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Published Version:
Schmidt H., Gutierrez A.J.C., Romani A., Crescentini M., Borger K., Chacon R., et al. (2023). The PROGRESSUS project-Highly efficient and trustworthy electronics, components and systems for the next generation energy supply infrastructure. Institute of Electrical and Electronics Engineers Inc. [10.23919/AEITAUTOMOTIVE58986.2023.10217204].

Availability:
This version is available at: https://hdl.handle.net/11585/950584.2 since: 2023-12-13

Published:
DOI: http://doi.org/10.23919/AEITAUTOMOTIVE58986.2023.10217204

The PROGRESSUS project - Highly efficient and trustworthy electronics, components and systems for the next generation energy supply infrastructure

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***Abstract* — High-power requirements of ultra-fast charging stations and the uptake of many low-power charging stations give rise to special challenges when designing smart charging infrastructure. In support of Europe's 2030 climate targets, the EU-funded PROGRESSUS project aims to propose a next-generation smart grid demonstrated by the application example of a smart charging infrastructure integrating seamlessly into current smart-grid architecture concepts. To do so, it will research new efficient high-power converters that support bidirectional power flow. It will also develop a novel smart charging algorithm for a group of AC charging stations taking local electricity consumption and generation into account. Furthermore, new DC microgrid management strategies for energy efficiency and service provision that consider renewable energy sources, storage and flexible loads will be investigated. Moreover, novel high-bandwidth sensor types for intrusion-less measurement will be explored. Finally, security measures based on hardware security modules and blockchain technology to protect services and track energy certificate transactions are investigated. The project's solutions will promote a more environmentally friendly and efficient next-generation energy supply infrastructure.**

The paper is structured as follows. Section I provides a brief introduction to the PROGRESSUS project while the subsequent sections present selected project results. In Section II a highly efficient EV charging station including a buffering battery is presented. Section III describes an innovative EV charge station management system that maximizes the grid utilization. In Section IV a solution for tradeable green certificates featuring blockchain and hardware-based security is presented while Section V describes an innovative high bandwidth Hall sensor for control and monitoring.

Keywords — energy, smart grid, power conversion, energy management, EV charging, connection resistance, blockchain, hardware security, sensing, current sensor

I. INTRODUCTION – THE PROGRESSUS PROJECT

The European Commission has set ambitious targets to accelerate the transformation of the energy sector so as to provide secure, affordable and sustainable energy supplies to the consumers through the creation of a fully integrated and highly efficient internal energy market [1].

In this situation, a deep structural change of the energy systems is currently taking place, through the integration of Renewable Energy Sources (RES), and Energy Storage Systems (ESS) into a decentralised power system, targeting to improve efficiency, flexibility, and robustness. However, the new power grid faces continuously growing challenges related to technology advances (Internet of Things (IoT), connected devices (EVs, etc.), while it needs at the same time to be secure and take into account the environmental concerns about greenhouse gas emissions that cause climate changes and air pollution in urban environments. Since transportation in Europe accounts for over 25% of CO_2 emissions [1], a migration to a sustainable electromobility powered by RES is urgent. Similarly, since energy supply accounts for a similar share [3], a switch to more efficient grid paradigms with decreased CO_2 emissions and energy consumption is mandatory.

In this context, the PROGRESSUS project which comprises 22 partners from 5 European countries, therein 4 large enterprises, 8 SMEs and 10 partners from academia steps in as a vigorous initiative with a key objective to reduce the greenhouse gas emissions related to mobility and grid power generation. This target will be met under the design and development of a series of technologies and methodologies that also target to reduce the peak power consumption from the grid by at least 30%, and to increase the efficiency of the grid's components in order to enable and support a wide-spread diffusion of electromobility and renewables such as photovoltaics.

The research in PROGRESSUS focuses on solutions for microgrid scenarios at the low voltage level up to the connection point to the medium voltage distribution grid. In that context, three technical areas and their interactions form the core of the activities and structure the project work: i) Power conversion: highly efficient, high power converters for EV charging. Main aspects are improved conversion efficiency and a bi-directional energy flow that considers local storage and RES. Modular approaches and the use of wide bandgap semiconductors play a key role. ii) Smart energy management for EV charge systems which maximise

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the utilization of the resources plugging seamlessly into existing installations and at the same time supporting the integration of the novel high power chargers developed in PROGRESSUS. Consideration of diverse information, e.g. demand / supply profiles, grid state, user requirements and more are essential. iii) Monitoring and Control: approaches to provide the highest possible level of security to protect the smart grid against hacks and attacks and to securely track the origin of the energy from the source to the consumption, e.g. EV charging, introduce blockchain networks and hardware based security. Furthermore, innovative sensors that measure currents for the control of converters and energy management are researched. Intrusion less measurement, low cost and most importantly high measurement speed are targeted. Novel sensing elements using magnetic principles are investigated.

