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Electrical protection systems for grid forming bidirectional electric vehicles in island grids

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Executive Summary

Now that unidirectional charging is largely mature, the market is focusing on applications and use cases which are enabled by bidirectional charging. From the perspective of electrical protection it must be ensured that all reasonably foreseeable risks are covered. Starting from the known European electrical systems designed for unidirectional charging, it is analyzed if adjustments in the protection systems are needed when the load becomes a source and the current flows into the other direction. From the technical perspective there are two use cases which must be distinguished. The grid following mode where the vehicle is feeding back energy while being connected to the external grid, and the grid foarming mode where the vehicle builds an island grid while being physically disconnected from the external grid. This paper focuses on the grid foarming use case with a single electric vehicle being the energy source within this island grid. The methodology of the risk assement is based on the CENELEC Guide 32 [1]. The main takeways are that further protective measures are required and that a harmonized approach on how to create island grids and how to ensure protection is required within the framework of standardization.

Keywords:V2H (vehicle to home), V2G (vehicle to grid), electric vehicle supply equipment (EVSE), safety, standardization

1 Introduction

The international standard IEC 61851 – *'Electric vehicle conductive charging system'* [2] is defining the safety relevant aspects of electric vehicle charging systems. In the current version of 2017 (Part 1) bidirectional charging is not considered. For the further development of the standard, it is necessary to analyze what risks arise from reversed energy flows and how these can be countered.

The objective of this paper is an analysis of the hazards and risks with regard to bidirectional energy flows from the vehicle into the AC grid using an AC or DC charging station. While the overall analysis was performed for V2H (vehicle to home) and V2G (vehicle to grid) this paper focuses on the off-grid (island) use case. Further local generation units like photovoltaic- or home storage systems are not considered.

Therefore, all potential faults within the system are analyzed and resulting fault- and over-currents are evaluated. In addition, exemplary remedial measures are shown for those cases for which the result of the risk analysis shows that there is an unacceptable hazard.

As a starting point for the analysis, the equivalent circuit diagram for unidirectional charging in TN grounding systems according to IEC 61851 is used, including protective devices that are state of the art in standard household connections in Germany (see figure 1). Mode 3 (AC) charging with galvanic isolation by using type 2 connector and Mode 4 (DC) charging using CCS2 connector is considered. Since this analysis focuses on island grid operation without connection to the external grid, a grid tie switch is placed behind the electrical meter at the grid connection.

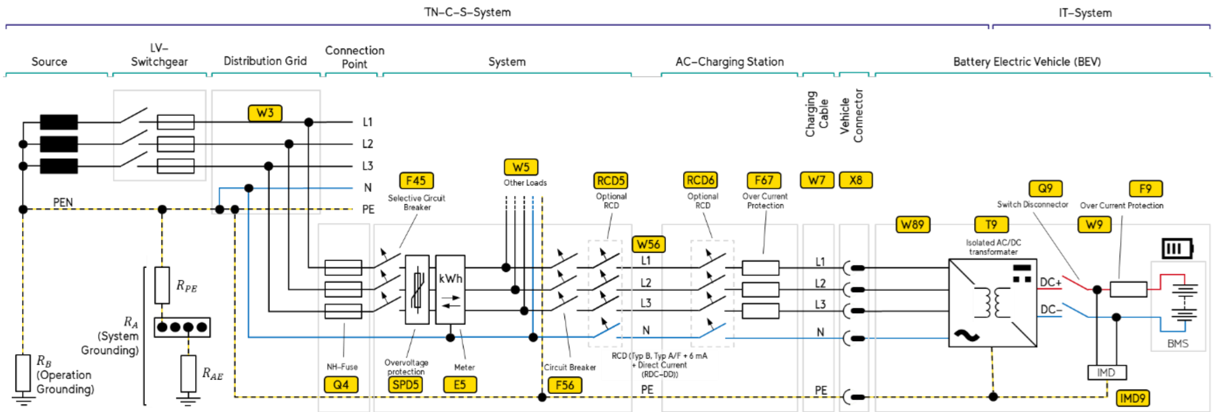

Figure 1: Electrical scheme of a 3-Phase low voltage grid with an electric vehicle connected over an AC charging station as single source. This represents a typical household installation in Germany.

