) zu implementieren.

Die PLC-Technik hilft uns, den Kabelbaum eines Akkusatzes zu reduzieren, indem die vorhandenen Hochspannungsleitungen des Fahrzeugs als Hauptübertragungskanal genutzt werden. Dies führt zu einem billigeren Akkusatz, indem die Menge des verwendeten Materials, die Produktionszeit sowie die Komplexität des Zusammenbaus reduziert werden.

Schlüsselwörter: Powerline Communication; Batteriemanagementsystem; Elektrofahrzeuge; Impedanz-Messung; leitergebundene Emissionen; Finite-Elemente-Methode

Received July 14, 2020, accepted December 9, 2020, published online January 19, 2021
© The Author(s) 2020

1. Introduction

Compared to combustion engine cars, electric cars produce less noise and pollution. These factors are what attracts so many new and old established companies to invest in electric cars.

The traction battery pack is the most important part of an EV and it currently consists of a number of li-ion battery cells connected to each other in parallel and series with the aim of sourcing high DC voltage and current to the electric motor driver which pulls the car. For safety purposes, li-ion cells need to be constantly monitored for important factors like state of charge (SOC), state of health

(SOH) and temperature. In order to do this, the state of the art EVs, exploit a wire harness, connecting the main battery management

This paper is an extended and enhanced version of the conference paper [11].

Pake Talei, Arash, Infineon Technologies, Graz, Austria; and Institute of Electronics, Graz University of Technology, Inffeldgasse 18, 8010 Graz, Austria
(E-mail: paketalei@student.tugraz.at); **Pribyl, Wolfgang A.**, Institute of Electronics, Graz University of Technology, Graz, Austria; **Hofer, Günter**, Infineon Technologies, Graz, Austria

Fig. 1. Top: a simplified diagram of BMS that uses wire harness; Bottom: the same system using PLC as communication method (Color figure online)

system (BMS) to each cell (or each group of cells) that are normally equipped with their own local circuit called CSC (cell supervision circuit). A BMS is responsible for getting information from each battery cell and making proper decisions. The transaction of data and command between BMS and CSC is being done through a dedicated data wire harness.

2. PLC and its advantages

PLC technique will help us to get rid of this wire harness. This is done by sending and receiving a carrier signal over the existing high voltage (HV) cable. Using this method, we are able to transmit and receive information without using any separate wire which reduces the cost of wire, the special connectors and production time. Another important achievement of using PLC is that the battery pack can be made in any geometrical form the producer wishes, since no one needs to worry any longer about the quantity and length of the wire harness.

Figure 1 displays a very simplified battery-inverter-motor system which is used in all types of EVs. The thick blue and red lines represent the high voltage (HV) cables. Here we can see the difference between the state of the art BMS that uses special data wires (top) and the PLC implementation (bottom)

3. The PLC channel

Before implementing a PLC system, it is important to understand the behavior of the PLC channel in different frequencies. A normal

Fig. 2. Sketch of a prismatic cell

battery pack is comprised of battery cells, power bars and the fitting materials that keep battery cells in place. These fittings are not electrically connected to the cells.

This means it is possible to realize the behavior of PLC channel by understanding the power bars and the battery cells.

A power bar can be easily simulated using a finite element modeling tool or calculated using existing formula since it does not have a complicated geometry.

The impedance of a battery cell, on the other hand, needs to be measured. The reason for this is that these battery cells have a complicated geometry and the production companies do not reveal their product secrets, for example, the exact number of layers, the thickness or the exact type of materials used. That is why measuring the impedance of a battery cell will be faster and more accurate than simulating it. This can be done with different equipment which we will talk about.

4. Choosing the right measurement equipment

The device under test (DUT) is a prismatic cell and the target is to measure its impedance from the two poles. Figure 2 shows a general prismatic cell.

There are two types of known equipment that are suitable for this purpose. [1] and [2] have used an impedance analyzer while [3], [4] and [5] used a vector network analyzer (VNA).

An impedance analyzer does not cover the frequency range that we are interested in. We want to measure a frequency range between 100 KHz and 1 GHz and the existing impedance analyzers do not cover this frequency range [6].

E5061B VNA from Agilent is used in order to measure the impedance of the cell, which brings up the first challenge:

5. How to connect the DUT to the VNA

This VNA has 2 RF ports and is capable of measuring all four types of S parameter (S11, S12, S21 and S22). Since this VNA has 50 Ω system impedance, a coaxial cable with 50 Ω characteristic impedance must be used between the DUT and the VNA which can be easily calibrated using a normal open-short-load-through calibration kit.