For each of the before mentioned areas solutions will be presented in the next sections.

II. Power Conversion – EV Charging Station

In order to fully realize the potential for bidirectional fast charging, there is a need for modular and decentralized charging stations. In this work, we present the development of a modular 50 kW fast charger with an integrated battery storage system for connection to a local DC-microgrid. The charger can facilitate bidirectional charging from the grid and the connected vehicle independently, as long as the internal battery storage permits - simultaneously increasing charging capacity while reducing the necessary distribution grid peak-load.. This introduces additional degrees of freedom for the energy management system of the DC-microgrid.

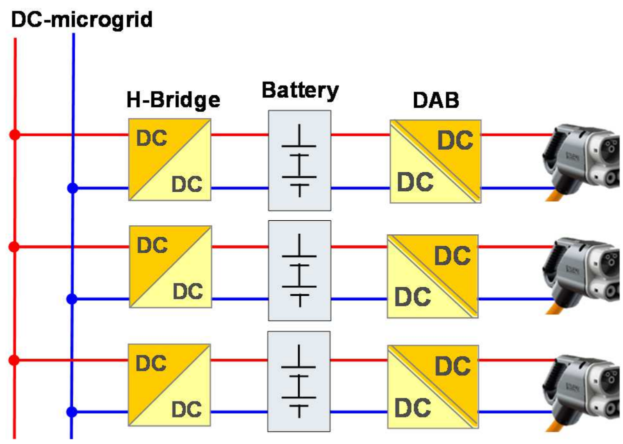

Fig. 1. Conceptual overview of multiple battery integrated charging stations in a DC-microgrid. Each charger consists of a non-isolated H-Bridge connecting the internal battery to a LVDC grid. The charging is controlled via a DAB connecting the battery to the vehicle.

The fundamental concept of the charger is illustrated in Fig. 1. A non-isolated DC/DC converter is utilized to connect the charger to the local DC-grid. This converter is arranged in a 9-phase H-bridge configuration, enabling the battery and grid voltage to overlap.

The battery is connected to the vehicle via a 2-port Dual Active-Bridge Isolated Bidirectional DC-DC-Converter (DAB-IBDC), which regulates the charging process and isolates the vehicle from the grid. With this system, the energy management of the DC-microgrid is enhanced, providing a reliable and efficient bidirectional charging solution.

A. 9-Leg H-Bridge Converter

The H-Bridge Converter utilized for linking the battery storage to the grid is comprised of 9 phases. It has been demonstrated that multi-phase DC/DC converters improve efficiency in low and part load operation, as individual phases can be turned off at low loads [1]. Furthermore, interleaving multiple phases allows for low ripple currents even at high loads, thus reducing the requirement for input and output capacitances. Fig. 2 shows a single phase of the converter.

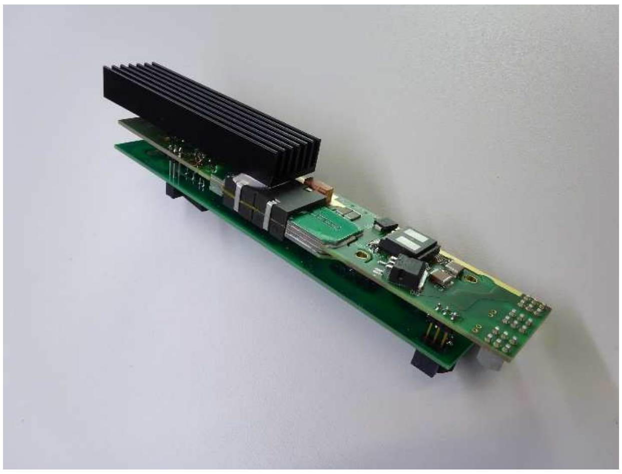

Fig. 2. Single phase of the 9-phase H-Bridge DC-DC Converter with partially removed heatsink. Each half bridge consists of two Infineon 1.2 kV, 90 mΩ SiC MOSFETs which are integrated into a single top cooled HV-QDPak. The inductor is integrated into the PCB and matched in hight to the QDPak to allow for a single heatsink design for the whole phase.