2 Methodology

The analysis must ensure that all reasonably foreseeable hazards and risks are identified and covered. For this purpose, a risk analysis is carried out according to CENELEC Guide 32 - *'Guidelines for Safety Related Risk Assessment and Risk Reduction for Low Voltage Equipment for risk analysis and self-assessment'* [1].

There are different methods on how to analyze the correspoinding risk as described in IEC 61508 (functional safety - universal), ISO 26262 (functional safety - vehicles) or EN 60812 (FMEA - Failure mode and effects analysis). Nevertheless none of them match the specific needs for an analysis of an electrical low voltage system. Therefore the cenecl guide 32 was established to adapt different methods for this purpose. The guide, however, offers a very generalized approach and leaves a lot of room for interpretation as to how exactly the analysis should be carried out. For the systematic classification of hazards the risk graph shown in figure 2 is used. The risk is assessed according to three elements: extent of harm [S], probability / frequency of hazard & exposure [F] and prevention possibility [P]. This classification results in a risk index that indicates the need of risk mitigation.

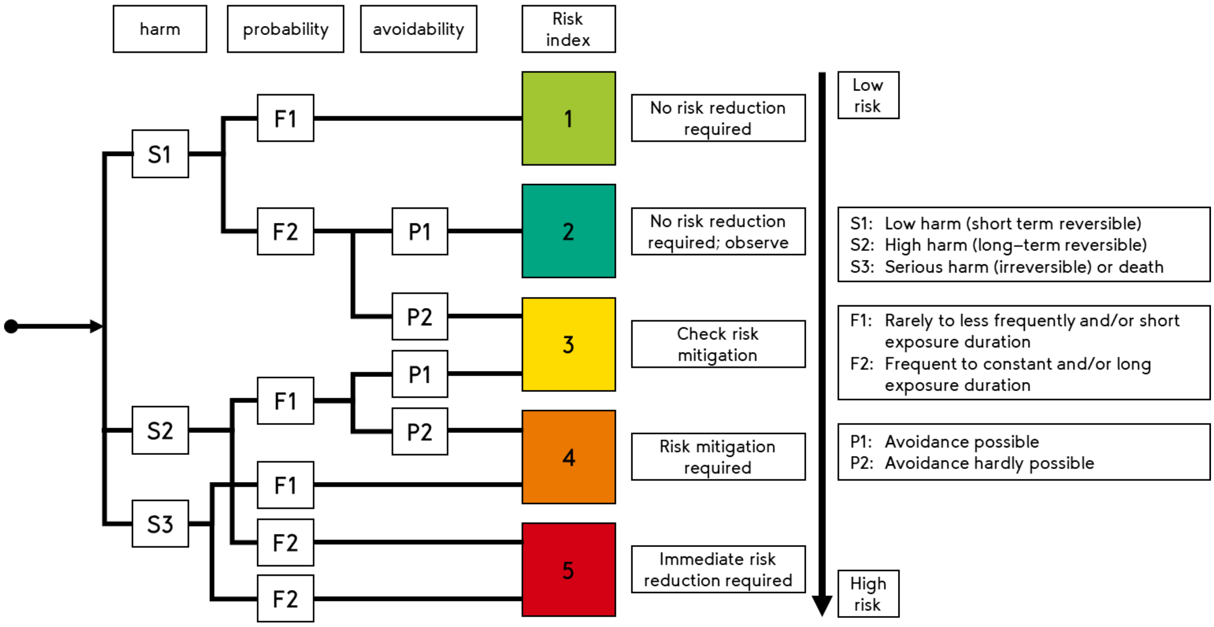

Figure 2: Risk graph for systematic classification of risks based on the Cenelec Guide 32

Within the Risk assessment described in this paper, the system is analyzed by the components of its electrical circuit diagram, which is close to the FMEA approach. In particular, all conceivable fault cases on the individual line sections are considered. Rather than focusing on the failure probability of existing protection components, the functionality of those with reversed energy flow direction is analyzed. The analysis is performed in a three step approach.

First, all thinkable potential faults are named for every component in the system by function, failure and impact of this failure. Therefore it is ensured that no dangerous risks have been overlooked. Some failures will not come with a critical impact and thus do not need to be considered in the risk analysis. For those that might be cirtical faults the risk graph is used to determine if a risk reduction is required (step 2). In the third step, potential measures to minimize the risk are investigated. It should be noted that no development work on the exact implementation of the safety measure are carried out as part of the risk analysis. Therefore, a functional description of the safety measure is given, at which point a hazard is to be eliminated and possible solutions are shown. This does not exclude the possibility that there are alternative ways to contain the hazard.

