GridShield on a Multilayered Electric Grid

BRAND HAUSER, University of Twente, The Netherlands

The transition to mass adoption of electric vehicles comes with challenges regarding the electric grid as simultaneous charging of electric vehicles might lead to overloads and outages. GridShield is a novel mechanism to prevent grid overloading due to simultaneous charging. In previous research it has been shown, through simulations, that GridShield is effective in the low voltage distribution network at preventing these overloads. In this paper, an automated generator, capable of producing the fictitious networks and necessary files for validating the GridShield system in various up-scaled simulation scenarios is presented. These generated networks fit to the specifications of real-world electricity grids in the Netherlands, along with a level of randomness to accentuate the validity of testing. Additionally, this paper presents a hierarchical implementation of the GridShield protocols as a solution for a multi-layered electricity grid. Simulation results show that each configuration significantly reduces the occurrence and duration of overloads without a significant reduction in energy served. Using the previously developed AIAD algorithm, the addition of GridShield controllers at the roots of the MV and LV distribution networks provides a 78% reduction in overload occurrence while minimizing the duration of overloading to prevent damage to the grid.

Additional Key Words and Phrases: Electric vehicle charging, Electric distribution grid, Energy transition

1 INTRODUCTION

As transportation contributes a large portion of the carbon emissions driving climate change, electric vehicles (EVs) are seeing large increases in market share over internal combustion engine vehicles. This increase in market share will lead to an increase in peak loads on the local electric grid. A likely scenario where many people within a neighborhood arrive home from work within a small window of time being the main cause of this increase. As they would require their EVs to be charged prior to leaving home for work the next day, most people would plug in their EV at this time to charge. The synchronization of charging creates a significant increase in electricity consumption at a time of day when neighborhood grids are already experiencing peak loads on average. With greater EV market penetration these peaks will grow substantially, potentially leading to overloading of the electric grid at the low voltage (LV) distribution level. It has been shown in [4] that even small scale EV adoption can lead to overloading of the grid, which can lead to outages.

The crux of the problem is that the electric grid as it exists today was not constructed with this demand and the resulting peaks in mind. To combat this problem, energy management systems have been developed to prevent such overloads. But these systems can fail due to several factors including malicious attacks. GridShield has been developed as a localized fall back mechanism. Within GridShield, a computation device with a LoRa transmitter is attached to the transformer [6] as shown in Fig. 1. This device includes a sensor to measure the current flowing from the transformer. Combined with LoRa receivers installed in the EV chargers, this constitutes a one-way communication system between transformer and EV chargers. Through this setup, the transformer can notify the EV chargers when they must reduce their power draw due to overload conditions thereby reducing/eliminating the potential for failure and subsequent outages. Simulations, run in the DEMKit simulation environment [2], as described in [10] have shown that GridShield, in combination with an additive increase additive decrease (AIAD) or additive increase multiplicative decrease (AIMD) algorithm, can be effective in an LV neighborhood network. This constitutes a first step in protecting the electric grid from the overloading that likely will become more commonplace as EV adoption continues to grow.

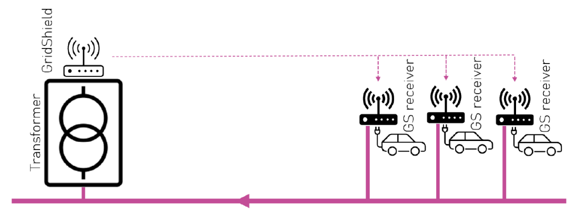

Fig. 1. GridShield Schematic [10]

The electric grid is a multilayered system consisting of generation, high voltage (HV) transportation, medium voltage (MV) distribution, and LV distribution. As such, the protection of the grid must also be a multilayered system. Protecting the grid on the LV networks prevents overloads in local areas. While these local areas do not pass the point of drawing more current than their capacity allows, GridShield does allow them to operate at or near full capacity. Just as many EVs on a local network charging at full capacity can lead to overload, many LV networks running at full capacity can lead to overload in the MV regional networks. In other words, the sum of the power drawn from many lower level networks that are running within capacity can be greater than the capacity of the higher level network they receive power from. Overload on this MV level could lead to a region-wide outage, affecting a far larger number of commercial and residential customers.