To achieve high efficiency at a switching frequency of 100 kHz and enable grid and battery voltages up to 950 V, 1.2 kV 90 mΩ SiC-MOSFETs from Infineon are employed. Each half-bridge is integrated into a single HV-QDPak to attain a compact design. A wide bandwidth TMR sensor from Infineon is used for current measurement. Due to its high bandwidth, the corner frequency of the current controller can be significantly increased in comparison to commercially available hall-effect sensors. Since the converter acts as droop-controlled regarding the DC-grid a high current control corner frequency is beneficial to the stability of the microgrid. According to [5] a high corner frequency reduces the need for additional capacitances at the grid side, which complements the reduced need for capacitances for ripple reduction due to the 9-phase interleaving.

B. Dual Active Bridge

The DAB-IBDC consists of a high-frequency (HF) transformer and two full-bridges. It connects the vehicle to the storage system and is required for galvanic isolation. The maximum rated power of 50kW per module can be customized as desired by parallel interleaving multiple DAB-modules, which additionally reduces the DC-link capacitor RMS current. With the Yokogawa WT5000 a nominal-load-efficiency $\eta = 97{,}7\%$ with $U_{\text{in}} = U_{\text{out}} = 800\,\text{V}$ is stated. With a fixed converter DC-link-voltage-ratio, the DAB shows ease soft-switching capability from partial to full load. The Zero Voltage Transition (ZVT) is lost at very light load condition, since the absolute value of the available inductor current at the switching moment falls below the minimal current, which is needed for a complete Zero Voltage Switching (ZVS) operation of the corresponding switching half- or full-bridge. Methods of obtaining optimal control-parameters for cascade feedback control and their influence on transient processes of a DAB converter are studied in [6]. Research on modulation approaches is ongoing to optimize RMS-current, while achieving light load ZVT and operate wide voltage ranges. Optimization objective is an operating range wide efficiency improvement with augmented voltage ranges.

C. Load buffering battery

As part of the development of the charging station a battery module was developed to buffer peak electricity demands. With a single battery module consisting of a series connection of 14 cells belonging to the SELV category for easy handling, the modules are designed for stacking in serial configuration to reach higher voltages. Therefore communication with a single module is realized via a galvanically isolated bus, so that a central control unit can monitor voltages, down to a cell level, as well as in module temperatures. Focus of development was the thermal design of the battery module. To reduce the electrical resistance, and therefore in I^2R losses, on the inter cell connections. A parameter set was found to enable direct laser welding of aluminum busbars to the battery tabs, without excessive, damaging heat introduction into the cells. This parameter set results in 30% reduction in electrical resistance and therefore I^2R losses. Also, to reduce mechanical stress on the pack's components during high electrical load peaks, elasticity was introduced into the design of the battery module. FEM assisted design was used to determine cutouts around the mounting point of the PCB of the battery electronics and introduce a wave-like structure to the aluminum busbars of the inter cell connections. Additionally, elastomeric pressure pad was inserted between the single cells, to absorb some of the mechanical expansion.

III. Energy management - EV charging

GreenFlux develops a charge station management system for electric vehicles. This means many charge stations are being operated on their platform. One of the functionalities the platform provides to charge stations of electric vehicles is performing energy management. For this, an algorithm was developed in the PROGRESSUS project.

Energy management of charge stations of electric vehicles means the control over the maximum power consumption of the connected electric vehicle. This way, the GreenFlux platform is able to limit the maximum power consumption of electric vehicles. In a situation without smart charging, electric vehicles will always be able to charge at their maximum speed. Meaning there is no control over their consumption pattern.

Grid connections to buildings or groups of charge stations are often limited in size. This restricts the power available for EV charging and thus the number of charge stations that can be installed on a location. Expanding the grid connection is one way to solve this problem. However, this is often not possible due to grid constraints. Even if it is possible to expand the grid connection, infrastructure and maintenance cost grow with a larger connection. Therefore, this solution will significantly increase the costs related to the grid connection and therefore EV charging. An alternative solution to tackle this problem is smart charging. By smart charging electric vehicles, the existing connection can be used much more efficiently. As a consequence, more charge stations can be installed on the same grid connection resulting in a reduced need for grid upgrades and therefore lower costs.