Finally, in the third step the risk is reassessed after the implementation of the safety measure. Here, a weakness of the applied methodology becomes apparent. Since, for example, the electric shock with damage severity S=3 always leads to a risk index of 4 or 5, regardless of its probability F, remedial measures are required. If the fault case is covered by an additional protection component, the risk still remains in principle the electric shock, so that one cannot get the risk index lowered below a threshold value that is acceptable. For this reason, it is assumed that the remedial action used ensures the protective function and the resulting risk in the next step is non-availability, which is not critical.

3 Functionality of protective devices for bidirectional energy flows

Table 1 contains a qualitative assessment of the most important active protection elements with regard to their functionality with reversed energy flows. Here, only the technical functionality of the components is considered, i.e. whether the components are physically influenced in their function by the direction of the energy flow. From this, it cannot yet be derived whether, for example, sufficiently high short-circuit currents can occur at all at a certain point in the equivalent circuit diagram with reversed energy flow direction or whether an RCD can see a fault in the specific case. This is considered within the risk analysis. There are special designs for some components which are only designed for unidirectional energy flow, these should not be used for bidirectional applications.

Table 1: Consideration of the active protection devices

Protection device	Influence current direction	Explanation
Fault current protection (RCD)	RCDs available with any feed direction	Measurement of the total current of the phases and neutral. Feed direction usually arbitrary. This must be assumed for bidirectional energy flows.
Overcurrent protection (OCP / MCB)	No impairment due to reversed current direction	Overcurrents trigger the switch by electron magnetism or heating, this is independent of the current direction.
Overvoltage protection (SPD)	No impairment due to reversed current direction	Prevent overvoltages due to lightning by means of varistors and are independent of the operating current.
Isolation monitoring (IMD)	No impairment due to reversed current direction	Monitor insulation by means of superimposed measurement signal. The process is independent of the operating current.

According to VDE 0100-722 [4] (par. 531.3.101), there are various options for installing the residual current device (RCD), which are shown in Figure 3.

An RCD is required for plug-in connections or end circuits or portable consumer equipment, but not for fault protection of distribution circuits (VDE 0100-722 [4] par. 531.3.6).

Incorrect combinations of RCDs can cause false tripping or blinding of (type A) RCDs. Therefore, type B RCDs must not be connected upstream of type A RCDs (VDE 0100-530 [5] par. 531.3.1).

In addition, VDE 0100-722 [4] (par. 712.531.3) states that type B RCDs must be used unless galvanic isolation is provided or EN 62109-1 [6] is met and the manufacturer declares that a type B RCD is not required.