A rule of thumb states that after calibration it is possible to ignore some extra cable length if the length is shorter than one tenth of the wavelength (λ) on which the device under test (DUT) is running [2]. This point is an important point, which unfortunately, is not used properly. To explain it in practical terms, we do some measurements.

In Fig. 3 we can see one 15 cm and one 100 cm coaxial cables, which are used to measure two different DUTs.

Figure 4 displays two curves showing the relationship between one-tenth of the wavelength versus the frequency and the frequency in which the wavelength is equal to 85 cm (in this case around 35 MHz). The reason for 85 cm is that the VNA is calibrated

Fig. 3. Measurement cables

Fig. 4. $\frac{\lambda}{10}$ and cable length relation Fig. 5. Measuring 50 Ω DUT with two different cable lengths (Color figure online)

with 15 cm cable, meaning that 15 cm of the 100 cm cable is de-embedded and 85 cm is not. The DUT is then measured with both 15 cm cable (which is equal to zero after calibration) and then a 100 cm (which is equal to 85 cm).

This means that if we use a 100 cm cable, all the measured values lower than 35 MHz are acceptable however the values which are read after 35 MHz are not reliable values even if they are close to the real value. We can see this in Fig. 5.

The DUT is a 50 Ω calibration resistor and we can see that the blue curve is reading exactly that value (excluding the measurement noise) however, the red curve exhibits a swinging behavior. In this

Fig. 6. Measuring 0 Ω DUT with two different cable lengths (Color figure online)

case we can accept the values of the red graph when it is lower than 35 MHz with 2% error ($\frac{51-50}{50} = 2\%$). For values higher than 35 MHz, however, the swing goes much higher and in some cases the impedance is very close to 45 Ω which is not acceptable.

However, the $\frac{\lambda}{10}$ rule of thumb is not always as reliable as the results shown in Fig. 5. To demonstrate this, a second DUT is measured. This time a 0 Ω (short of a calibration kit) is measured with both cables. The result is plotted in Fig. 6.

The blue curve is the measurement with 15 cm cable and it is mostly showing a very low resistance value (which is reasonable) however this is not the case for the 100 cm cable. In this case we see a huge difference between the two results (as opposed to the first case with 50 Ω).

Here at 35 MHz the red curve is 320 times higher than the blue curve (64 Ω compared to 0.19 Ω) and the $\frac{\lambda}{10}$ rule of thumb does not apply here. In fact, in this case $\frac{\lambda}{1000}$ is more plausible. In other words, we should not have any extra cable length which is not calibrated when we are measuring a very low impedance DUT and this is exactly what we are going to measure on a prismatic cell (prismatic cells have small impedance).

6. Choosing the right S parameter

A two port VNA can measure four types of S parameters (reflection and transmission coefficients).

The S parameter then needs to be converted to Z11 parameter (impedance) in order to be useful. [7] Contains the equations which are needed to convert the reflection and transmission coefficients to impedance. Equation 1 maps S11 to Z (S22 is ignored since in this case S22 and S11 yield the same result). Mapping S21 to Z, divides into two equations (Eq. (1) and Eq. (3)).

The reason for this is the different methods of attaching a DUT to the VNA which are termed series through and shunt through. Figure 7 display the schematics and the connection of the DUT to VNA.

$$Z_{DUT} = 50 * \frac{1 + S11}{1 - S11} \quad \text{Eq. (1) - S11 to Z} \quad (1)$$

$$Z_{DUT} = 50 * 2 * \frac{1 - S21}{S21} \quad \text{Eq. (2) - S21 series through to Z} \quad (2)$$

$$Z_{DUT} = \frac{50 * S21}{2(1 - S21)} \quad \text{Eq. (3) - S21 shunt through to Z} \quad (3)$$

Each of the connection types has a specific impedance measurement accuracy. This means, that they are each suitable for a specific impedance range. Table 1 shows the impedance range and the suitable S coefficient from [7].

Table 1. Reflection coefficient and their related impedance range

S coefficient	Impedance range
S21 – Shunt through method	1 m Ω – 100 Ω
S11	1 Ω – 1 k Ω
S21 – Shunt series method	10 Ω – 50 k Ω

Fig. 7. A) S11 – B) S21 series through– C) S21 Shunt through

Taking this into account, special care must be taken in order to choose the proper reflection coefficient when we are measuring the DUT.

