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GridShield—Optimizing the Use of Grid Capacity during Increased EV Adoption

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Abstract: With the increasing adoption rate of electric vehicles, power peaks caused by many cars simultaneously charging on the same low-voltage grid can cause local overloading and power outages. Smart charging solutions should spread this load, but there is a residual risk of incidental peaks. A decentralized and autonomous technology called GridShield is being developed to reduce the likelihood of a transformer's fuse blowing when other congestion solutions have failed. It serves as a measure of last resort to protect the grid against local power failures from unpredicted congestion by temporarily limiting the virtual capacity of charging stations. This paper describes the technical development and demonstrates how GridShield can keep a transformer load below a critical limit using simulations and real-world tests. It optimizes grid capacity while ensuring grid reliability.

Keywords: energy security; energy network; smart charging; load management; charging infrastructure; electric vehicles

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1. Introduction

Electric vehicles (EVs) play an important role in the transition to a more sustainable society. The charging of these cars, however, is putting a strain on the low-voltage electricity grid as their popularity grows [1]. New or larger grid connections for charging infrastructure are frequently delayed or rejected in the Netherlands for congestion reasons, and even higher vehicle electrification is still expected in the coming decade. In the coming years, some residential areas are likely to experience power outages because of the increased peak load from home chargers [2].

Replacing transformers and cables across the country to increase peak capacity in response to EV adoption forecasts and the electrification of heating is deemed impractical, if not impossible, and would drastically increase costs for all users [3]. Smart charging, tariffs, and market-based alternatives will be the primary solutions to mitigate peak grid congestion, but these are still being developed and are subject to regulatory changes. Furthermore, existing grid congestion solutions and technologies, as well as those currently being developed, are mainly focused on the medium-voltage grid and on daily or hourly forecasts. Therefore, the authors are developing GridShield, a decentralized solution to complement primary peak congestion mitigation. It helps to protect the low-voltage grid from local power failures caused by unexpected congestion by temporarily reducing the virtual charging capacity at charging stations. Preventing a power outage is good for both people who drive electric cars and people who use electricity in their homes or businesses.

1.1. Grid Congestion from EV Charging

The typical grid connection for a Dutch residential house is 3×25 A, which is approximately 17 kW. However, because traditional household electricity usage is much lower, the Dutch grid was designed for an average simultaneous power consumption of 1.5 to 4 kW per household, depending on the age of the grid. Home chargers for EVs, on the other hand, typically draw between 3.7 and 11 kW, and charging frequently occurs at the same time, which leads to a high simultaneity factor. With the projected increasing rate of EV adoption, it is expected that in a matter of years, typical behavior—such as charging the EV in the early evening after commuting—will easily exceed the physical limit of the low-voltage grid, resulting in regular local power outages. Simulations by ElaadNL show that, in a neighborhood with 250 households and 100 EVs, peak load can be exceeded daily if there is no implementation of smart charging; see Figure 1. The Netherlands is expected to have approximately 3000 such neighborhoods by 2025. Moreover, ElaadNL concluded that occasional peak overload could happen with as few as 50 EVs in a neighborhood [2].

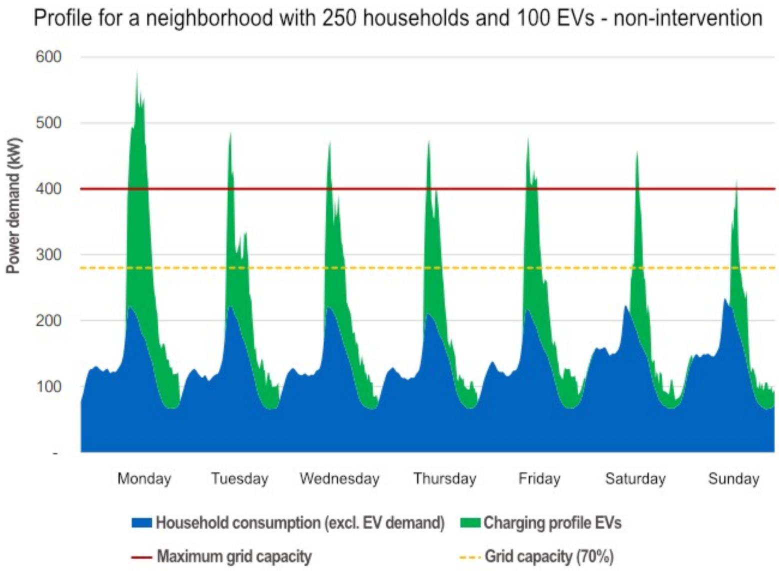

Figure 1. Uncontrolled EV charging is expected to cause regular power outages in 2025.

Smart charging solutions or (Home) Energy Management Systems ((H)EMS) should be able to spread many of these flexible loads within the current grid capacity if properly designed and implemented; see Figure 2. Schoot Uiterkamp et al. [4] have proposed a robust fill-level approach that utilizes baseload and energy generation forecasts to perform online control to optimally peak-shave a household load using an EV. Algorithms for smart charging and optimal integration within energy markets and distribution systems are a widely studied field. Many papers have surveyed different strategies to optimize and coordinate a fleet of electric vehicles. Vandael et al. [5] have proposed a scalable, three-step approach that utilizes the aggregated flexibility of a fleet of EVs to optimize the dispatch control signals towards charging stations. This serves as the foundation for an event-driven method that achieves optimal market integration in the face of EV arrival uncertainty [6]. Alternatively, optimization can be used to optimally charge EVs, such that they mitigate voltage problems in low-voltage distribution grids [7]. These are just a few examples from the literature on the optimal charging of one or more EVs with different objectives [8–10].

However, smart charging is not mandatory, and although price incentives can align with grid congestion problems, they are not a guarantee to protect the grid from peak load as grid limits are currently not enforced [11]. Furthermore, the market is still immature, and implementation is lagging [12]. As a result, the Distribution System Operators (DSOs) need a method of last resort to protect the grid from unforeseen congestion and to protect its users from the worst-case scenario: local power outages.