Although simulations in the DEMKit simulation environment have shown the GridShield protocols to be effective on LV distribution grids, these simulations did not include any of the higher layers of the electric grid or the hierarchical control necessary to prevent overloads at those levels. This paper looks to answer the question of whether or not GridShield can be effective in a multilayered electric grid. It does so by investigating and analyzing a hierarchical implementation of GridShield. In such, the GridShield controller located at the root of the sub-network that comprises an LV network, as in the previous research, is preceded by a GridShield controller at the MV/LV transformer. The two controllers

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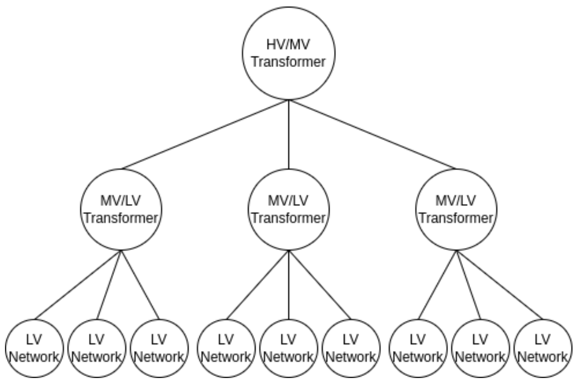


Fig. 2. GridShield Hierarchy Tree Graph

are implemented in a parent-child relationship where the parent communicates to the child in a similar manner as the GridShield controller in the previous research communicated with the car chargers. A further level of hierarchy is established with another GridShield controller located at the HV/MV transformer, that is the root of the MV network, as the parent of the GridShield controllers at the MV/LV transformers. This hierarchy is depicted in the tree graph of Fig. 2, where each node in the graph, as the root of its own sub-network, is the parent of any connected child nodes below it. In the diagram, the MV Transformer node is the parent of the LV Transformer nodes. The LV Transformer nodes are then the parents of a set of LV Network nodes to which they are connected. The diagram could be further expanded to include the EVs (left out for brevity) as the children of the LV networks representing the leaf nodes of the overall graph. As such, each parent node can send communications to and therefore direct the actions of its children.

The main contributions of the research described in this paper are:

- Generation of varied fictitious network graphs to be used for validation of GridShield protocols through simulations.
- Analysis of the stability and performance of GridShield protocols when applied in a hierarchical implementation.

2 GENERATION OF NETWORK GRAPHS

Validation of a hierarchical GridShield implementation requires a network graph containing thousands of nodes and connections in a multilayered configuration that reflects realistic parameters of the electric grid. By having a wide range of synthetic, but realistic, networks the algorithms can be validated by showing stable responses under varied conditions in simulation. Data gathered from such simulations will also be valuable in assessing the effectiveness and efficiency of the protocols. Generation of such large network graphs by hand would be a tedious and time consuming process. Additionally, the data of actual networks within the Netherlands and elsewhere are often out of date, non-existing, or difficult to obtain making the modeling of real-world networks difficult to impossible. As such, a program that could generate graphs constructed according to user specified configurations and realistic grid parameters, would make a significant impact on these projects.

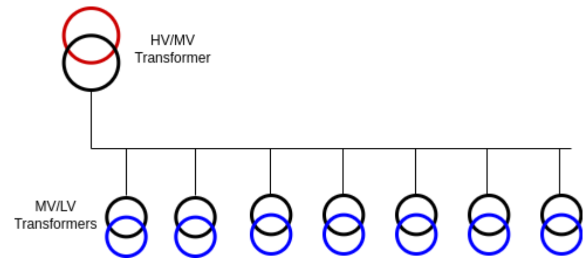


Fig. 3. MV Distribution Network

In the case of the research described in this paper, the output of this network generator would be those network files required by DEMKit for the execution of simulations. In order to cover many use cases, a parameterized implementation of such a generator as well as abstraction of the generation of the network graph from the creation of the output files would be desirable.

The following subsections provide further insight into the requirements of the network generator and the graphs it produces.

2.1 Layout of the Electricity Grid

Testing of GridShield in a hierarchical configuration requires network graphs representative of the MV and LV distribution layers of the electricity grid. While the specifications presented in this section are focused on the electric grid in the Netherlands, the models developed may be applicable to a larger area of North-Western Europe. Each of the following layers can be assigned as a separate GridShield layer in the hierarchical implementation. This involves a GridShield controller implemented at the root of the layer with the roots of the next layer assigned as children. For the LV network layer, the children are the car chargers located at the houses connected to the network.