7. Noise sensitivity

A probability density function (PDF) of Eq. (1), Eq. (2) and Eq. (3) helps us to have a better insight of the difference of each of the mapping functions that convert the reflection coefficient into Z parameter (S11 to Z11 etc.).

A new simulation is run for this purpose. A white Gaussian noise has been added to the S parameter in the equations Eq. (1), Eq. (2) and Eq. (3) with a signal to noise ratio (SNR) of 10. The S parameters are swept from their minimum possible value to their maximum

Fig. 8. PDF of Eq. (1), Eq. (2) and Eq. (3) **Fig. 9. PDF of Eq. (1), Eq. (2) and Eq. (3) from 1 k Ω to 100 k Ω**

possible value and the Z parameter is calculated based on the S parameters. A histogram for each of the Z parameters from Eq. (1) to Eq. (3) is then plotted. The result is shown in Fig. 8.

It is interesting to note that from 1 m Ω up to 5 Ω , S21-shunt-through is the best method since the distribution of values is twice that of S11 and four times that of S21-series-through. From 11 Ω to around 50 Ω , S21-shunt-through and S11 are almost the same however from 50 Ω up to 1 k Ω , S11 and S21-series-through are better than S21-shunt-through. From 1 k Ω to the end, S21-series-through works the best. The performance, however, is not much different from that of S11. This is shown in Fig. 9.

[3], [4] and [5] have used S11 to measure the impedance.

8. Attaching the coaxial cable to the DUT

As is depicted in Fig. 2, the two poles of a prismatic cell are far from each other, meaning that the two ends of the coaxial cable need to be separated from each other, in order to connect it to the positive and negative poles. This is shown in Fig. 10.

The important point here is to notice in the moment when we do this the separated wires no longer behave in the same manner as the rest of the coaxial cable with the known 50 Ω characteristic impedance. The $\frac{\lambda}{10}$ rule of thumb also will not be applied since these two are now just two inductors. This means that under no circumstance are we allowed to ignore the existence of these wires and their impact on the measurement values.

This point is very important since the DUT exhibits very low impedance and these two wires (inductors) will, at best, exhibit the

Fig. 10. Coaxial cable with separated ends

Fig. 11. Two views of the medium connector

same impedance (if not more) and for precisely this reason, it is wise to make these wires as short and as rigid as possible so that their impact on the real DUT values will be kept minimal.

One of the ways of minimizing the effect of these wires is to use a medium connector as it is shown in Fig. 11.

This is made using of two firm wires, which are 3.5 cm long and 1.35 mm thick. The inductance of each of the wires are around 28 nH (56 nH in total). This extra inductance must then be de-embedded from the final result.

Using this medium connector, we are first able to calibrate a coaxial cable and then connect its one side to the VNA and the other side to this medium. Then the two ends of this medium will be connected to the two poles of the battery cell (the DUT).

9. First test

The first step is to test our hypothesis and to see them in action. For this an empty housing cell is connected to the VNA. This housing was completely empty of any material and the only things in it were the two poles. The two poles are completely separated from each other and there is absolutely no electrical connection between the two. This means that, ideally, the measurement result should be capacitive.

For this test E5061B (Agilent VNA) is used and since this was the only test, another reference point was needed for validation. Since a finite element method (FEM) simulation is the best method for complex models, an ANSYS HFSS model is used as the reference. The test setup and the HFSS model are displayed in Fig. 12.

Figure 13 shows a result comparison between measurement, simulation and estimation. Here, we see that the measurement and simulation are very close to each other.

In order to estimate the capacitance, we simply take the 56 nH (from the connector medium) and add a capacitance in series and

Fig. 12. Top: Test setup – Bottom: HFSS model for FEM analysis

Fig. 13. An overlay of lab measurement, HFSS simulation and estimation (Color figure online)

calculate the impedance. 31.3 pF is the capacitance value which fit. However, there is a difference in the depth of the resonance (valley). As we can see in Fig. 13, the blue curve (measured) has the least depth. It is followed by the HFSS simulation and then the estimated curve. The reason for this is the existence of resistive values which, are not used in the estimated curve. In other words, the estimated data, which are purely mathematical, do not include all of the physical losses. They includes only the DC resistance of the medium connector. The most important parts for us, however, are the HFSS simulation and the lab measurement which are both very close to each other. At this point we can go further and measure a real battery cell.