GreenFlux performs energy management on charge stations over the internet using the Open Charge Point Protocol (OCPP). This allows for two-way communication between charge stations and the GreenFlux platform. A charge station communicates its' power consumption to the platform. In turn, the platform is able to set a maximum charge rate to an individual charge point. The result of sending such a signal is that the charge point will never provide more power to a connected electric vehicle than that setpoint.

In PROGRESSUS, GreenFlux developed an algorithm able to manage the power consumption of a group of charge stations on the same location. The algorithm makes sure that the collective power consumption of the group of charge stations never exceeds the allowed maximum. The aggregated maximum can be constant or made dynamic over time by taking local renewable energy generation and local energy consumption into account. This can be done in real-time using measurements from a local meter. Subsequently, the algorithm makes sure this maximum is never exceeded by distributing the available power over all charge stations on the location. This is not equally divided over all charge stations. Instead, the algorithm distributes the available power in the most efficient way by taking the following elements into consideration:

- occupation of charge stations;
- start time of the charge sessions;
- charge station constraints;
- EV charging behaviour and EV driver preferences;
- offline charge stations

Besides the points mentioned above. The algorithm is able to distinguish between the three phases of the electricity grid. It does this by measuring the power consumption of the phases independently.

The impact of smart charging on EV drivers is limited. The reason for this is two-fold. Firstly, users are usually parked for much longer than necessary to be fully charged. Examples of this are parking at work during the day or at home during the night. As a consequence, there is flexibility to delay charging of the EV and still be fully charged in the end. The second reason is the truly smart scheduling of the algorithm as it takes multiple inputs into account to disaggregate the available power as efficiently as possible. As such, one of the elements it takes into account are the EV driver preferences. By having this in place, drivers can request priority in charging when they are in a hurry. They can do this via Charge Assist, an app developed for EV drivers which they can also use to start or stop a charge session. When drivers do this, the algorithm provides them power before it provides power to charge stations that have not requested priority. As a result, the impact of smart charging on EV drivers is little, also for EV drivers that are parked for a short duration.

Contrary to the low impact of smart charging on EV drivers, the benefits for the electricity grid and location owners are clear. Performing energy management on charge stations allows for a reduction in the peak power consumption on location level of up to 90%. Alternatively, ten to fifteen times more charge stations can be operated on the same grid connection when applying the smart charging algorithm of GreenFlux. In real-life scenarios, the need for a lower grid connection has led to savings for location owners up to €2.400

per charge station in capital expenses and up to €740 per charge station per year in operating expenses. An additional benefit of the improved utilization of the grid connection through smart charging is that the pressure on distribution system operators to expand the grid connection is significantly reduced.

IV. Energy Management – Green Certificates

In smart grids, the different entities that produce and consume energy (prosumers) exchange quantities of energy that are often difficult to monitor and track. In addition, new forms of monitoring are required that distinguish between different energy sources (renewable and fossil). Blockchain networks, because they are not based on energy-hungry proof-of-work methods, can be used in smart grid applications, particularly in the use case of tradable green certificates [7].

Blockchain offers trust and decentralization as its main characteristics. Based on Decentralized Ledger Technologies (DLT), blockchain distributes a database (ledger) among the entities belonging to the network, thus improving security. In addition, blockchain offers privacy, as the hashes it uses make it impossible to identify the data relating to a specific user. Immutability and traceability are also important features in blockchain applications, achieved through the transactions carried out in the ledger by the different users. All transactions are stored in the ledger and can never be altered. Transactions change the content of the decentralized database, so they must be approved by the entities that make up the blockchain according to the roles established within it. In this way, any change is communicated to the various entities that maintain the integrity of the database [8].

In the case proposed in the article, the blockchain network keeps a record of green certificate transactions between prosumers, identifying each green certificate issued by an ID and tracking it through the digital certificates of an issuer (the prosumer who creates the green certificate) and a receiver (the prosumer who requests green energy).

