Electric Mobility and Smart Grids: Cost-effective Integration of Electric Vehicles with the Power Grid

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Abstract: In order to integrate a large number of electric vehicles (EVs) with the power grid, an update of the existing grid infrastructure is necessary. The most promising solution in this context is a smart grid, which is a combination of a power grid and a communication network. Furthermore, a smart power grid infrastructure enables the so-called smart charging of EVs. Hence, higher peak demands or violations of power grid-constraints can be avoided by means of smart charging. In addition, it allows the charging of EVs when the electricity price is low or the generation fuel mix is less carbon intensive. Furthermore, all EVs must be equipped with an integrated on-board charger with smart charging capability. This type of charger is integrated in the already existing motor inverter. The major objectives of an integrated on-board charger are reductions of manufacturing costs, maintenance costs, size and weight of the EV. Inverter bridge based chargers can be operated bidirectional. Hence, this type of charger also enables vehicle-to-grid (V2G) operation. In this paper several charging strategies as well as charger topologies will be presented and assessed. Furthermore, the concept of our fault tolerant integrated on-board charger is shown.

Keywords: electric vehicle, smart power grid, battery charger, charging strategy, fault tolerant system

1 Introduction

In the future, combustion engine based vehicles will be replaced by plug-in hybrid electric vehicles (PHEVs) and pure electric vehicles (EVs). The major objectives of this transition are reductions of emissions (e.g. CO2 gases) and noise as well as a significant improvement of the vehicles' energy efficiency. In addition, rising fuel costs and stricter emissions standards will accelerate this process of change. Hence, auto manufacturer and power supply companies will be faced with a lot of new technological as well as economic challenges over the next decades. Therefore, this paper is focused on cost-effective integration of EVs with the power grid by means of smart charging strategies and integrated on-board chargers [1].

The paper is organized as follows. Several charging strategies are presented and assessed in Section 2. In Section 3 we introduce different approaches for the implementation of chargers in EVs. The concept of our fault tolerant integrated on-board charger is briefly presented in Section 4. Finally, Section 5 concludes the paper.

2 Charging strategies

2.1 Simple charging and dual tariff charging

EVs are a new type of additional load on the power grid. The changes in the load profile depend on the number of EVs as well as on the used charging strategies. Hence, this paper deals with the following charging strategies:

- Simple charging
- Dual tariff charging based on simple time-of-use (TOU) pricing
- Smart charging

State-of-the-art charging strategies such as simple charging and dual tariff charging based on simple TOU pricing are not appropriate solutions for charging a larger number of EVs. In the case of simple charging, electricity costs are constant during the whole day. Hence, EVs start charging immediately when they arrive somewhere, trying to fully recharge their batteries [2]. Dual tariff charging is a well-known approach for shifting loads of households from day to night. Therefore, the electricity costs are low during the night and high throughout the rest of the day. Several research groups [2] [3] [4] have shown that both strategies causes peak demands such as morning and evening peaks. In these studies and simulations, profiles of other loads, different areas (e.g. residential, commercial, industry) and different seasons of the year have also been considered [3] [4]. Hence, a sophisticated charging strategy for the stabilization or reduction of peak demands in the load profile is required.

2.2 Smart charging

Higher peak demands and thus the necessity of extending the power grid can be avoided by means of smart charging. Further major objectives of smart charging are the reduction of electricity costs of consumers and the efficient integration of renewable energy sources. Hence, it also allows for monitoring the amount of electricity which is generated for charging the batteries of EVs by means of low carbon technologies. In the majority of cases smart charging is based on a novel smart power grid infrastructure. A smart grid is a combination of a power grid and a communication network.

A smart power grid includes an advanced metering infrastructure (AMI) and an appropriate data-communication infrastructure. It enables the smart charging as well as the vehicle-to-grid (V2G) operation on the grid-side. Hence, EVs can also be used as a distributed energy storage capacity (e.g. prevention of blackout). Furthermore, several energy control strategies and system architectures have been proposed by a number of research groups [1]:

- Local energy control strategy
- Global energy control strategy

- Centralized smart charging
- Decentralized smart charging

A local energy control strategy [1] optimizes local load profiles (e.g. load profiles of households). Hence, the operation of loads in households (e.g. washing machines) can be shifted to an appropriate time. In the case of a local energy control strategy a data-communication infrastructure and thus a smart grid is not mandatory. However, an AMI is required in every case. A global energy control strategy [1] optimizes load profiles of large-scale supply areas such as districts of a city. This control strategy is based on a smart power grid infrastructure. Furthermore, it offers more benefits than a local energy control strategy. In the case of centralized smart charging [1] a central entity (e.g. power supply company) controls the process of charging. The major drawback of this strategy is that it is impossible or difficult for consumers to influence this process. Hence, not all user requirements can be fulfilled. Therefore, it is more advantageous to utilize the decentralized smart charging [1]. It is based on the basic principle of a market place. A time-dependent price and generation fuel mix information is provided via the data-communication infrastructure. Furthermore, a software unit in the EV controls the process of charging. Further input parameters such as price limits are provided by the consumers. However, the major challenge of smart charging is the development of an algorithm for the calculation of the charging patterns. The system architecture of the smart grid is also of high importance.

Smart charging takes place either at the consumers' homes or at public places such as parking areas. Therefore, a division is made between smart charging at home and public smart charging.

Smart charging at home allows the charging of EVs when the electricity price is low or the generation fuel mix is less carbon intensive. It also considers other loads such as washing machines and refrigerators. The following different types of loads are known [3]:

- Critical loads
- Shiftable loads
- Interruptible loads

EVs are classified as shiftable loads. Smart EV charging at home will mostly be carried out slowly during off-peak time.

Public smart charging is mainly quick charging during daytime. The main objective of public smart charging is to charge the batteries of the EVs with the needed amount of energy during a defined time window. However, the electricity price is higher than average and the generation fuel mix could be more carbon intensive than average. Furthermore, both parameters depend on the moment of charging, the duration of charging and the amount of consumed energy. In addition, public charging infrastructure must be set up and maintained. It also increases the costs of the consumers. Quick charging also requires a three-phase power supply. The data-communication between the charging station and the EV can be realized by wire or wireless. In case of a wireless data-communication also the identification of EVs is challenging.

3 Charger topologies

All EVs must be equipped with chargers. Chargers are either unidirectional or bidirectional (e.g. inverter bridge based). A bidirectional charger is a combined AC/DC rectifier and DC/AC inverter. This type of charger enables V2G operation. Hence, EVs can also be used as a distributed energy storage capacity (e.g. prevention of blackout).