10. Measuring the battery cell

Figure 14 shows the test setup which is used in order to measure a fully charged battery cell. The black electric tapes are used as a safety measure and act as accidental short circuit preventers.

Fig. 14. Test object

Fig. 15. An overlay of two different measurements of the same DUT (battery cell) (Color figure online)

Figure 15 shows the calculated impedance Z_{11} , in magnitude and phase format, from the measured reflection and transmission parameter. The effect of the medium connector is already removed from the measurement and what we see is the measurement result without the extra inductance of the medium connector.

The blue curve is significantly smoother compared to the red curve that is exhibiting a noisy measurement. This is a sign of noise sensitivity of S_{11} reflection coefficient in comparison with S_{21} .

Taking the noise sensitivity into consideration, the drastic difference in impedance characteristics for frequencies below 1 MHz, can easily be explained. The S_{11} method is showing a wrong value for the impedance since it is not designed to work at this impedance range and it is reasonable for us to accept the impedance values that are the result of the S_{21} measurement.

For impedance values higher than $30\ \Omega$, it is wise to accept S_{11} values, however, we see that the two curves match each other so we may continue using S_{21} values. This can be seen from the PDF of these reflection coefficients in Fig. 8 as well.

11. Skin effect

The skin effect is one of the important (and often overlooked) impacts, when it comes to high frequency measurements of battery

Fig. 16. Magnitude and phase of 3 different quantities (skin effect, DC resistance and AC resistance) of a round straight wire with the length of 6 cm

Fig. 17. Combination of all three quantities from Fig. 16

cells. Figure 16 is a plot of the three different components of the impedance of a 6 cm straight wire with a round cross section and the diameter of 1.35 mm. Two quantities out of three are the AC (self-inductance) and DC resistance.

The third one is the skin effect and as we can see, it adds not only to the resistance of the wire, but also to the phase of the output. The value is not very large, however, when the DUT itself has a natural small resistance, the resistance caused by skin effect can have a considerable impact. In Fig. 17 all three quantities are added together so we can have a better understanding of the impact of the skin effect.

Fig. 18. Top: close-up view of the connector in Fig. 14. Bottom: schematic view of the same connector

It is important to note that the skin effect occurs not only in the medium wire. It also occurs in any type of conductor and is going to be maximized as the conductor gets thinner.

The conductors in a prismatic battery cell can be defined in three different groups. The positive and negative layers which are wrapped around each other. The positive and negative poles (made of aluminum and copper) and the aluminum housing which in some battery cells are connected directly to one of the poles. More information on the skin effect can be found in [8].

12. Capacitance of the medium connector

Inductance is not the only side effect that comes with the medium connector. Capacitance is another unwanted quantity that is automatically created in the parts like an SMA socket that is mounted on the printed circuit board (PCB) and in this case the two wires as well. This parasitic capacitance is normally very small and, in low frequencies (in this case, lower than 200 MHz), it does not have a noticeable influence on the measurement result. This, however, is not the case for high frequencies especially as we get close to 1 GHz. At this frequency, we must measure the parasitic capacitance and remove it from the measurement result.

Figure 18 shows the places where parasitic capacitance occurs.

Figure 19 displays the capacitance of the medium connector together with its impedance vs the frequency. It is clear that we can easily ignore this capacitance for the frequencies below 200 MHz since its corresponding impedance is much higher than the measured impedance which is shown in Fig. 15. From 200 MHz and higher, however, we must de-embed this capacitance.

The parasitic capacitance of the medium connector is connected in parallel with the DUT. In other words:

$$Z_{total} = \frac{Z_{DUT} * X_C}{Z_{DUT} + X_C} \quad (4)$$

Fig. 19. Top: The capacitance of the medium connector Bottom: the corresponding impedance

Fig. 20. Overall behavior of the measured magnitude (impedance) and phase of the battery cell

Z_{DUT} is the actual impedance of the battery cell, X_C is the impedance of the parasitic capacitance of the medium connector and Z_{total} is the overall impedance. From Eq. (4) we extract the Z_{DUT} :

$$Z_{DUT} = \frac{Z_{total} * X_C}{X_C - Z_{total}} \quad (5)$$

Now that we know how to de-embed the parasitic capacitance, we are able to see the real result.