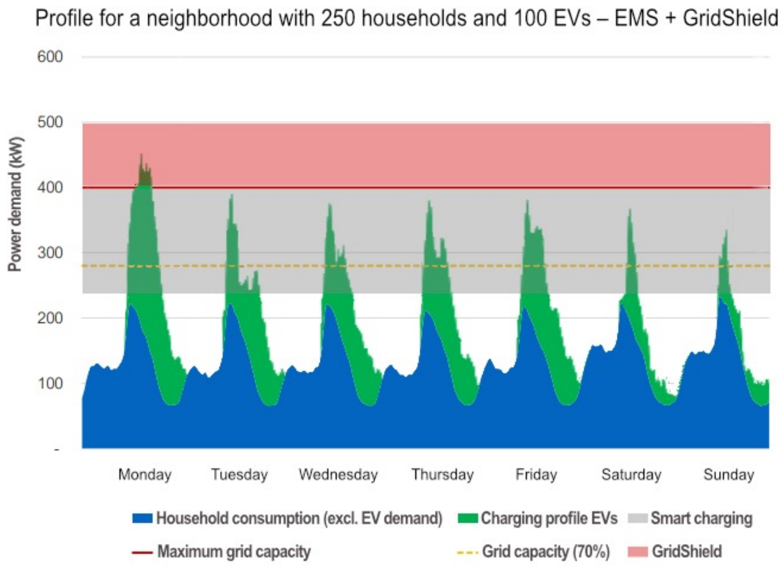

Figure 2. Smart charging can spread the EV load, but GridShield is needed to reduce peaks.

1.2. Robust Fall-Back Mechanisms to Prevent Grid Overloading

Although many smart charging solutions exist in the literature, these are not widely adopted in the real world. DSOs foresee local overloading problems in their networks due to EV charging in the near future due to rising EV sales. Hence, a protective control method is required to prevent outages in low-voltage grids due to EV charging.

By law, DSOs should maintain the distribution network but not interfere with the energy markets. However, it is not guaranteed that the energy market will result in a feasible solution with respect to grid limitations. Therefore, the Universal Smart Energy Framework (USEF) working group has come up with a traffic-light concept [13]. In this concept, the DSO is allowed to interfere with the market and impose direct control to resolve capacity and voltage issues. A similar concept is introduced by BDEW [14]. Next to this, a sort of direct control with the aim of protecting the grid is already implemented in PV inverters, which are obliged to cease production during times of overvoltage or overfrequency [15].

These developments have led to new methods for direct control over emerging technologies, such as heat pumps and EVs. These solutions can then coexist with market-based solutions and are to be activated during emergencies or if the market does not resolve overloading problems. Haider et al. [16] propose a scheme that optimally utilizes the flexibility of smart loads during contingencies. However, their solution relies on substantial coordination between local energy management systems and a central controller. This may introduce various vulnerabilities and failure vectors that can result in the malfunction of the system during critical moments in which the DSO relies on its operation.

Instead, it may be beneficial to have a very simple solution in terms of code and communication. Reduced complexity allows for the easier formal verification of algorithms to ensure that they work robustly under all circumstances. Furthermore, it reduces the cost of computation hardware, allows for fast execution and response, and avoids reliance on expensive solvers. Next, utilizing only one-way communication can harden these solutions against cyber-attacks (e.g., distributed denial of service (DDOS) attacks). One such simple method is the Smart Grid Ready interface, which allows DSOs to send signals to heat pumps to temporarily increase or decrease their power usage [17,18]. It is also shown that state information from the heat pumps, requiring two-way communication, has very little added value.

1.3. Contribution

This paper presents GridShield, a mechanism that grid operators can use in the near future to reduce interruptions in electricity supply and prevent damage to power infrastructure. It should reactively mitigate unpredicted events, such as congestion or EMS malfunctions, by instructing charging stations to temporarily reduce their electricity demand. GridShield is based on the aforementioned principles and acts as a mission-critical solution on which DSOs can rely.

The main functionality of GridShield is to protect low-voltage grids against unforeseen, temporary overloads that could cause service interruptions or premature wear. As a measure of last resort against local blackouts from EV charging peaks, GridShield will be designed to be robust, fast, and safe. Being designed by and for grid operators, it will have to take proportionality, privacy, and user experience into account.

Additionally, the solution provides feedback to the grid operator when GridShield is required to intervene, allowing for additional analysis of the local power grid. GridShield should also not introduce a new risk or point of entry for malicious actors, for instance in the form of cyberattacks.

The desired solution will play a critical role in the energy transition by ensuring the grid's continued operation while incorporating increasing EV charging demand. Thus, it helps to maintain a cost-effective power system. The primary solution to grid congestion is smart charging, which will take time, legislative changes, and good incentives to implement. Grid reinforcement as a temporary solution is prohibitively expensive and can take a long time to implement in the Netherlands due to shortages of both materials and personnel [3].

GridShield aims to help with optimizing the use of existing grid capacity and deploying reinforcements at the right time and location. Implementing GridShield is not a guarantee against power outages, but it minimizes the risk of it happening due to EV charging.

1.4. Scope

By clearly defining what GridShield does and does not do, we can maintain a robust and reliable implementation. There are already mechanisms in place for larger producers and users to protect the grid, such as re-dispatch and congestion management. However, these typically deal with national or regional congestion, not local, and they are not applicable to low-voltage connections. Therefore, the focus of our solution is:

- The low-voltage grid; the medium- to low-voltage transformer (10 or 20 kV transformed to 400 V), and low-voltage cables.
- All small customer connections, both with and without active energy management.
- Non-predictable, real-time situations.