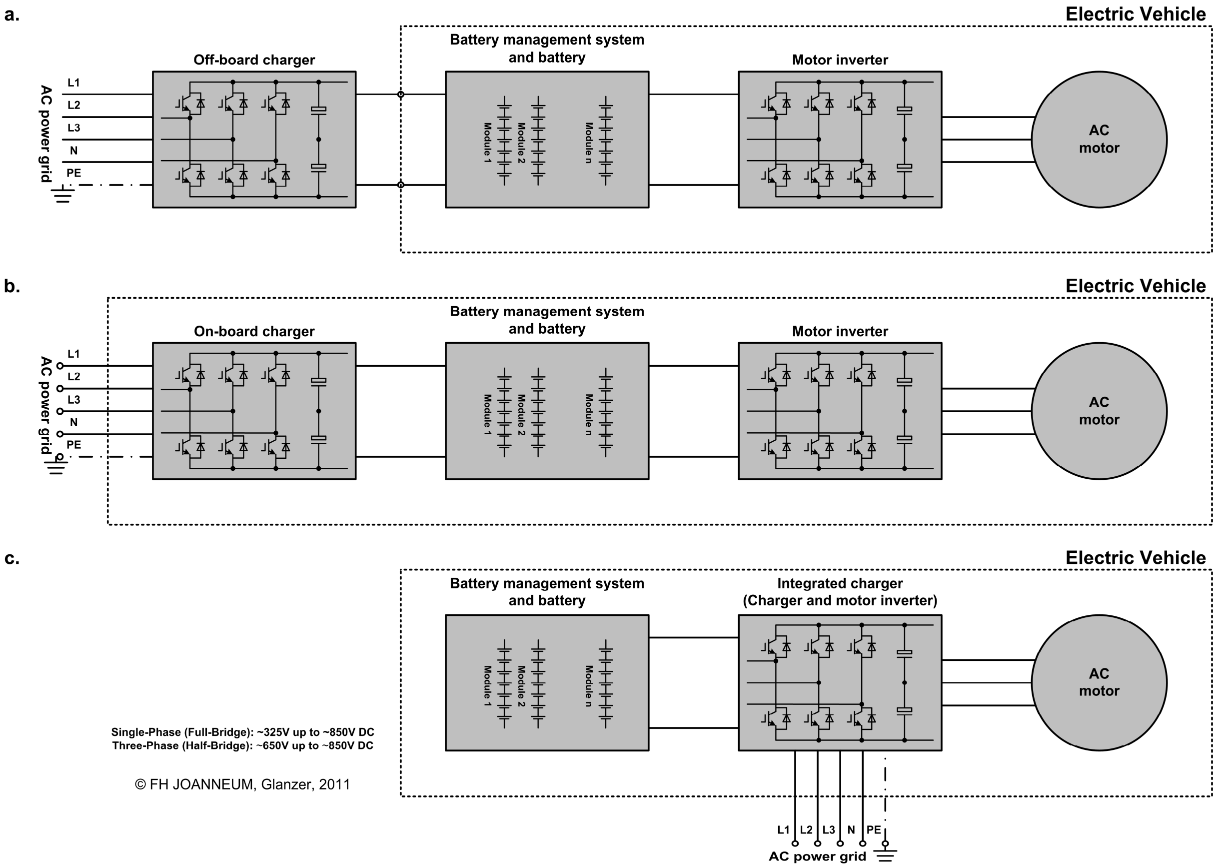

Figure 1. Block diagrams of (a.) an off-board charger topology, (b.) an on-board charger topology and (c.) an integrated on-board charger topology [1].

3.1 Off-board charger

In Fig. 1a. an off-board charger topology is shown. This type of charger is not a component of the EV. Hence, it supplies the EV with a DC voltage via the charging cable. In the case of public charging the off-board charger is a subunit of the charging station. Furthermore, the battery management system must be able to charge the battery of the EV with the provided DC voltage. Otherwise an additional on-board DC/DC converter is necessary. Hence, the major drawback of this topology is that it is impossible to charge the battery of an EV without a suitable charger on site. However, off-board chargers are well-suited for the quick charging of EVs.

3.2 On-board charger

In Fig. 1b. an on-board charger topology is shown. This type of charger is a component of the EV. The battery of the EV can be charged via an AC single-phase or an AC three-phase power supply. AC single-phase and AC three-phase sockets are available almost everywhere. In addition, the charger must be based on an inverter bridge to ensure V2G capability. The major drawback of this topology is that the EV contains two inverter bridges. One inverter bridge is a subunit of the bidirectional charger and the other one drives the motor. Hence, this topology is not the most appropriate solution.

3.3 Integrated on-board charger

Finally, in Fig. 1c. an integrated on-board charger topology is shown. As already explained, an EV contains at least one inverter for driving the motor. Therefore, the most efficient solution is to integrate the charger in the already existing motor inverter. Such a module is called integrated on-board charger [5] [6]. The major objectives of an integrated on-board charger are reductions of manufacturing costs, maintenance costs, size and weight of the EV. Hence, all power electronics components are concentrated in one single unit.

4 Concept of our integrated on-board charger

A block diagram consisting of our integrated on-board charger, a battery system and an AC motor is shown in Fig. 2. The diagram shows the bidirectional energy transfer from the battery to the motor (accelerating) and from the motor to the battery (braking). On the other hand, the bidirectional energy transfer from the battery to the power grid (V2G) and from the power grid to the battery (G2V) is shown.