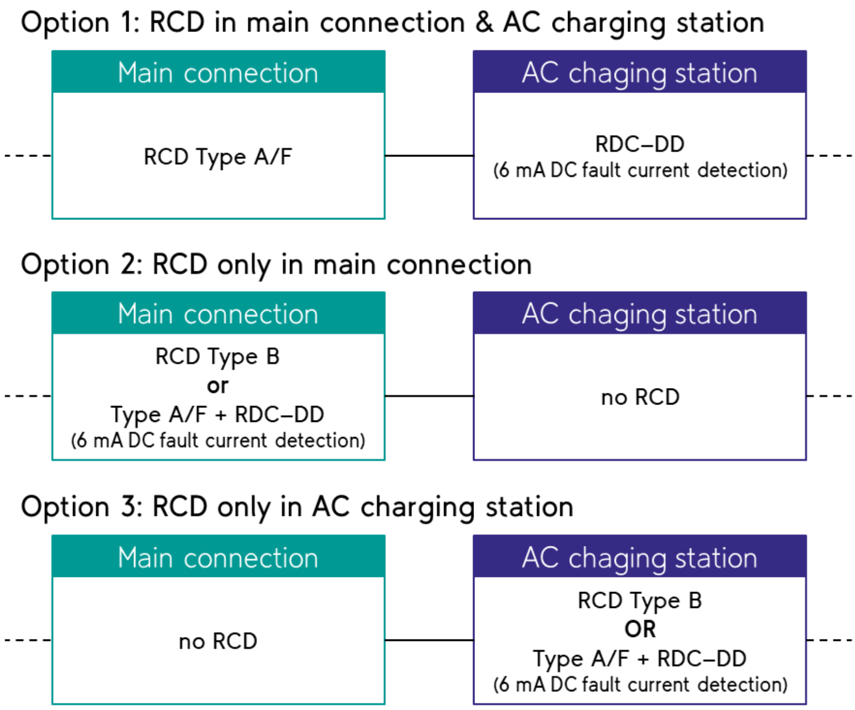

Figure 3: Possible arrangements for RCDs in mode 3 charging stations

4 Creation of island grids

In contrast to pure mains disconnection, where according to VDE-AR-N 4105 [7] (par. 6.4) only the three active conductors are to be switched for TN systems, according to VDE-AR-E 2510-2 [3] (par. 6.410) all-pole switching is required to create an islanding system. Hence, L1-L3 and N are disconnected to the external grid while the grounding of PE is still given. This results in losing the N-PE connection of the external grid and building an isolated IT grounding system. Since there is no requirement by standards to operate the island system with a specific grounding system, the vehicle manufacturer for the mode 3 (AC) use cases can decide either stay in an IT-System or build an N-PE bridge within the onboard charger, consequently building a TN-C-S system within the island again. For mode 4 (DC) use cases the system decision is oblied to the charging station manufacturer.

Figure 4 shows the disconnection of the external mains via the grid tie switch within the electrical scheme. The grey boxes covering the source, LV-switchgear, distribution grid and grid connection point illustrate that these are no longer physically connected.

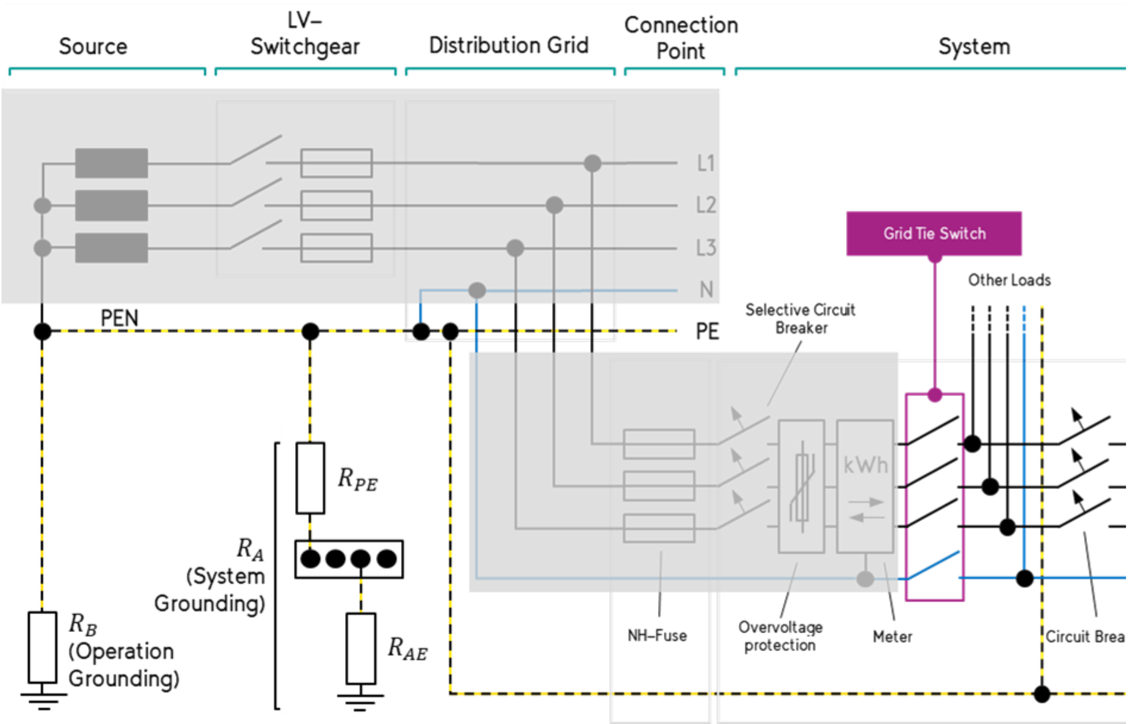

Figure 4: Isolated grid forming by means of grid tie switch

Both options for the grounding system have advantages and disadvantages and are considered within the risk analysis with their different behaviour in fault situations.