To keep the implementation simple, the current scope deals with the most pressing issue: congestion of local low-voltage network sections that contain controllable and flexible power in the form of Evs. The emphasis here is on typical west-European low-voltage underground distribution grids, where the capacity of outgoing feeders from the transformer forms the main bottleneck. As such, this research currently assumes that overloading of underground cables and voltage issues do not occur as long as the feeders are operated within their rated capacity. However, when real-time measurements of the load on the cables are available, these can also act as steering signals for the GridShield commands, comparable to the way measurements of the feeders are used in this study. The GridShield concept is not limited to this grid situation, and can likely be adapted for use in other countries and situations where EV charging may result in an unexpected peak load.

Overload detection based on potential (volt) was considered but rejected. The voltage is not uniform across a cable, and the transformer's fuse reacts to an overload in current (ampere).

Protecting the grid by steering other high-capacity consumption devices or feed-in, e.g., PV panels or vehicle-to-grid, is a future development that fits into the GridShield concept. Decentralized electricity generation and feed-in have the potential to both alleviate and cause congestion. When recommending hardware and writing communication standards for the development of GridShield, we take care not to introduce any barriers to the future use of the technology in these situations.

The remainder of this paper is structured as follows: Section 2 explains the technical details of GridShield. In Section 3, we show results from both simulations and field tests. The results are discussed in Section 4, where we argue that GridShield can protect a transformer fuse from blowing in unforeseen situations or due to a lack of smart steering, and we also discuss further work. Finally, Section 5 summarizes our conclusions.

2. Materials and Methods

GridShield acts as a software-defined, dynamic fuse that intervenes in problematic situations before the transformer overloads by lowering the capacity of connections. Unlike a fuse that is binary, this software fuse can gradually lower the current to a safe level, preventing physical damage and power outages. With the transformer module communicating unidirectionally with one or more charging station modules, it mitigates unanticipated congestion reactively and autonomously by requiring flexible loads (i.e., charging stations) to temporarily reduce their electricity demand.

The following sub-chapters explain the technical design of the modules (Section 2.1), the control logic (Section 2.2), and how they are tested in reality and simulations (Section 2.3).

2.1. GridShield Modules

2.1.1. Design Overview

The GridShield system consists of two types of modules: a transmitter module and one or more receiver modules, as illustrated in Figure 3. At a regular interval, the transmitter module takes measurements at the grid transformer. According to internal control logic and parameters that can be set by the grid operator, it determines if the grid is overloaded or not. If the grid is overloaded, the transmitter will broadcast an over-the-air message with an instruction to reduce the maximum power that a charger can draw to a given fraction of the nominal capacity. The receiver modules in the neighborhood pick up this message. They will determine whether the message applies to their grid connection and then convert the message into an instruction for the charging station that is connected to the receiver.

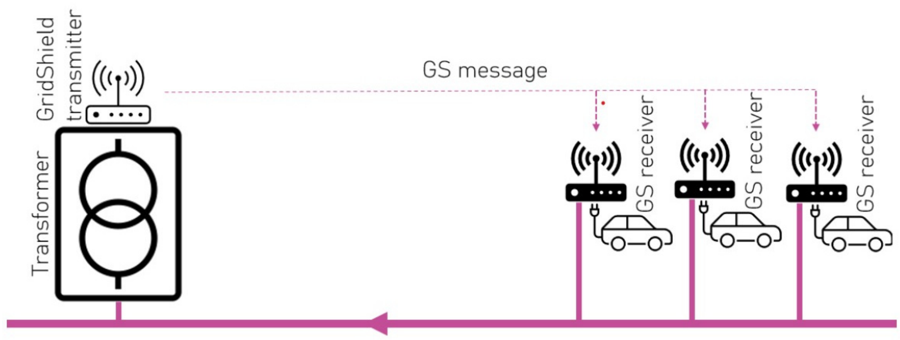

Figure 3. Schematic overview of the GridShield transmitter and receiver [19].

These modules work without any reliance on external infrastructure, such as wireless networks, internet service, cloud computing, or other forms of external processing or mediation. They also contain very little intelligence or analysis. This adds to their robustness, response time, and safety.

The transmitter module is installed inside the low-voltage transformer building, connected to a measurement device that is connected to the low-voltage cables. The interface between the transmitter module and the measurement device is usually in the form of some kind of data connection. The transmitter module must be programmed to communicate with the specific measurement device that is in use at the facility. At SlimPark, the test site described in this study, the measurement device uses a PAC-2200 controller with a ModBus TCP interface.

The receiver module is installed inside the charging station and is linked to the charging station controller, which controls the maximum allowed charging rate. The interface between the receiver module and the charging station is similar to the interface between the transmitter module and the measurement device. Charging stations usually implement a communication interface for such purposes. These interfaces, however, are non-standard, which means that the receiver module must be programmed to work correctly with a specific charging station type. In the test setup used here, the charging stations implement a ModBus TCP connection where writing to a single register will change the maximum allowed charging current.

Each charging station has one module installed. If there is more than one charging outlet, the charging station's internal logic is free to allocate the available current.

2.1.2. Communication between the Transmitter and Receiver Modules

The communication between the two sides of the GridShield protocol is unidirectional: messages are sent by the transmitter module and received by the receiver module. The transmitter module must be able to reach all the relevant grid connection points that it supplies power to. In the Netherlands, that usually means a required broadcasting range between 500 and 2000 m.

In the GridShield trials, LoRa radios of the type RFM95 were used in conjunction with off-the-shelf general-purpose mini-computer devices and interconnections. LoRa is a physical, proprietary radio modulation technique. It operates in the license-free sub-gigahertz radio band EU868 and has a real-world range of three kilometers [20].