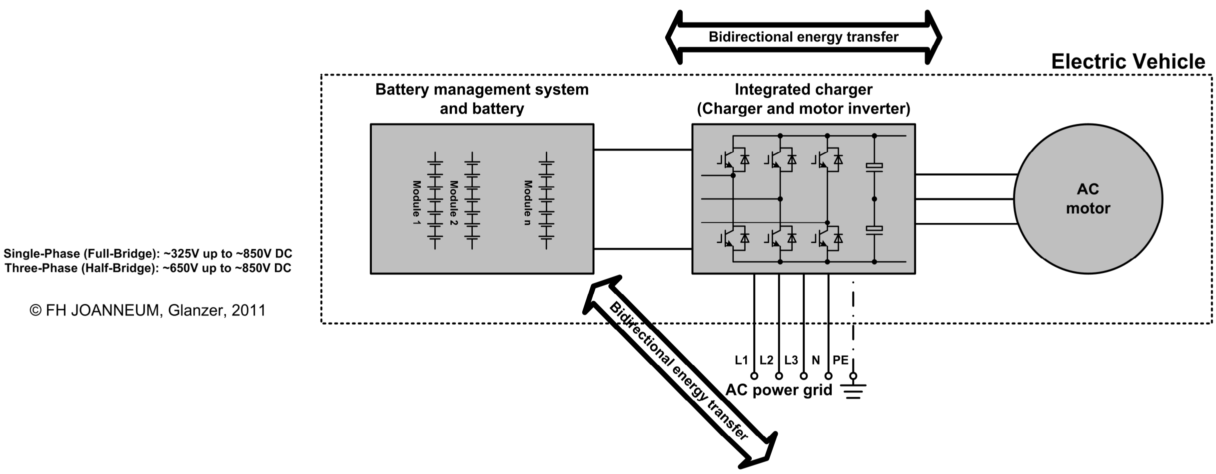

Figure 2. Block diagram of an integrated on-board charger topology.

Furthermore, in Fig.3. a detailed block diagram of the motor inverter sub-concept is shown. It gives an overview of a motor inverter and shows how it can be connected to the AC motor as well as to the battery system. However, it does not show the required measurement circuits in detail. The motor inverter consists of an insulated gate bipolar transistor (IGBT) module (inverter bridge), an IGBT driver board, DC-link capacitors, an adapter board for signal measurement and signal conditioning (voltage, current and temperature) and a microcontroller board. A field oriented control (FOC) algorithm, which runs on the microcontroller, generates pulse width modulated (PWM) signals for the IGBT module (inverter bridge). The measured voltages and currents on the AC side and the measured voltage on the DC side are the inputs of the FOC algorithm. In the case of an integrated charger the FOC must be extended by a voltage oriented control (VOC) algorithm and a mains filter is required.