13. Explaining the result

Ignoring the local and small resonances which are mainly created by the connectors and medium wires, by de-embedding the parasitic capacitance and the wire inductance we achieve the curve in Fig. 20.

In order to ensure that mistakes are not made, both the magnitude and the phase will first need to be examined. Not doing so, we might falsely understand the rising impedance of the DUT as being a purely inductive behavior. This is not the case, however, since the phase of the DUT is negative and this cannot be an inductor. Figure 21, Fig. 22 and Fig. 23 help us to understand to the result.

In these figures, the red square marks the lower side of the frequency and the black square marks the upper side of the frequency. In other words, the polar graph begins from the red square and moves toward the black square.

For frequencies lower than 10 MHz the system is capacitive. After 10 MHz an inductive element will get stronger that pulls the phase

Fig. 21. The result in polar format. The frequency range is between 100 kHz (red) to 10 MHz (black) (Color figure online)

Fig. 22. The result in polar format. The frequency range is between 100 kHz (red) to 180 MHz (black) (Color figure online)

toward 0 degree. At 180 MHz, the system shows an almost pure resistive impedance (13.23 Ω). At 1 GHz the inductive element will be at its strongest point.

To understand this behavior, we should understand the physical structure of a prismatic cell. A cell is comprised of wrapped sheets which are located tightly in an aluminum housing. At high frequencies the electrons tend to travel on the surface which is known as the skin effect. Since the wrapped sheets are very thin and enclosed in a tight box, the electrons will not find a thick conductor to travel into. As a result they proceed to the next layer and this loop continues until no more conductor remains and they then travel through the aluminum housing. This housing is the thickest conductor as well as the last layer. This is the reason for observing an almost inductive behavior at 1 GHz.

Since the measured impedance is a complex vector and it has all the necessary information, one can easily upscale the number of cells by using multiple results and combining them in series or parallel.

One of the important results is that there is no hard resonance in the cell (for the whole frequency range). This is important because in the process of upscaling, a resonance can propagate by multi-

Fig. 23. The result in polar format. The frequency range is between 100 kHz (red) to 1 GHz (black) (Color figure online)

Fig. 24. Power bar 3D model in HFSS

plying to higher and/or lower frequencies which can cause trouble especially for PLC purposed applications.

14. Power bars – the connection between cells

Figure 24 displays the 3D model of a power bar (power connector) which is being used in EVs. The two rectangular engraved parts in the model are the contact places between two battery cells. In other words, the carrier signal will pass through this power bar from these two engraved rectangles. The simulation result of this power bar, from these ports is shown in Fig. 25.

This power bar is made of aluminum and the DC resistance (from simulation) is around 28.3 $\mu\Omega$. At 1 MHz it shows 15 m Ω impedance and just like a normal inductor it increases tenfold per frequency decade, so much so that at 1 GHz we observe around 15 Ω of impedance. Ignoring the very slight variation in the inductance (which comes from the shape of the power bar and the skin effect), the inductance is about 2.4 nH. This information can be used to upscale the system.

15. The importance of electromagnetic emissions

Noise and unwanted signals always produce a limiting factor on the performance of a PLC system. One of the main sources of distortions originates from the devices that are powered by the main line [9]. Conducted emission is one of the main distortion sources in an electric vehicle and is mainly generated by the inverter.

An inverter, in an electric vehicle, is responsible for driving the electric motor and is connected between the electric motor and

Fig. 25. Simulation result: impedance (top) and inductance (bottom)

the positive and negative high voltage line, known as HV+ and HV-. Electromagnetic interference (EMI) of fast switching inverter has to be taken into consideration, when attempting to design a BMS based on PLC.

An inverter is made of two main parts. The first part is the electronic commutator, which commonly comprises a microcontroller (uC) and gate drivers, and its job is to control the speed and torque of the electric motor. The electronic commutator achieves this by measuring the speed of the rotor and regulating it by utilizing the pulse width modulation technique (PWM).

The second part of an inverter is a three-phase full bridge switch that drives a three-phase brushless DC (BLDC) motor or a permanent magnet synchronous motor (PMSM). The full bridge is typically made from MOSFET or IGBT and are driven by the uC unit. Figure 26 shows a simplified three-phase BLDC inverter.