It is worth mentioning the ability of some blockchain networks to execute software applications. These applications are executed through smart contracts, which run on the ledger and perform actions predefined by the users that make up the blockchain network. Typically, the exchange of energy in a blockchain-based smart grid is executed through smart contracts where quantities of energy are sold and purchased from different prosumers. However, the introduction of tradable green certificates (TGCs) adds value to these exchanges. Although a TGC can represent a certain amount of energy, it also brings information as proof that the energy comes from a renewable source. This information, as well as others such as digital identity, company, type of renewable energy source, date of issue, etc., can be stored on the blockchain.

What makes blockchain networks different is the underlying cryptographic framework, which enables the security of device-to-device communication in these networks. Blockchain networks use cryptographic material such as public/private crypto keys and certificates. In addition, blockchain networks make intensive use of cryptographic operations such as signing, signature verification or key generation. Typically, the keys and certificates involved in the blockchain are stored in a “software wallet”. Software alone is not enough to protect cryptographic keys and certificates as the stored data can be read, modified and distributed effortlessly. In order to avoid an easy access and manipulation to this cryptographic material, a hardware-based security becomes necessary. Hardware security modules offer a solution which relies on: high entropy key generation; tamper-proof protection, enabling secure storage of private keys or sensitive information; key back-up and restoration; hash and signature algorithms implemented in hardware [9].

Both signature algorithms and key generation mechanisms are used by prosumers in the enrolment process and when invoking smart contract functions. In the enrolment process, prosumers generate a key pair in the Hardware Security Module (HSM) before sending a Certificate Signing Request (CSR) to the blockchain's certification authority to obtain an X.509 certificate for later interaction with the blockchain. When prosumers invoke smart contract functions, the result is a transaction whose hash is signed by the HSM.

By integrating a hardware security module into a blockchain-based green certificate trading system, prosumers can use hardware secure elements to implement and protect the cryptographic tools used to interact with the blockchain. In addition, through the smart contracts, they can help automate these processes, eliminating intermediaries, saving costs and avoiding bureaucracy.

The proposed design system is built using a permissioned blockchain network called Hyperledger Fabric (HLF). In HLF, prosumers act as clients of the network in which they interact with each other. Prosumers can belong to different organizations through which they are admitted to the blockchain, while the blockchain is formed by a consortium of companies or individuals. The design was implemented in a demonstrator setup which is shown in Fig. 3.

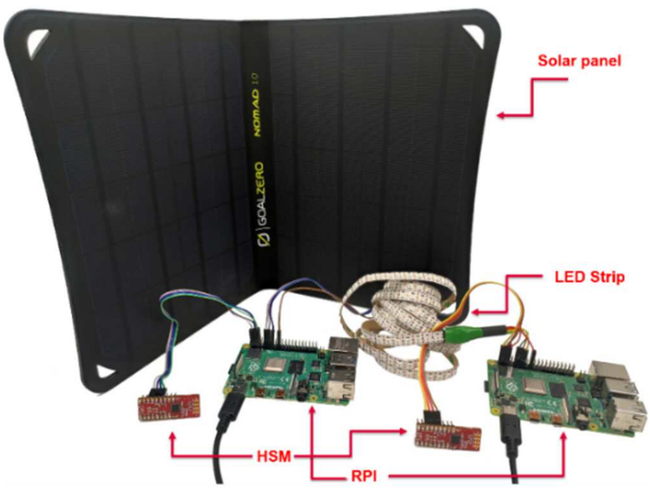

Fig. 3. Tradeable Green Certificates Demo Setup

The blockchain has been deployed on a computer, where each blockchain entity (peers, orderer and certification authority nodes) is a virtualized container, and each prosumer has been deployed on a Raspberry Pi, to which an HSM has been connected to perform the necessary cryptographic operations. Inside the setup, Fig. 3, one of the prosumers has a solar panel connected to it, producing energy, while the other has a strip of LEDs connected to it, consuming energy. Through the logic implemented in smart contracts, when the consumer turns on the LED strip, the producer will generate a certain amount of TGCs, depending on the amount of energy produced and stored, which will be sent to the consumer. The consumer will use them to light the LEDs using green energy. If the amount of energy stored by the manufacturer does not reach the amount needed to light the LEDs for the required time, the energy used will be non-green energy and the consumer will not receive any TGCs during that time. Fig. 4 shows the operational flow of the system.