2.1.1 MV Distribution Layer. The medium voltage distribution layer provides electrical connections on a regional area network. The HV/MV transformer at the root of this network steps down the voltage from a high voltage transportation network. The voltage on the output, or secondary, side of the transformer can range from 3-25 kV and would connect to 50-250 MV/LV transformers [11]. A typical MV distribution network in the Netherlands will operate at 10.5 kV [1]. These networks, in the Netherlands, are typically constructed with a single cable connected to the transformer, from which electricity is distributed to the MV/LV transformers in series [1, 11] as shown in Fig. 3. The capacities regarding power in Watts (W) and current in Amperes (A) are calculated according to the formula in equation (1), where $P_{max,n}$ is the maximum power the network is expected to draw at any one time for n number of houses served within the network, α and β are constants equal to 0.23×10^{-3} and 0.016 respectively, and V_1 is the the average annual electricity consumption per house of 4300 kWh. Further explanation of this formula and its variables, including the derivation of the α and β constants can be found in chapter 3.5 of [11].

$$P_{max,n} = \alpha \times V_1 \times n + \beta \times \sqrt{V_1} \times \sqrt{n} \tag{1}$$

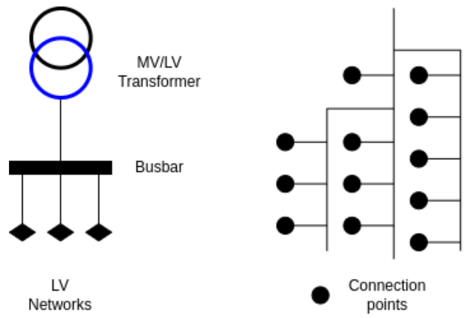


Fig. 4. LV Distribution Layers: Left - LV Transformer, Right - LV Network

2.1.2 LV Distribution Layer. The low voltage distribution layer provides electrical connections to a local area network. The LV distribution layer can be subdivided into two layers that will hence forth be called the LV Transformer Layer and the LV Network Layer. The MV/LV transformer at the root of the LV Transformer Layer, steps down the voltage from the medium voltage distribution network. The voltage on the output side of the MV/LV transformer in the Netherlands is 400 V. The output of a MV/LV transformer connects directly to a busbar from which the connections to the LV networks are made as shown in Fig. 4 [11]. An MV/LV transformer may connect 50 - 250 connection points (houses, apartments and businesses) [11] through these LV networks. These networks are often constructed in a tree formation. There are many configurations possible for this network. For the purposes of this paper, a single branching tree, containing a main tap line with branch lines emanating from it will be used as shown in Fig. 4 [5]. The lengths of the cables, distance between connection points as well as the number of connection points per network in the generated network are chosen at random from ranges taken from [5, 8], as described in section 2.2. Capacities for these layers were calculated using equation (1) as described for the MV distribution layer in section 2.1.1. A simplified representation of a full, generated network can be seen in Fig. 5.

2.2 Randomization

To produce the variations in networks that may provide further insight towards the implementation of protocols such as GridShield, the network generator should include a level of randomization while keeping within the specifications of the design of the electricity grid. To accomplish this, the minimum and maximum of several parameters were included in the code of the generator as gathered from [5, 8]. For example, the length of a branch off of a main tap line within an LV network within the city can range from 160 to 280 meters [5]. Limitations such as this make for a realistic model while also preventing the non-resolvable load-flow simulations that would arise due to the physical limitations of system components. Upon creation of such a branch, the generator makes a random choice from within this range using a normal distribution. The probabilities of this normal distribution are based on the μ (population mean), as gathered from [5], and σ (standard deviation), set as a percentage of μ as no such data was found. In cases where the μ was not found in literature, an estimation was used.