2.1.3. GridShield Messages

The message transmitted by GridShield contains the following information:

- The relevant cable number that the limitation applies to. Each receiver module is pre-configured with a cable number based on the physical grid connection. Since multiple cables may run through an equally reachable area, the GridShield signals must be selective between these cables.
- The maximum value is expressed as a percentage $\phi(t)$ of the charging station's regular connection capacity $P_{\mathrm{EV}}^{\max}$, i.e., the charging station power allowed by GridShield becomes $P_{\mathrm{EV}}^{\mathrm{GS}}(t) = \phi(t) \cdot P_{\mathrm{EV}}^{\max}$. This implementation is further explained in Section 2.2.1. The receiver module is configured with a nominal grid capacity, usually equal to the contracted maximum capacity of the grid connection at the charging station. In the Netherlands, this is usually 3×25 A or 3×35 A.
- Fields concerning the security of the message are further explained below.

GridShield's most critical security requirement is that the receiver module is capable of determining whether a message it receives is legitimate, i.e., that it was transmitted by the actual trusted transmitter module connected to the relevant grid transformer. For GridShield, the messages contain the following elements that make this possible:

- The time at which the message was sent. Messages older than some predefined age are discarded by the receivers. This prevents malicious transmission or the accidental retransmission of an earlier, valid message.
- A random 4-byte nonce; the receivers remember each of these "nonces" as long as the message is valid according to the previous criterion. This prevents a valid message from being retransmitted within the cut-off period.
- A cryptographic signature; the transmitter module has an embedded private ECDSA key, which is used to sign the contents of the message. The receiver modules have the accompanying public ECDSA key, which can be used to verify that the message (1) was signed by the corresponding private key and (2) that the message was not altered after it was signed.

These three components mean that each GridShield message can be sent unencrypted through the air while still ensuring trust between the receiver and the transmitter. By embedding the private key in a dedicated hardware component, it is impossible to retrieve the private key from the transmitter module. The public key does not need to be kept secret and can be published by the grid operator to allow trouble-free installation of additional receiver units in the area after the initial provisioning of the transmitter module.

2.2. Control Logic

2.2.1. Transmitter Algorithm

The GridShield transmitter must determine which signals to broadcast after reading the measurements from the low-voltage substation. This can be considered a classic control loop, and as such some classic control algorithms can be considered. Research reported in [6] tested and compared three GridShield implementations with respect to power limit violations and energy not served to EVs: (1) AIAD (Additive Increase, Additive Decrease); (2) AIMD (Additive Increase, Multiplicative Decrease); and (3) PID (Proportional–Integral–Derivative). The authors conclude that AIMD performed best as a control strategy for overloaded distribution grids. Hence, this control scheme is used for implementing the GridShield concept simulations and the presented real-world tests.

The AIMD algorithm was originally developed for the fair usage of limited bandwidth on the internet, but has recently been used, e.g., for power grid stabilization [8]. The GridShield implementation of AIMD in this work is based on [19,21] and is presented in Figure 4. We see that when the GridShield transmitter detects an overload at the transformer, i.e., $P_{\text{trafo}}(t) > P_{\text{trafo}}^{\text{max}}$, it will decrease the maximum charging power factor $\phi(t)\beta$ by a multiplicative factor $\phi(t) = \beta \cdot \phi(t-1)$. When the $\phi(t)$ problem is resolved, the algorithm enters the additive increase phase, where αy by a factor $\phi(t) = \phi(t-1) + \alpha$.

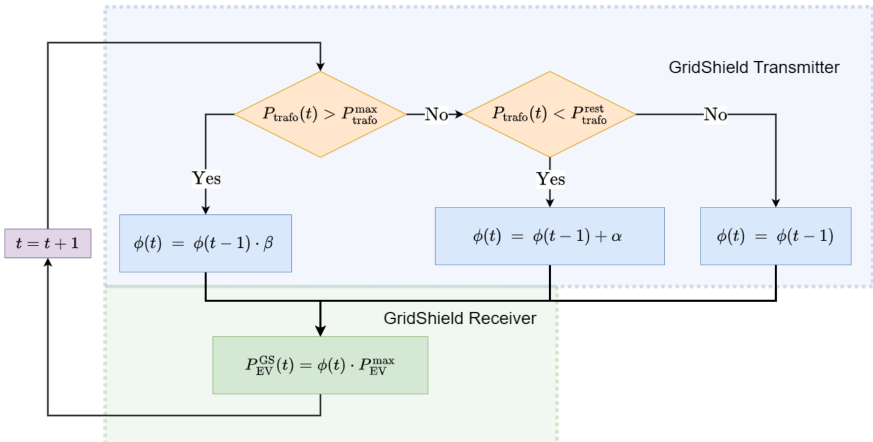

Figure 4. Block diagram of the AIMD GridShield algorithm. Blue: sender-side implementation. Green: receiver-side implementation. Adapted from [21].

Notice that oscillations between the increase and decrease phases may occur around the transformer limit if we start the increase phase immediately when we are below the limit. Thus, a deadband is introduced to prevent them. The power is reduced until it is below the limit $P_{\text{trafo}}^{\text{max}}$, but the increase phase is only entered when the transformer power is below a certain *restoration limit* $P_{\text{trafo}}^{\text{rest}}$. Effectively, the algorithm does not change $\phi(t)$ when $P_{\text{trafo}}^{\text{rest}} \leq P_{\text{trafo}}(t) \leq P_{\text{trafo}}^{\text{max}}$. Using multiplication to decrease the load means that the initial steps cause a larger decrease, while further steps are more granular. This allows a fast initial response to an overload event, and a more fine-grained control to further lower the allowed current. The upwards trajectory is a fixed step increase, preventing the algorithm from increasing the power too quickly.

The specifics of the control algorithm can be further optimized to meet one or more objectives, such as:

- Minimize overloading the transformer.
- Maximum use of capacity, i.e., being close to the limit of the transformer, comes at the cost of more fluctuation in the charging session.
- Limit the number of GridShield messages.
- Fairness amongst EVs.

2.2.2. Receiver Control Logic

The receiving module multiplies the received percentage value (for instance, 60%) with the configured grid connection limit to arrive at the current limit (ampere) used for the charging station. A complicating factor is that some EVs need a minimum of 6 A to charge. If the GridShield signal results in a limit lower than 6 A, vehicles could stop charging. Aside from the possible under-utilization of the electricity grid in such a case, the sudden halt in charging by many vehicles can result in a large swing in power. This, in turn, could lead to oscillation of the control system after the power is increased to the equivalent of >6 A per charging station.