IT systems have some special behavior, so it must be ensured that other devices such as loads in such an isolated grid are compatible with this type of grounding. Since RCDs will not work within such a system anymore additional measures are required. According to VDE-AR-E 2510-2 [3] (Para. 6.410.2.1), an insulation monitoring device (IMD) must be provided as a protective measure.

In the alternative solution, a grounded (TN) system created by establishing a star point replica in the feeding converter by means of a connection between the neutral conductor and PE it must be ensured that this connection only exists while operating in island mode and is deactivated before returning to grid parallel mode. Therefore a safe communication with an appropriate safety integrity level (SIL) between the grid tie switch and the converter is required.

5 Results of the risk analysis

The risk analysis is applied to the electrical system shown in figure 1 by the 3-step mehtodolgy described in chapter 2. For the island system and the use case of mode 3 (AC) there are 15 elements to be taken into account with in total 57 potential faults. Of those potential faults, 16 are considered being critical and are taken to step 2. An example for the analysis of one element within this step is given in table 2 for a 3-phase low voltage end circuit within this system. Interruptions of active conductors result in non-availability which is not a critical state for a charging station. Therefore those cases are not further analyzed. On the other hand, short circuits or ground faults are further processed in steps 2 and 3.

Table 2: Possible faults on a line (TN System, 3-Phases, 230/400V)

Function	**Failure**	**Impact**	**Criticality**
Transmission of electrical energy	Interruption (L1-L3)	Not availability	No, non-availability is not safety relevant
	Interruption (N)	Not availability	No, non-availability is not safety relevant
Insulation of the individual conductors (L, N, PE) from each other	Insulation failure (L-N / L-L)	Overcurrent / Short circuit	Yes, overtemperature / fire
	Insulation failure (L-PE)	Overcurrent / Ground fault	Yes, electric shock
	Insulation failure (N-PE)	Short circuit	No: For IT system the fault loop cannot close. For TN system balanced potentials are ensured.
Contact protection (L1-L3)	Insulation failure (L-grounded parts)	Overcurrent via PE	Yes, electric shock
	Insulation failure (L-touch)	Touch current	Yes, electric shock
Potential equalization (prevention of possible touch potentials)	Interruption (PE)	Potential differences dangerous to touch	No: IT system: isolated system, interrupted IMD measuring loop leads to disconnection. TN system: double fault necessary, then RCD intervenes
Carrying short-circuit currents until cleared by protective elements	Interruption (PE)	Protective effect of automatic shutdown no longer available	No: IT system: isolated system. TN system: double fault necessary, then RCD intervenes

To make the fault cases comprehensible, the respective fault loops are drawn into the equivalent circuit diagram. As an example the error loop for a ground fault on an end circuit within the system is shown for the TN-System in figure 5. The N-PE bridge is added here already since otherwise the error loop could not close. In this case the RCD of the end circuit would see the fault the same way as it would be when the external grid would feed the error.

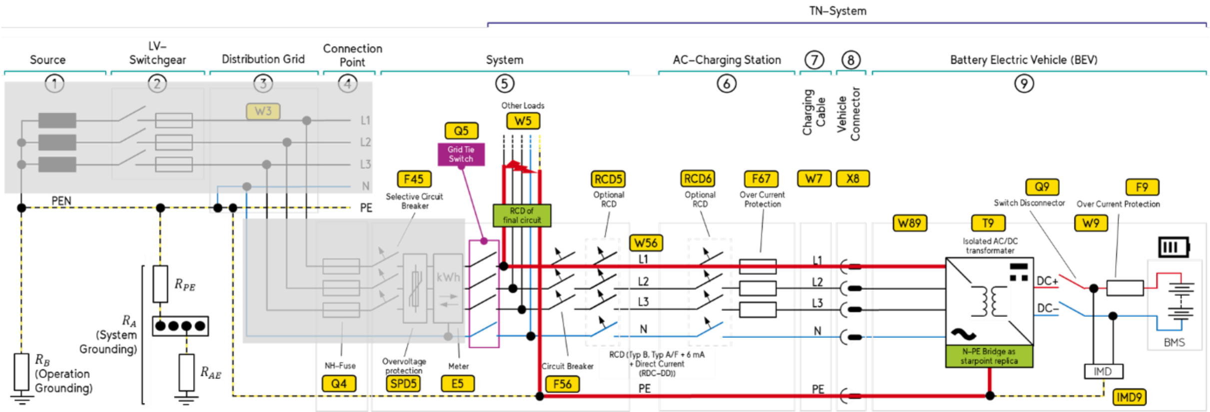

Figure 5: Electrical scheme of a 3-Phase low voltage grid with an electric vehicle connected over an AC charging station as single source. This represents a typical household installation in Germany.