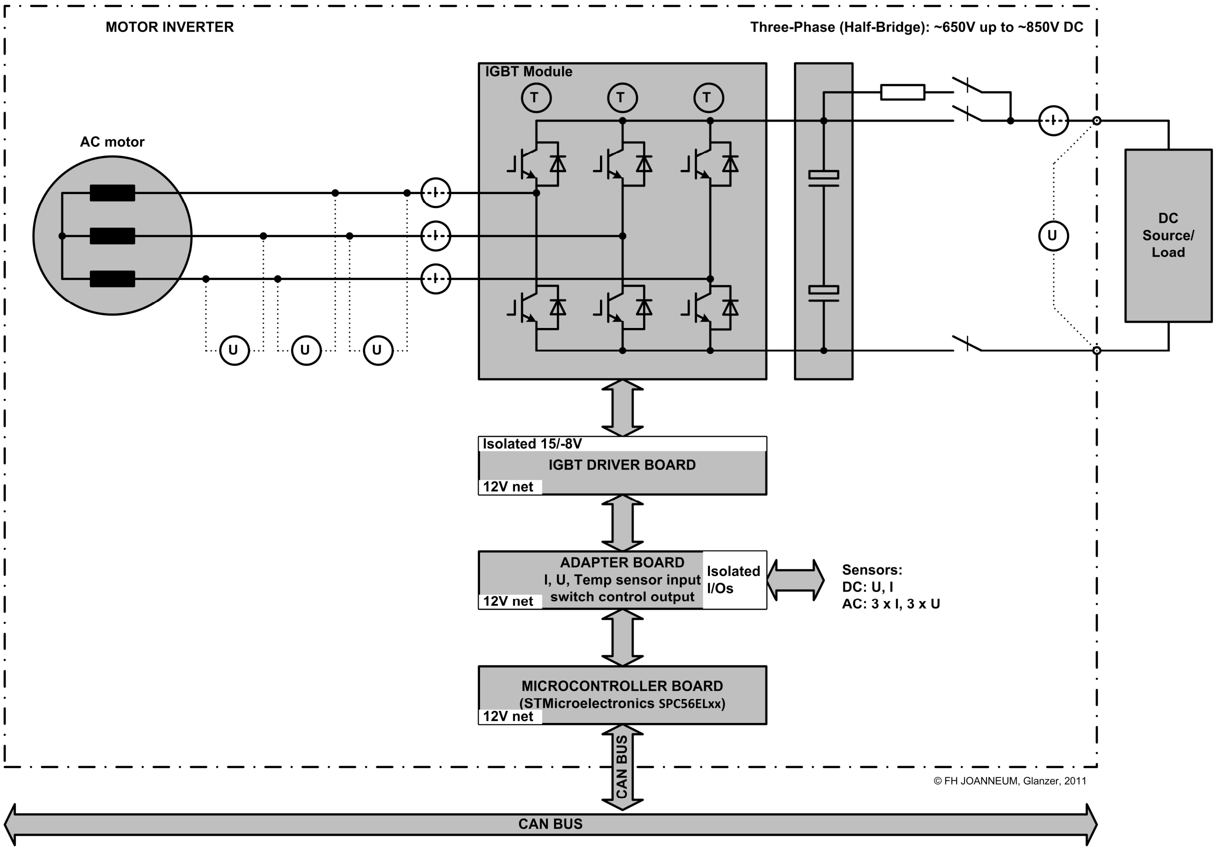

Figure 3. Block diagram of a motor inverter. The connections to the motor, the battery system and the CAN bus are also shown.

The major difference between a charger inverter and a motor inverter is that the motor inverter must be fail-operational in some particular driving situations (e.g. overtaking of other vehicles). Hence, in the case of a failure it must be possible to switch the motor inverter to a save state as well as to keep it switched on. This continuous operation of the system can be achieved by means of a redundant system. Therefore, integrated chargers must fulfill strict requirements in terms of fault tolerance.

The types of semiconductor switch faults are divided in single switch short circuits, phase leg short circuits, single switch open circuits and single phase open circuits [7] (Fig.4.). In the case of a semiconductor switch module (IGBT module) the whole module must be switched off if only one switch fails (three-phase operation). Hence, a promising approach might be to operate two or even more inverter bridges with the same or a lower output power in parallel (Fig.5.a.). The proposed method is based on a so-called cascaded inverter topology [7]. In the case of semiconductor switch modules which consists of one high-side and one low-side switch (half bridge) the whole leg must be switched off if only one switch fails (Fig.5.b.). Therefore, a fourth redundant leg is required. This method is based on a so-called phase redundant topology [7]. Finally, in the case of semiconductor switch modules which consist of only one switch (high-side or low-side) a faulty switch must be replaced by a redundant switch (Fig.5.c.). Hence, also a fourth redundant leg is required [8]. This method is based on a so-called double switch redundant topology [7]. In addition, all other components of the integrated charger must also be fault tolerant.

Furthermore, novel silicon carbide (SiC) MOSFETs and parallel interleaved inverter topologies are essential for the reduction of power losses and the size of passive components (e.g. inductances).

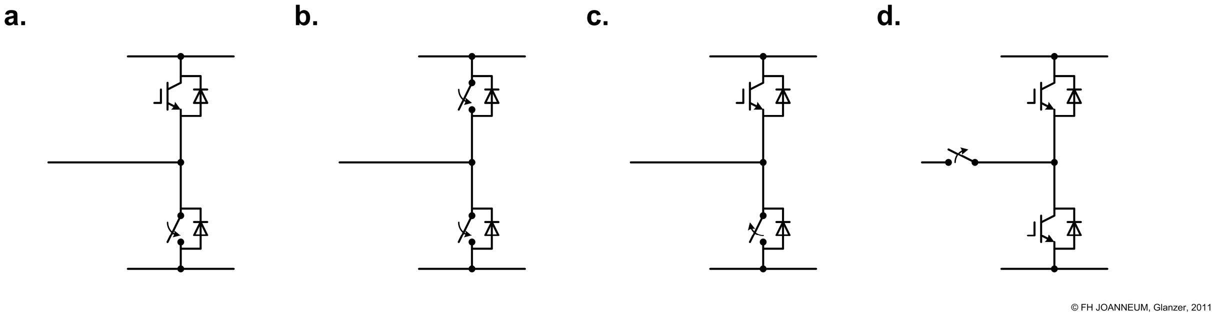

Figure 4. Semiconductor switch faults: (a.) single switch short circuit, (b.) phase leg short circuit, (c.) single switch open circuit and (d.) single phase open circuit [7].