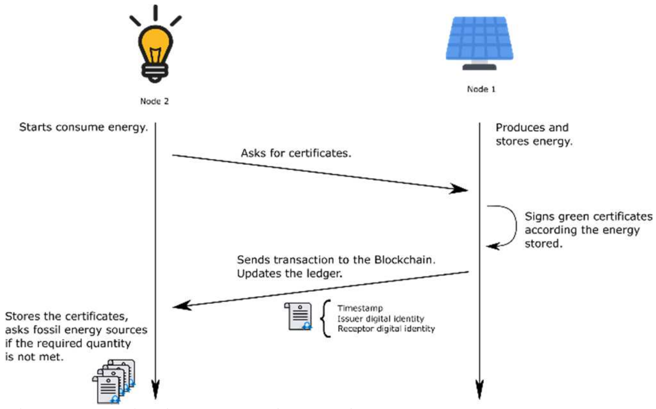

Fig. 4. Interaction between producer and consumer

In this way, following this interaction flow and through the presented hardware, the two nodes interact with each other producing TGC and using them to consume energy, keeping all the records of TGCs transaction in the blockchain. All these interactions are done and automated through smart contracts.

V. Broadband Current Sensors

As power systems become smarter and their organization and interactions become more complex, sensors and communications play an essential role in pursuing control, stability, and efficiency of smart grids and their related power conversion hardware. Electric currents are among the basic physical quantities that have to be sensed at various levels: at low level in the control loop of power converters, at an intermediate level in microgrids, at a higher level in smart meters and optimization flows. In this perspective PROGRESSUS pursued the development of a new generation of integrated current sensors with above-state-of-the-art acquisition bandwidth. Broadband current sensing is functional to keeping the pace with power converters operating at higher switching frequencies, and to develop novel smart metering applications such as non-invasive load monitoring, where appliances and their consumptions are analyzed and recognized in terms of features of their current consumption patterns in a centralized measurement point, without the need to install embedded sensors in all the electric loads. On top of that, microelectronic technologies offer the potential of achieving such wide bandwidth along with high miniaturization, leading to the potential integration of the current sensor dies into packages of power devices to provide smart function and low costs of production.

More specifically, PROGRESSUS investigated the use of recent smart power technologies, i.e. Bipolar-CMOS-DMOS (BCD), to increase the bandwidth of Hall-effect current sensors with no need for any additional fabrication step with respect to the standard process. The idea behind this achievement is an analysis of the intrinsic bandwidth limits in CMOS purely Hall sensors [10][11], which mainly reside on the read-out circuitry; specifically, the methodological limit set by the application of the spinning-current technique to reduce the offset [12][13] and the practical limit set by the capacitive load introduced by the front-end electronics and the probe itself [14].

To overcome these limitations, different technical solutions were investigated and proposed during the PROGRESSUS project. A novel design for the Hall-effect probe with an inherent static offset reduction was proposed as a first solution to avoid the need for the spinning-current technique. Furthermore, a current-readout approach was applied to the X-Hall probe the reduce the impact of the capacitive load at the probe-electronics interface and widen the acquisition bandwidth above 10 MHz, which is a 10 times improvement with respect to state-of-the-art purely Hall sensors.

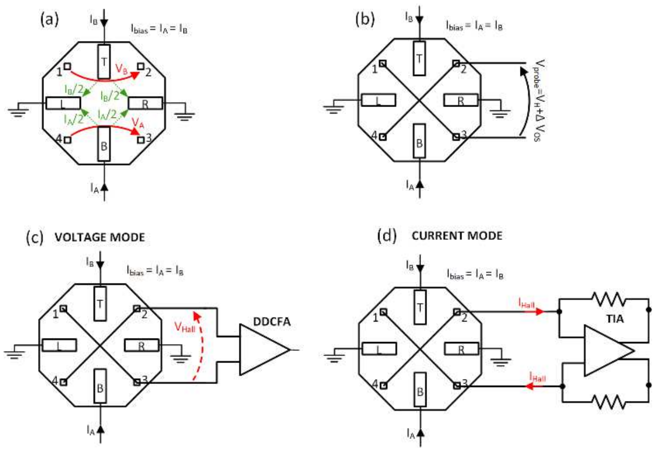

Fig. 5. A simplified representation of the broadband current sensing architectures exploiting the X-Hall probe developed in PROGRESSUS: (a) Simplified representation of voltages and currents on the octagonal probe; (b) X-Hall probe, (c) X-Hall probe in voltage mode with DDCFA for voltage readout, and (d) X-Hall probe in current mode with TIA for current readout.