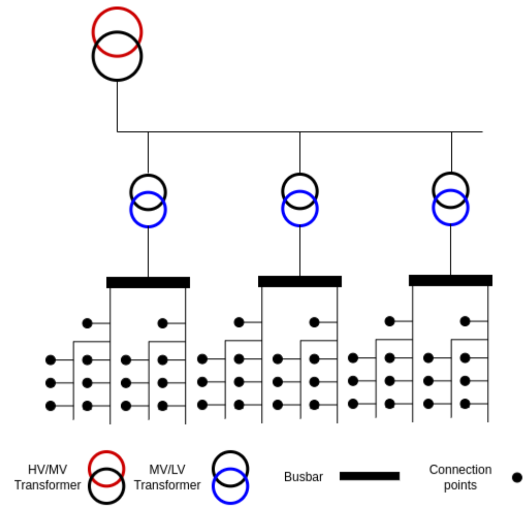


Fig. 5. Generated Network

Randomization was applied to the following characteristics according to the specifications provided:

- Number of LV networks per LV transformer - 4 to 6 (reduced to minimize execution time of simulations)
- Type of LV network, i.e. suburb, village, country - with probabilities of 60%, 30% and 10% respectively
- Number of connection points, e.g. houses, per LV network

Type	Max	Min
Suburb	50	30
Village	45	25
Country	40	20

- Distance between connection points

Type	Max	Min
Suburb	103	17
Village	80	34
Country	260	68

- Length of tap line within a LV network

Type	Max	Min
Suburb	400	240
Village	750	600
Country	1500	900

- Length of branches from the tap line

Type	Max	Min
Suburb	280	160
Village	510	360
Country	780	360

- Location within tap line of branch root

2.3 Implementation

Given the motivation and specifications noted in this section, the first step to the research described in this paper is the creation of such a network generator. The program is written in an object-oriented fashion such that the network is first created as a list of node objects with a numerical ID and information such as the type of node, e.g. house, transformer, etc. forming a structure similar to a linked list. This avoids the use of a large and sparse matrix as commonly used by electrical engineers. Each node contains information regarding the connection between that node and the previous node in the network such as the ID of the previous node and the length of the feeder cable connecting them. Transformer nodes, and LV network root nodes contain information regarding the number of houses below them within the overall network. Lists comprised of all HV/MV transformer, MV/LV Transformer or LV Network root nodes are created during node generation. This allows for the calculations regarding the capacities of the transformers and LV networks after generation with a level of randomization. The pseudo-code in Algorithm 1 shows how the capacities of the fuses are calculated using the formula in equation (1).

Algorithm 1 Discrete Fuse Capacities

```
procedure CALCULATECAPACITIES
    n ← number of houses
    v ← voltage
    t ← network type
    consumption ← 4300                                  ▷ kWh per year
    power ← (α * consumption * n) + (β * sqrt(consumption) * sqrt(n)) * 1000
    current ← power/v/3
    if t = LV then
        fuseChoices ← [125, 160, 250, 400, 630]
    else
        fuseChoices ← [100, 125, 160, 250, 400, 630]
    end if
    for fuseChoices do
        if choice > current then
            current ← choice
            break
        end if
    end for
    power ← current * 3 * v
    return power, current
end procedure
```

Once all nodes have been generated and appropriately connected, the necessary files for DEMKit simulation are written. This configuration allows for the abstraction between network generation and output file creation as described above. Implementation in this fashion allows for multiple simulations to be run on a single network map, while retaining the ability to modify parameters such as the GridShield configuration.

3 EXTENDING GRIDSHIELD

At the outset of the research in this paper, the GridShield controller code included two algorithms for calculating reduce signals (the signal sent to EV chargers instructing a reduction in electricity draw) that proved successful [10]. Both algorithms are based on computer networking protocols such as the Transmission Control Protocol (TCP), continuing a common trend of using internet protocols to control congestion in power grids [7]. AIAD, is a step-wise algorithm in which, upon detection of an overload, the reduction signal is increased by one step at a time (*additive decrease*) until the violation is resolved. Once the electricity draw is reduced below the *upper restore limit* (further explained in section 4.2) the system enters the *additive increase* phase, where the reduction signal is decreased by one step at a time, thereby increasing the electricity draw, until another overload occurs or the reduce signal decreases to 0. The AIMD protocol functions identically on the *additive increase* phase, but uses a *multiplicative decrease* that decreases electricity draw by a factor of the total rather than one step to produce a faster decrease. As such, the overload condition is resolved in one step.

Upon completion of the calculations built into the respective algorithms, the reduce signal is sent to the EV chargers through a one-way communication LoRa network. In the case of the AIAD protocol, the reduce signal is an integer equivalent to the number of Amperes by which the EV chargers should reduce their consumption. In the case of the AIMD protocol, the reduce signal is either 1 or 0 as an integer representation of True or False, denoting whether or not there is an overload situation in progress.