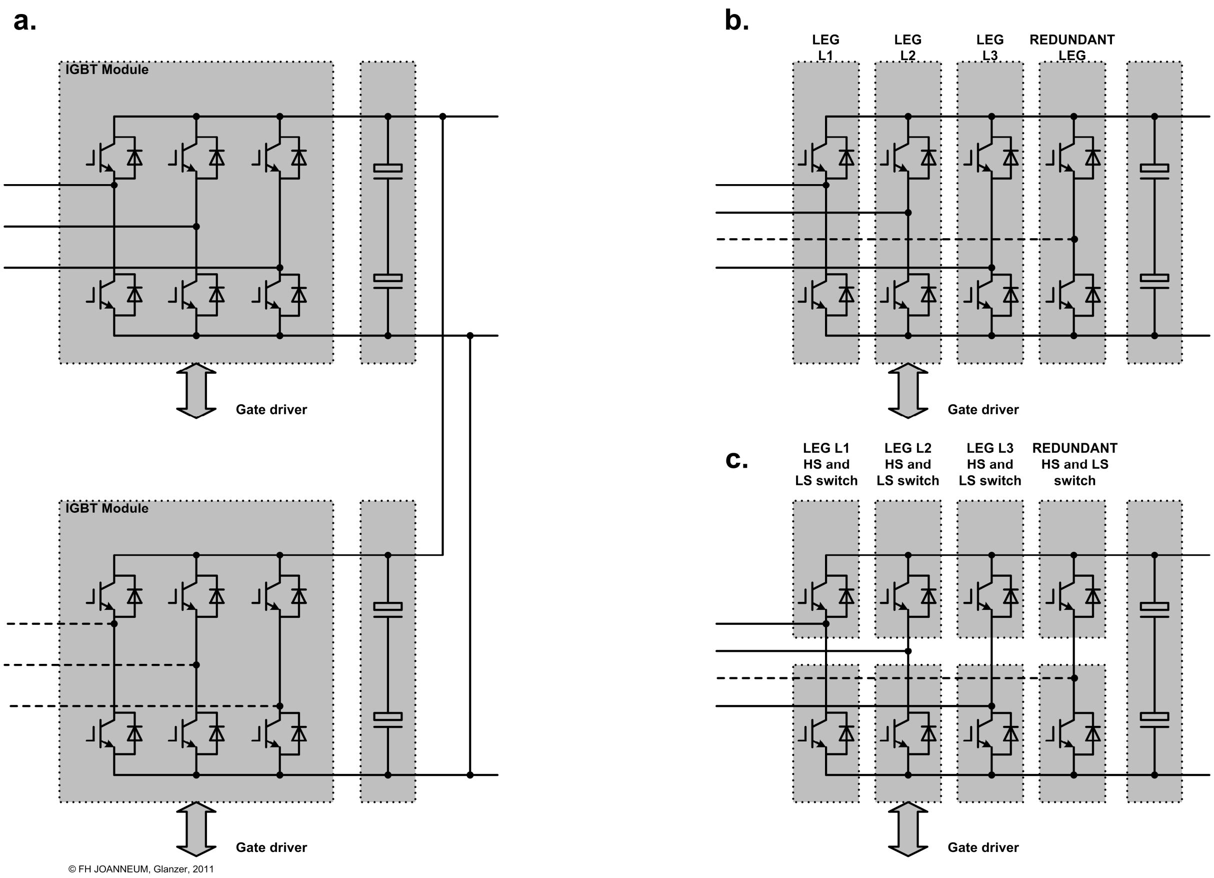

Figure 5. Redundant inverter topologies: (a.) cascaded inverter topology, (b.) phase redundant topology and (c.) double switch redundant topology.

5 Conclusions

Several energy control strategies and charger topologies have been presented and assessed. It has been shown that these strategies and smart power grids are required to avoid higher peak demands in the load profile. Furthermore, the most promising solution seems to be a global energy control strategy in combination with decentralized smart charging. Further major objectives of smart charging are the reduction of electricity costs of consumers and the efficient integration of renewable energy sources. Smart power grids and electric mobility opens up new possibilities in terms of demand-side management and distributed energy storage. Hence, they are also advantageous for power supply companies. The paper showed, that bidirectional integrated on-board chargers with smart charging functionality are necessary. The integration of the charger in the motor inverter is a cost-effective solution. Furthermore, the weight and size of EVs can be reduced using an integrated on-board charger. However, this type of charger must be fail-operational.

6 References

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