A possible solution to this issue in an area with several charging stations would be for the receiver module to perform randomization to determine whether to continue charging at 6 A or to cut it off completely at 0 A. If, for example, the current limit results in a 5 A charging limit, the station could use a 5/6 random chance to let the station continue at 6 A and a 1/6 chance to turn the charging off at 0 A. In aggregate, this results in an average charging current of 5 A across many charging stations.

2.3. Living Labs and Simulations

GridShield is being implemented and researched in three living labs of different scales, contexts, and users: at the University of Twente (UT), Province House Zwolle, and at the world's largest, bidirectional charging car park at insurer a.s.r. in Utrecht [22]. All three locations combine solar energy, charging stations, batteries, and an Energy Management System. The users vary from short-stay visitors to full-day parking. Furthermore, SlimPark (UT) researches the end-users' needs and preferences via a link to an app that provides insight into how and when the generated solar energy can be distributed as efficiently as possible among the plugged-in cars.

The GridShield implementation is being simulated for validation and optimization in DEMKit. DEMKit, an open-source toolkit developed at the University of Twente, simulates devices, grids, and control components for researching multi-energy systems [23]. A validated model of a neighborhood in Lochem [1] was used to simulate GridShield interventions in a typical Dutch residential neighborhood.

3. Results

3.1. GridShield Prototype

3.1.1. Hardware- and Software-Agnostic Modules

The hardware for the transmitter and receiver units is identical. A custom software application written in Python is used to perform the required operations. The first GridShield prototype modules are built using the following off-the-shelf hardware components:

- A Raspberry Pi 2 Model B.
- A LoRa "hat" for the Raspberry Pi, based on the SX126X LoRa radio module.
- A standard 20 cm long, 900 MHz-range, SMA-connected antenna.
- An HD44780-compatible display unit for configuration and monitoring during tests.
- Connections to the measurement device and the charging station were made via the regular on-board Ethernet port to transport ModBus TCP messages.

A global supply chain shortage of relevant components prompted the development of a second set of prototypes. These use an industrial Linux-based mini-computer with on-board serial ports (Artila Matrix 500). A custom PCB carrying the RFM95 LoRa radio was developed, which connects to the Matrix 500's on-board SPI interface. These Linux boxes do not support the Python programming language; therefore, the GridShield application code was ported to C to run on these devices. As a result, it has been established that the concept is software- and hardware-agnostic. The modules are designed to be easily installed and to connect to an existing metering system (on the transmitting side) as well as to the charging post (on the receiving side). Once connected, the modules work autonomously.

3.1.2. Privacy and (Cyber) Security

GridShield works in a controller–agent setting. Charge points—agents—listen to a controller unit in the transformer. Because communication is one-way, cryptographically signed, and only local, i.e., not through the internet, the attack surface of the software environment is reduced. Furthermore, the module does not gather and store privacy-sensitive data. The only data registered are the load on the transformer and when and how GridShield intervened.

An inherent characteristic of GridShield is that it provides protection for the grid against some large-scale, remote cyberattacks. Protection against overload attacks follows automatically from the way GridShield intervenes when the technical boundary of the grid is exceeded. Other attacks, such as oscillation attacks below the maximum capacity, cannot be mitigated by GridShield.

Furthermore, the solution must be applicable to existing infrastructure, which means that it can only control the maximum allowed charging current. Other information, such as user preferences and the state of charge, is currently not communicated to the charging stations in practice, and is unavailable to GridShield due to the one-way communication.

3.2. DEMKit Simulations

DEMKit simulations, reported in [24], tested the effectiveness of GridShield in a typical Dutch neighborhood with 80 single-phase connected households and one EV charging station per household. Each EV has a battery capacity of 100 kWh and can charge at a maximum power of 7.4 kW (equivalent to 32 A). The arrival and departure times of the EVs and the required amount of charging, as well as the base load power profiles of the households, have been generated by the Artificial Load Profile Generator [19].

Figure 5 shows that 80 EVs in a typical residential neighborhood will drastically overload the transformer if there is no smart charging or energy management applied ("uncontrolled"). This scenario can also represent a situation in which the connection between charge stations and the back office that sends smart charging profiles is faulty or disrupted, causing charge stations to revert to a maximum charge setting. Using GridShield, a power outage is avoided with an acceptable delay in charging time.

The scope of GridShield is limited to dealing with temporary, local, unforeseen situations, with smart charging or an EMS primarily protecting the grid from overloading. However, when other solutions fail or are not implemented, these results show that GridShield functions as a coarse but effective EMS.

3.3. Real-World Test: SlimPark

The SlimPark Living Lab on the campus of the University of Twente is a solar carport with integrated charge stations connected to a real-time dynamic energy management system. The grid connection, acting as the transformer in this experiment, powers nine EV chargers and a battery. To test different scenarios, the power levels of four chargers, as well as the solar array and the battery, can be manipulated. During tests, GridShield intervenes and lowers the power of these four EV chargers when necessary, such that the power drawn from the grid stays below a pre-defined limit.

3.3.1. Scenario 1: Additional Car Triggers GridShield

In the scenario demonstrated in Figure 6, three EVs are charging and the load is just below 60 A, which is the fictive transformer limit within this test setup. When EV4 starts charging, the current exceeds this limit.