The X-Hall probe (Fig. 5a) is realized as an octagon-shaped Hall plate with eight contacts placed along the edges [15]. Four contacts are exclusively used to bias the device (B, T, L, R) and four contacts are used to sense the output voltages (1, 2, 3, 4). The functional separation between contacts allows for optimizing their geometrical design. The Hall plate is DC polarized by applying two equal currents I_A and I_B to two opposite contacts (e.g., B and T) and by connecting the other two bias contacts to a reference voltage (e.g., ground). This polarization scheme forces a uniform current density distribution over the device, while polarizing the probe in four orthogonal directions [15]. The two bias currents flow in opposite directions, leading to the generation of two differential output voltages V_A and V_B showing an opposite Hall effect V_H (Fig. 5a). On the contrary, the additive offset voltages $V_{OS,plate}^{(A)}$ and $V_{OS,plate}^{(B)}$ are very likely concordant since there is a unique active region:

$$V_A = V_H + V_{OS,plate}^{(A)}$$
$$V_B = -V_H + V_{OS,plate}^{(B)}$$

To add an extra boundary condition to the charge distribution along the device, the sense contacts are shorted to form an "X" (see Fig. 5b) and force the equality:

$$V_A = -V_B = V_{probe}$$

Under the hypothesis of concordant offset voltages and substituting this last equation in the previous, the only possible solution implies zero residual additive offset to the voltage

V_{probe}. Actually, the offset voltages are created by both global and local effects. While the global effects can be assumed to act uniformly on the probe, the local effects inherently act on a specific and confined region, therefore they break our original hypothesis. As a result, the output voltage V_{probe} of the X-Hall device still suffers from a residual offset ΔV_{OS} which is lower than the intrinsic offset. The output voltage can be expressed as:

$$V_{probe} = V_H + \Delta V_{OS}$$

The X-Hall architecture offers a fair offset reduction without the need to spin the bias current, thus allowing for wider operating bandwidth. To complete the sensor and exploit the bandwidth capabilities of the X-Hall probe, a low-offset, broadband, differential voltage amplifier with minimum input capacitive load is required to read out and amplify the microvolt-level Hall voltage (Fig. 5c). These challenging requirements were met by designing a differential-difference current-feedback amplifier (DDCFA) [16]. With this architecture, it was possible to realize a current sensor prototype based on the Hall effect with a bandwidth as high as 4 MHz.

Although the X-Hall probe removed the methodological limit, the voltage measurement realized by the DDCFA is intrinsically prone to the RC time constant defined at the probe-electronic interface. This limitation can be overcome by moving from a voltage measurement to a current measurement (Fig. 5d) [17]. In this case, the output voltage of the X-Hall probe, which is generated by the accumulation of charges on the edges of the device due to the Hall effect, is forced to be zero by a low input-impedance fully-differential transimpedance amplifier (TIA). As a consequence, a current proportional to the Hall effect flows from one output contact to the other and it is transduced and amplified by the TIA.

With this architecture, the purely Hall-effect current sensor can achieve a bandwidth higher than 10 MHz while keeping low input-referred noise and reasonably low power consumption. The realized prototype demonstrated the highest noise/power/bandwidth figure of merit in the literature, with a value of 569 MHz/A2mW; five times better than hybrid coil-Hall solutions.

VI. Conclusion

In this paper we have presented selected results of the PROGRESSUS project which support the European 2030 climate targets by enabling a next generation energy grid which is prepared for the mass deployment of electric vehicles and which considers storage and renewable sources. Highly efficient charge stations including load buffering batteries combined with innovative EV charge station systems maximize the utilization of the energy grid infrastructure and at the same time take into account local renewable energy generation and users preferences. A novel approach to implement tradable green certificates introducing blockchain networks and hardware security modules was presented. Furthermore, a broadband Hall-effect current sensor was described which meets the requirements of the necessary control and monitoring functions of the next generation EV charging infrastructure and appliances demonstrating the highest noise/power/bandwidth FOM.

Acknowledgment

This work has received funding from the Electronic Components and Systems for European Leadership Joint Undertaking under grant agreement No 876868. This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation programme and Germany, Slovakia, Netherlands, Spain, Italy.

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