5.1 Critical failure for island grids

The grid tie switch is identified as a critical component. It must be ensured that it is open before creating an island grid. Otherwise, other parts of the grid like a neighbour house could be unintentionally energized which could lead to dangerous situations.

Short circuits are critical independently of mode 3 (AC) or mode 4 (DC) systems since converters can not provide short-circuit currents higher than their rated currents. Isolating transformer in the inverter protects against short circuit of the battery. Therefore usual circuit breakers and fuses do not trigger. The converter must be able to detect any kind of short circuit e.g. by undervoltage detection.

Insulation failures resulting in ground faults or touch currents are more complex. It depents on the grounding system. For IT-Systems 1-pole fault does not lead to any direct hazard as no fault loop closes. Since the error must be detected, an isolation monitoring device (IMD) is a possible solution to solve this risk. If the island grid is grounded and operated as a TN-System it must be distinguished between mode 4 (DC) and mode 3 (AC). While other end circuits in the system are protected by their given RCD (see figure 5), the supply line from grid connection to the charging station is critical. Mode 4 (DC) Systems are fixed installations and the charging cable itself is on the DC side within an IT-System. Therefore the exposure to potential failures is much smaller. For mode 3 (AC) systems the charging cable which is pluggable and very exposed as well as the AC wire between vehicle inlet and converter are additional critical components. To detect a failure on those lines the converter must be able to detect ground faults. Hence an additional RCD very close to the converter is a potential solution.

6 Conclusions and outlook

In summary, the following conclusions can be derived from the analyses.

6.1 Fault detection close to generator

A critical fault identified is the mode 3 charging cable since it is very exposed and the protection systems for unidirectional charging systems can not see a ground fault in the bidirectional case. The AC/DC converter representes the generator for the electrical system. Therefore, it must be ensured that for Mode 3 (AC) use cases, the vehicle is able to detect and disconnect any kind of short-circuit and ground-fault situations most likley within the inverter or onboard charger. Consequently, for Mode 4 (DC) applications, the inverter in the charging station must be able to detect and disconnect any type of short circuit and ground fault situations. Existing components between the grid connection and the battery must be suitable for bidirectional operation. In particular, this concerns RCDs. It is the duty of the manufacturers to develop suitable concepts for this purpose but as part of the standardization process, it should be determined whether this is the responsibility of the vehicle or charging station manufacturers.

6.2 Creation of island grids

According to VDE-AR-E 2510-2 [3], there are various options for creation of an island grid with regard to the grounding system (IT or TN system). This results in different requirements for the necessary protection systems. Especially for the mode 3 (AC) use cases a common approach by all automotive OEMs should be forced to ensure interoperability. Furthermore, there must be safe communication between the mains coupling switch and the vehicle in mode 3 (AC) or the charging station in mode 4 (DC). This is currently not covered by the standardized systems and a safe communication in consideration of safety integrity levels (SIL) via a type2 charging cables is not possible.

6.3 Further electrical systems

This paper focus on TN grounding systems in 3-phase low voltage grids which are common in Germany. However there are further grounding systems like TT (e.g. Italy) or IT (e.g. Norway) as well as single-phase and split-phase low voltage grids (e.g. USA). Therefore a separate analysis is required to ensure all possible fault situations are covered. Since vehicles can pass borders and connect in different systems, for mode 3 (AC) use cases safety must be ensured for all potential types of grids with the same vehicle.

6.4 Microgrids and parallel generators

Grid foarming is relatively simple when there is just one generator within the system. Since there are also photovoltaic- and home storage systems available with island mode, those systems must be able to coordinate the different generating units. For neighborhood concepts, this could go beyond a single house and increase the overall blackout protection up to a self-sustaining system.

References

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Presenter Biography

Simon Haverkamp studied Electrical Engineering at the RWTH Aachen University in Germany with a focus on electrical power grids. He is working for over 9 years at umlaut Part of Accenture Industry X in the field of electric mobility. At this point he is managing the team which is responsible for technical and hardware related topics with respect to charging infrastructure. His team works on topics like technical and processual requirement analysis, risk assessments, conformity- and interoperability-testing for charging station manufacturers and -operators as well as automotive OEMs worldwide.