Fig. 26. A typical simplified full bridge three-phase inverter (Color figure online)

Fig. 27. A full bridge inverter when it is conducting

The generated motor torque level has a direct relationship with the current that is flowing through each phase of the BLDC motor. This is being controlled by changing the duty cycle of the PWM. When a full bridge inverter conducts, it is allowed to pass current only through two phases of the motor. This is shown in Fig. 27. In this figure, the IGBTs are replaced with switches to simplify the concept of current flow. The current that passes through the two phases of the BLDC motor is displayed with blue dotted line. As shown on this figure, the whole circuit is essentially a DC voltage source connected in series with a switch and an inductive load. Switching an inductive load produces conducted emission, which is dependent on the switching frequency and the rise and fall time of the load current. This emission must be limited in a pre-defined region.

In order to measure the noise level that is produced by the inverter, a simplified test setup is used. In this test setup, two IGBTs are switching a 300 uH inductor, which has a 0.15 Ω of DC resistance to simulate two phases of a BLDC motor. The voltage source emulates the battery pack of an electric vehicle that is 300 V DC.

The switching frequency is set to 20 kHz, (the border of human hearing limit) with 5% PWM duty cycle, which is being generated by a signal generator.

In order to be able to measure the conducted emission, a line impedance stabilization network (LISN) must be connected between the DC source and the inverter. LISN prevents any possible external distortion from entering the network while providing us with the two probing points that are suitable for standard measuring equipment such as oscilloscope or a spectrum analyzer. In this case, a spectrum analyzer is connected to the probing points. Figure 28 shows the diagram of the test setup.

In addition to the LISN output, the IGBT current and the transient voltage between HV+ and HV- are measured with an oscilloscope as well. The current is measured with a current clamp (Tektronix TCP404XL) and the voltage is measured with a high voltage probe. The 300 uH inductor and the 0.15 Ω resistor are the inductance and the wire resistance of two phases of a BLDC. The important point here is to notice that during the current and the voltage measurement, the LISN is not used. It is used only to measure the conducted emission.

Fig. 28. Circuit diagram of the test setup

Fig. 29. Oscilloscope measurement of overall switching behavior (Color figure online)

Figure 29 displays the three main signals of the switching system that are measured with the oscilloscope. In this figure, the magenta graph is the voltage of the high voltage cables. The blue graph is the steady state current of the IGBT and the Turquoise blue graph is the transient current of the IGBT.

The first test is the “turn on” test. In this test, the IGBT is turned on and the transient current and voltage are measured with an oscilloscope. Figure 30 shows the oscilloscope screen of the captured signal.

The transient current during the turn-on, rises from 0 A to 190 A that takes 112 ns and settles at 112 A. This is the sharpest transient slope in the turn-on cycle, which is calculated with Eq. (6).

$$\frac{di}{dt} = \frac{190 \text{ A}}{112 \text{ ns}} = 1.696 \frac{\text{A}}{\text{ns}} \quad (6)$$

The peak-to-peak transient voltage between HV+ and HV– is around 80 V.

Fig. 30. Oscilloscope measurement of the turn-on test

The instantaneous peak dissipated power in the coil is around 5.4 kW and the average dissipated power during the turn-on time is close to 4.3 kW. Since the duty cycle is set to 5% the average dissipated power in a cycle is 215 watts.

The second test is the “turn off” test, which is shown in Fig. 31. The IGBT current drops slower than in the previous case and has a direct influence on the voltage change of the high voltage lines. The fastest transient slope in the turn-off cycle lasts around 40 ns, which is 2.8 times shorter than the turn-on cycle. The slope with which the current drops to 0 A is shown with Eq. (7), which is around 88% of the turn on slope.

$$-\frac{di}{dt} = -\frac{60 \text{ A}}{40 \text{ ns}} = -1.5 \frac{\text{A}}{\text{ns}} \quad (7)$$

Because of a lower di/dt that occurs in the turn-off cycle, the voltage drop on the high voltage line is also lower than the turn-on cycle. Compared to 80 V peak-to-peak during the turn-on, in the turn-off cycle the voltage drop reduces to 30 V peak-to-peak.

Fig. 31. Oscilloscope measurement of the turn-off test

Fig. 32. Conducted emission measured with the spectrum analyzer

As mentioned above, the probing ports of the LISN is connected to a spectrum analyzer. The detection mode is set to average that helps us to see the power of conducted emissions, which transmit through the main HV+ and HV− cables. The output of the spectrum analyzer is shown in Fig. 32.