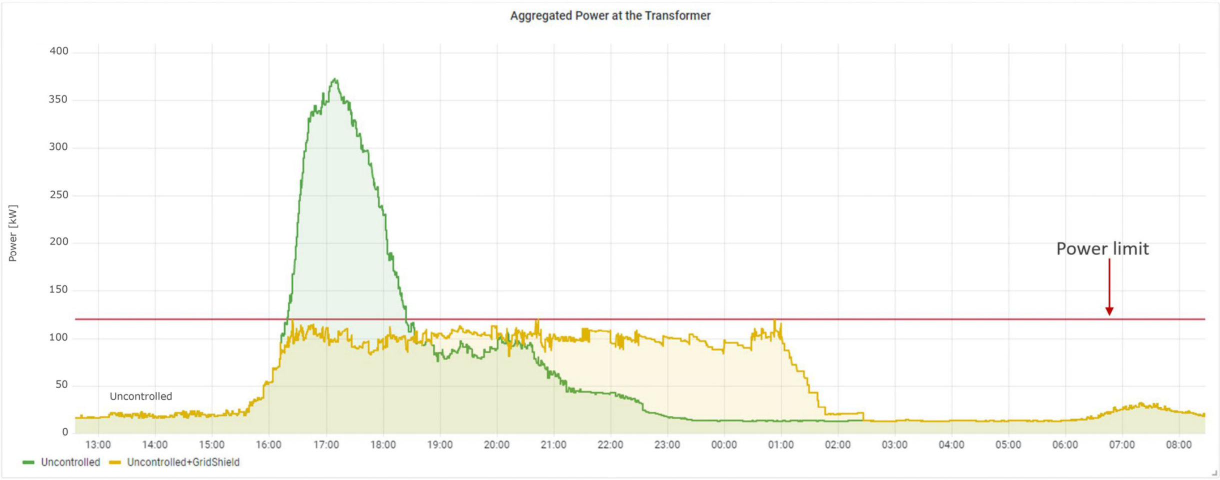

Figure 5. Digital twin simulation of a Dutch neighborhood with 80 EVs.

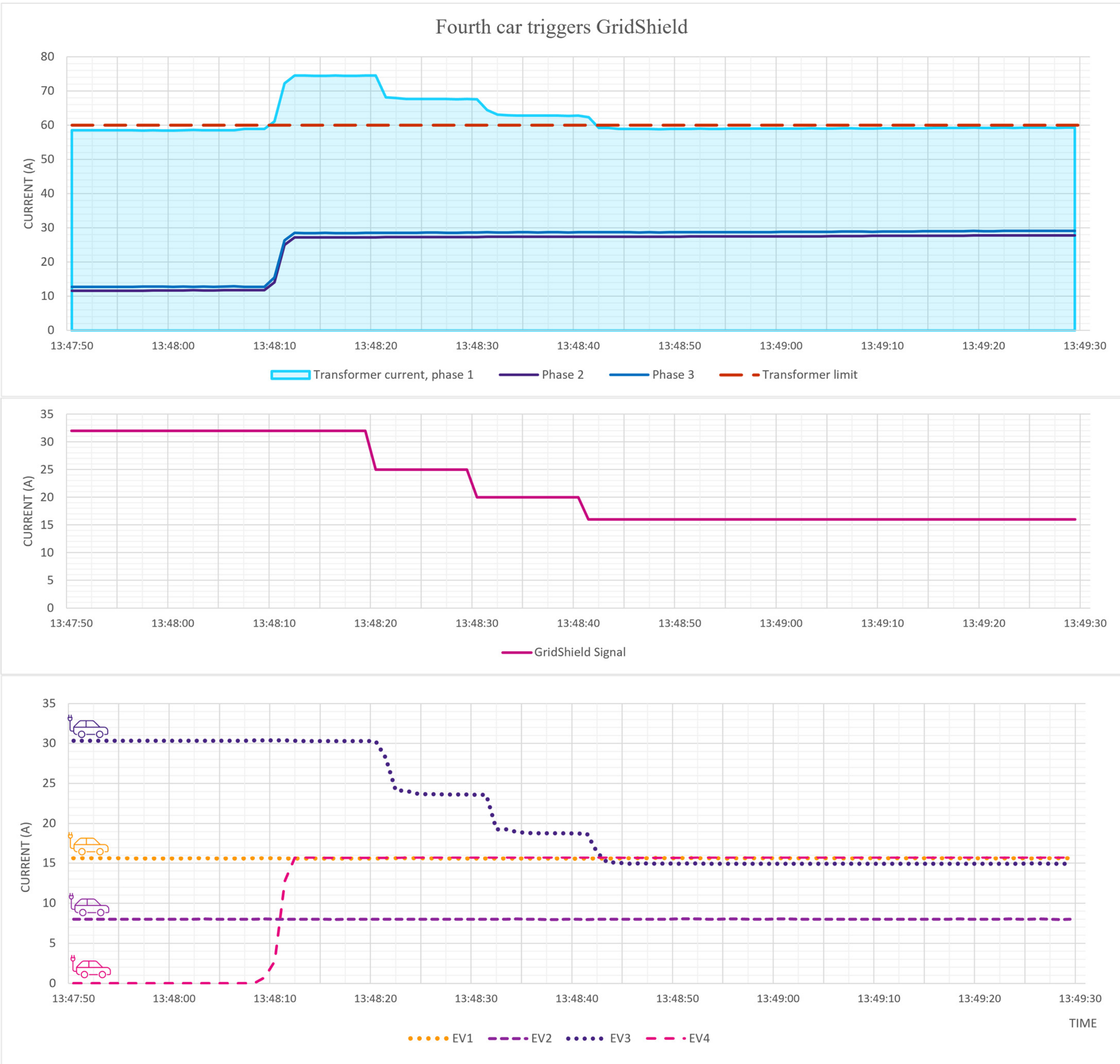

Figure 6. Transformer current, GridShield signal, and EV charging when an additional EV overloads the system.

Maximum charging power of the vehicles prior to GridShield intervention:

- EV1: 16 A, phase 1;
- EV2: 8 A, three phases;
- EV3: 32 A, phase 1;
- EV4: 16 A, three phases.