This figure shows the received noise from the frequencies ranging from 200 kHz up to 300 MHz. By analyzing this figure, it is clear that the strongest distortions occur at lower frequencies and as the frequency increases, the conducted emission decreases. From 20 MHz upwards, the conducted emission is generally below 70 dBuV. Converting this value to volts results in a distortion with 3.2 mV amplitude, meaning that the transmitted or received carrier signal will be distorted with a maximal voltage of 3.2 mV and the amplitude of the carrier signal must be higher than this voltage so the receiver can reliably demodulate the data.

At 25 MHz, the emissions are much lower than before, around 50 dBuV or 3.16 μ V. This means by increasing the carrier frequency by only 5 MHz (from 20 MHz to 25 MHz), the distortion will reduce by a factor of 1000. Accordingly, the amplitude of the carrier signal can be much lower, compared to the previous case (20 MHz carrier frequency). As a result, less power is needed to produce and transmit the carrier signal.

The proposed data rate for BMS applications is 2 Mbps [10]. Utilizing a 25 MHz carrier signal for modulation techniques such as frequency shift keying (FSK) or phase shift keying (PSK) allow us to reach a data rate which is higher than 2 Mbps and as it was

explained before, the conducted emission at this frequency is very weak.

16. Conclusion

The main focus of this paper was to characterize the impedance of a prismatic li-ion battery cell in order to be used in a PLC application for a BMS system in EVs.

The challenges of the impedance characterization and how to overcome these challenges were explained. The process was carried out in three different ways, consisting of mathematical calculation, FEM simulation and lab measurement.

The frequency range of the measurement begins from 100 kHz up to 1 GHz which is beyond the scope covered in the existing literature.

The overall behavior of the impedance is as follow:

- The DUT is almost purely capacitive with a very low impedance for low frequencies up to around 30 MHz
- From 30 MHz both the phase and the impedance rise up until at 1 GHz the DUT is almost purely inductive

And finally, by measuring the conducted emission in an emulated inverter in the lab, it was clear that by using a carrier signal with a frequency higher than 25 MHz, the modulated data can be reliably demodulated since the distortion level in the higher frequency range is very low.

Another advantage of using this carrier frequency is that the impedance of the battery cell will be independent of the SOC and the SOH. One of the reasons is the skin effect. As the frequency of the test signal increases, the penetration depth will decrease. Accordingly lesser quantity of the cell material will be relevant to the impedance of the cell. It is for this reason that a test signal with a low frequency is used, when the impedance measurement is required for the purpose of estimating the SOC or the SOH.

Funding Note Open access funding provided by Graz University of Technology.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access Dieser Artikel wird unter der Creative Commons Namensnennung 4.0 International Lizenz veröffentlicht, welche die Nutzung, Vervielfältigung, Bearbeitung, Verbreitung und Wiedergabe in jeglichem Medium und Format erlaubt, sofern Sie den/die ursprünglichen Autor(en) und die Quelle ordnungsgemäß nennen, einen Link zur Creative Commons Lizenz beifügen und angeben, ob Änderungen vorgenommen wurden. Die in diesem Artikel enthaltenen Bilder und sonstiges Drittmaterial unterliegen ebenfalls der genannten Creative Commons Lizenz, sofern sich aus der Abbildungslegende nichts anderes ergibt. Sofern das betreffende Material nicht unter der genannten Creative Commons Lizenz steht und die betreffende Handlung nicht nach gesetzlichen Vorschriften erlaubt ist, ist für die oben aufgeführten Weiterverwendungen des Materials die Einwilligung des jeweiligen Rechteinhabers einzuholen. Weitere Details zur Lizenz entnehmen Sie bitte der Lizenzinformation auf <http://creativecommons.org/licenses/by/4.0/deed.de>.

References

1. Ouannes, I., Nickel, P., Dostert, K. (2014): Cell-wise monitoring of lithium-ion batteries for automotive traction applications by using power line communication: battery modeling and channel characterization. In IEEE ISPLC 2014–18th IEEE int. symp. power line commun. its appl. (pp. 24–29). <https://doi.org/10.1109/ISPLC.2014.6812322>.
2. Bolsinger, C., Brix, J., Dragan, M., Birke, K. P. (2017): Investigating and modeling the transmission channel of a prismatic lithium-ion cell and module for powerline communication. J. Energy Storage, 10, 11–19. <https://doi.org/10.1016/j.est.2016.12.001>.
3. Ruddle, A. R., Teo, Y. X., Chen, J. (2018): In Electromagnetic modelling strategies for EMC analysis of automotive traction batteries (pp. 1395–1398).
4. Ruddle, A. R., Chen, J., Teo, Y. X. (2017): In Measurement of RF impedance for automotive 18650 cylindrical lithium ion cells (pp. 1–5).