GridShield intervenes, lowering the maximum current allowed on the chargers to a new stable value of 16 A. We see that only EV3 is affected by the GridShield signal, because it is the only one charging above 16 A. In this experiment, GridShield required three iterations of decreasing control signals before the current was at a safe and stable level. In this case, a gradual decrease was a safe option that avoided excessively harsh interference in the charging. Depending on the nature of an energy system, the GridShield response can be programmed accordingly.

3.3.2. Scenario 2: Additional Car and Increased Baseload

Initially, this scenario is the same as scenario 1, but here changes to the base load are added; see Figure 7. We mimic an increase in base load by letting a battery located at the pilot site draw more power. At 14:01:17, the underlying base load increases and counteracts some of the decrease achieved by GridShield. In reality, this could be caused by heat pumps or any other type of high-power device.

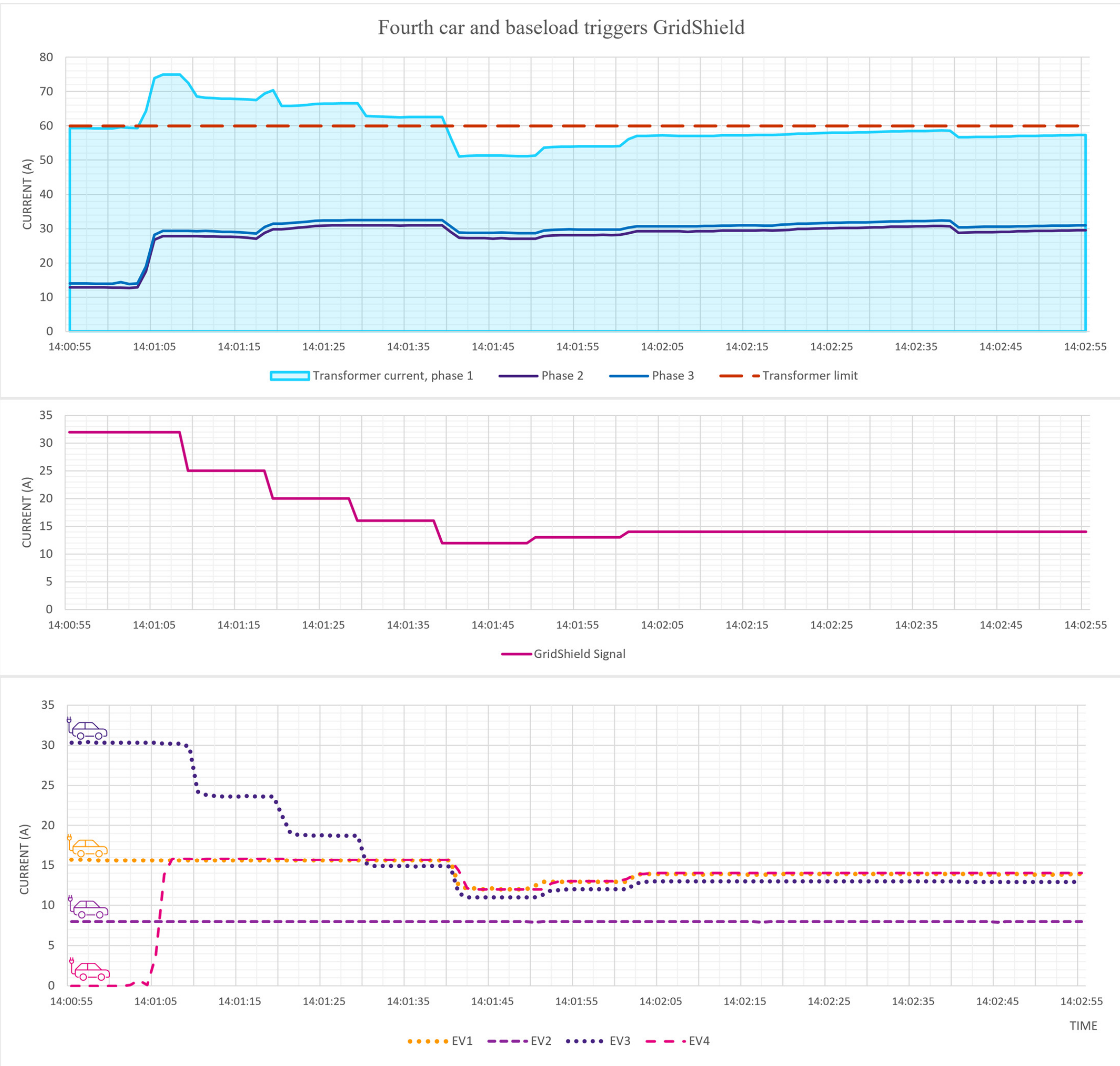

Figure 7. Transformer current, GridShield signal, and EV charging (ampere).

Due to the increased baseload, GridShield has to intervene more than in scenario 1. Charging has been decreased to 12 A, which affects all cars except for EV4, which is charging at 8 A. GridShield then determines that there is sufficient capacity on the transformer to safely increase the charging limit. Increases are made in 1 A steps until a stable situation is reached at 14 A.

GridShield lowers the virtual capacity of the charge stations, so EVs charging at a higher capacity are affected first. The power charge of cars charging at a lower capacity but on three phases, EV2 and EV4, is affected less or later by GridShield intervention, as illustrated in Figure 8.