5. Jiaqi, C., Ruddle, A. R., Teo, Y. X. (2017): In Predicting the RF impedance of cells in series for automotive traction battery applications (pp. 1–5).
6. Kyoh, S. Challenges and solutions for EUV lithography. Online. Available: https://www.keysight.com/upload/cmc_upload/All/ChallengesandsolutionsforImpedance.pdf.
7. K. Technologies Keysight technologies performing impedance analysis with the E5061B ENA vector network analyzer.
8. Landinger, T. F., Schwarzberger, G., Jossen, A. (2020): A physical-based high-frequency model of cylindrical lithium-ion batteries for time domain simulation. IEEE Trans. Electromagn. Compat., 62(4), 1524–1533. <https://doi.org/10.1109/TEMC.2020.2996414>.
9. Lampe, L., Tonello, A. M., Swart, T. G. (2016): Power line communications: principles, standards and applications from multimedia to smart grid. 2nd ed.
10. Landinger, T. F., Schwarzberger, G., Rose, M., Dollhaeubl, S., Hofer, G., Talei, A. P., Jossen, A. (2020): In Power line communications in automotive traction batteries: a proof of concept (pp. 1–5). <https://doi.org/10.1109/isplc48789.2020.9115412>.
11. Talei, A. P., Pribyl, W. A., Hofer, G. (2019): Wide frequency range impedance measurement of a Li-ion prismatic cell for power line communication technique. In SMACD 2019–16th int. conf. synth. model. anal. simul. methods appl. To circuit des. proc. (pp. 109–112). <https://doi.org/10.1109/SMACD.2019.8795281>.

Authors

Arash Pake Talei

received his B.Sc. in electrical engineering in Iran and his M.Sc. from Carinthia University of applied sciences in control engineering. He currently is doing his Ph.D. in TU Graz, focusing on the power line communication method and battery management systems for electric vehicles. His research interests are power line communication, battery management systems, control engineering, electro-motors and inverters.

Wolfgang A. Pribyl

born in 1953. He received his Dipl.-Ing. (Msc.) and PhD degree from the TU Graz in 1977 and 1981, respectively. From July 1981 to September 1984 he was design engineer for CMOS circuits in medical and ICT applications, from June 1982 onwards head of a design group in the Development Centre for Microelectronics of Siemens AG in Villach, now part of Infineon. From October 1984 to

November 1985 he was a delegate to the first Siemens IC-Design Centre in the US (Silicon Valley) leading a design group in the area of local networks. In December 1985 he returned and got the project lead of the 4 Megabit DRAM of Siemens AG Munich. After this, he was setting up and heading the “Institute for Electronic Systems Design” of Joanneum Research in Graz, engaged in application oriented R&D. He returned to Siemens from August 1993 to December 1998 as managing director of the Development Centre for Microelectronics of Siemens AG, now Villach and Graz with the overall technical and business responsibility. Its main activities were

mixed A/D- and smart power circuits for automotive, industrial and ICT. From January 1999 to December 2002 he was member of the Board (C.T.O.) of austriamicrosystems AG, leading the technological direction of the company. Since January 2003 he is a consultant in electronics and microelectronics and is also frequently acting as expert for the EC / ICT / H2020. Since September 2005 he is professor for electronic systems at the TU Graz. Since September 2011 he is CEO of Joanneum Research, Graz, an RTO active in several fields of applied research, among those microelectronics and electronic systems.

Günter Hofer

(Senior Staff Engineer) was born in Graz, Austria, in 1969. He received the Dipl.-Ing. Degree in electrical engineering from the Technical University of Graz, Austria, in 1998. Since graduation, he has been with the Microelectronics Development Center of Siemens AG, now Infineon Technologies, in Graz, Austria. His main interest is the concept and design of analog and mixed signal circuits on communication systems for ISM Transceiver, RFID Interfaces, Sensor interfaces and Battery Management Systems. Since 2013, his main focus is Battery Management Systems for electrical vehicles, highly concentrated on EMC robust Communication and Impedance Measurement. He coached a huge amount of master thesis and PHD works on several Universities in Europe. He holds several patents and is co-author of more than 20 papers in international journals and conferences.