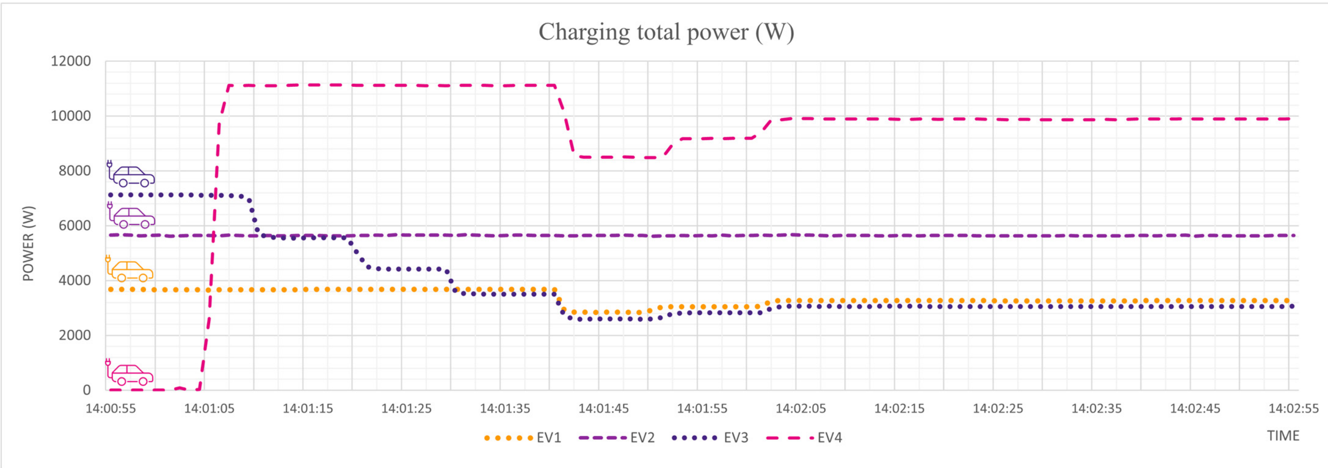

Figure 8. Total charging power per EV, during GridShield intervention.

4. Discussion

4.1. Discussion of Results

Simulations and real-world field tests demonstrate that GridShield can prevent local power outages. It functions as a software-based smart fuse that intervenes before the physical fuse in the transformer is overloaded, by temporarily and gradually reducing the capacity of charge stations following the programmed AIMD algorithm. We have simulated and tested many different scenarios, and plan to test even more, and on a larger scale, in our living labs. GridShield consistently intervenes and restores the current to a safe level, allowing charging to resume at its initial rate when it is safe for the grid.

As previously stated in Section 2.2, the algorithm settings can be changed to suit different preferences and circumstances. Both scenarios demonstrate the usefulness of the AIMD algorithm: decreases are large in the beginning to have a swift effect, and increases are gradual to keep the system safe. It touches on the balance between reacting fast enough but not overreacting. While a transformer can tolerate being overloaded for a period of time, it is undesirable and causes component wear. At the same time, it is desirable to minimize the impact on EV users.

GridShield intervenes if the current on any one phase is over the threshold, but the signal to the charge station applies to all phases. To keep GridShield robust, fast, and safe, its functionality is simple and does not take phase imbalance into account. Steering per phase adds complexity. Additionally, most currently available chargers are not technically capable of steering charging per phase. There is a role and incentive here for smart charging and technical innovation to manage phase imbalance. Charging power (W) is less of a problem for the local grid if the charging is spread over all three phases.

Based on the available measurements in the transformer, GridShield can react when *one* cable is overloaded, sending a signal to charging stations on that cable, or it can react when the sum of the cables is overloaded. When a charging station is installed, it should be linked to the appropriate GridShield transmitter, including information on which cable it is on.

When GridShield intervenes, the EV temporarily charges at a lower capacity. The effect on the state of charge will vary depending on the situation and implementation. The Smart Charging project Flexpower supports the conclusion that a temporary limitation of charging capacity has a minimal effect on the total energy charged [25]. Furthermore, GridShield is intended as a last resort to prevent power outages. Therefore, its effect on the user experience should be positive, compared to the alternative scenario in which the system would suffer a power outage. Issues such as the minimum charge and expected state of charge should primarily be discussed and researched in the context of smart charging.

GridShield modules are technology-agnostic and can be configured to work with a variety of different technologies, including heat pumps, batteries, and vehicle-to-grid installations. We foresee the demand for such solutions to appear in the near future and be integrated into GridShield.

GridShield is designed to have an easy and low-cost implementation. It connects to existing measuring equipment in the transformer. The hardware and software needed for the modules are minimal and technology-agnostic. The preferred long-term solution for charging stations is that the GridShield logic is incorporated into the existing controller logic. The installation of a simple LoRa-chip (or other communication protocol) could be required if it is not already available. Alternatively, a complete GridShield receiver module as described in Section 3.1 can be (retro)fitted.

4.2. Future Work

Having demonstrated the concept's viability, the optimization of how and when GridShield will intervene is further researched, validated, and tested in both simulations and real-world tests.

Closely related to this technological development is the progress on the regulatory basis for private charge point implementation of GridShield. In the Dutch regulatory context, intervening at charge points on household connections is not straightforward and will require regulatory changes. We do not expect this to affect the hardware design or the communication model, but we do foresee that it will influence the exact workings of the algorithms used, because "fairness" is subjective. An interim solution in lieu of regulatory change could be to make contractual agreements at public or semi-public charging stations, with or without economic incentives. This solution is relevant to the Dutch context, and its applicability will vary by country.

5. Conclusions

The increased electrification of vehicles is causing a strain on the Dutch electricity grid at peak times. Aside from grid reinforcements, it is projected that Smart Charging, (H)EMS, and tariffs can prevent the grid from overloading. However, these systems are expected to not be implemented sufficiently to keep up with the predicted local grid congestion. Furthermore, communication with centralized smart systems may fail or be hacked, resulting in immediate local grid overload.

This paper has shown that it is possible to build a robust, decentralized system capable of autonomously preventing the grid from becoming overloaded in unforeseen circumstances. Simulations and real-world tests presented show that GridShield intervenes before a potential power outage by temporarily reducing the capacity of charging stations and restoring capacity when congestion subsides. Due to its unidirectional, autonomous design, it is deemed compatible with Dutch and EU privacy laws, and its functionality provides protection against overload attacks in the context of cybersecurity.

GridShield protects all grid users with minimal inconvenience for the EV user by preventing unpredicted, temporary, local power failures. It can help optimize the use of grid capacity during increased EV adoption and help enable additional charge points to be added in areas with grid congestion.

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