The existing GridShield concept was theoretically designed to implement a layered form of a communication interface. However, no previous research had been done on the implementation of such communications. Therefore, prior to running simulations of a hierarchical implementation, the controllers require modifications to receive and record the parent signal values and add them to the local signal calculations to be passed on to further children. Algorithm 2 shows a simplified version of how these calculations are made for the AIAD protocol. The plot in Fig. 6 shows the result of these calculations. It can be seen in the plot that each increase in the *reduceSignal* is accompanied by a sharp decrease in the *currentDraw*. With regards to the AIMD protocol, a logical OR equation is used to determine what message should be sent to the EV chargers as the reduce signal. In other words, if the overload situation at either the parent or the child is True, then the reduce signal sent to the EV chargers is 1, the integer representation of True.

After this initial modification to account for a parent signal within a child GridShield controller, simulations were run to analyze the hierarchical performance of the GridShield protocols. During this initial, scaled down testing phases of this research, observations were made regarding the performance of the hierarchical GridShield implementation in combination with the AIAD protocol. These observations lead to changes in the protocol as taken from the previous research [10]. This section will discuss those observations and the subsequent changes.

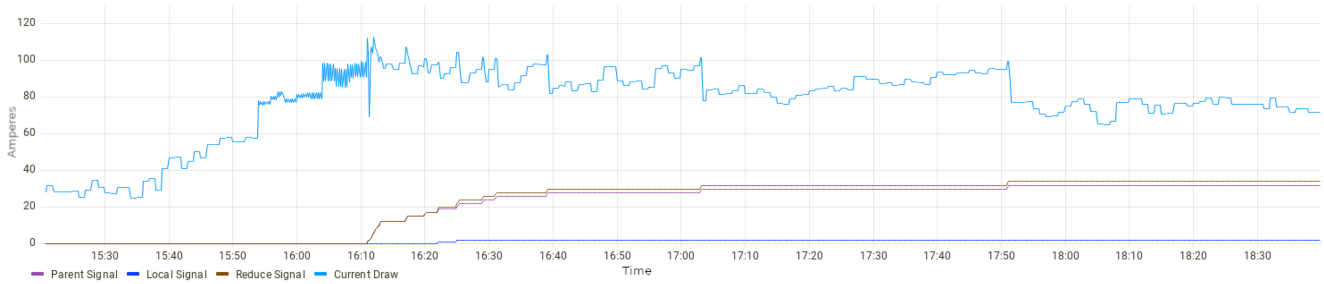


Fig. 6. Hierarchical Signals

Algorithm 2 Parent Signal Modification

procedure PARENTSIGNAL
    $parentSignal \leftarrow signalReceived$
    calculate $currentDraw$
    if $currentDraw >$ capacity **then**
        $localSignal + 1$
    else
        $localSignal \leftarrow \mathbf{max}(0, localSignal - 1)$
    end if
    $reduceSignal \leftarrow parentSignal + localSignal$
end procedure

3.1 Parent-Child Conflict

When a parent GridShield controller detects a potential overload, it will send a message to all children assigned to it. This message contains a reduce signal that is the number of steps that the child should reduce its electricity consumption. One step is equal to 1A or 250W as explained in [10]. When a child GridShield controller receives a message from a parent, this parent reduce signal is added to its own local reduce signal, which is then sent on to its children as the subsequent reduce signal as discussed in the introduction of this section. These children may be another hierarchical layer of GridShield controllers or the car chargers that comprise the lowest layer of the hierarchy.

The conflict therein, is that as the parent signal rises, the child's local signal would decrease equivalently in response. This is understandable, as the child was at an acceptable level of consumption and would seek to maintain that level. Therefore, the child's calculations of a local signal would evaluate to a number equivalent to the previous local reduce signal minus the parent signal. The sum of the two would then remain unchanged as shown in Fig. 7. This would maintain the non overload status at the child controller, but would not reduce the overload at the parent. The result would be that the overload condition at the parent would not reduce until the child signal reached 0. At this point the parent signal would keep climbing and the sum of the parent and child signals would finally increase leading to a reduction in consumption.

To account for this, a modification to the AIAD protocol was made such that a child signal cannot reduce unless the parent signal is equal to 0.

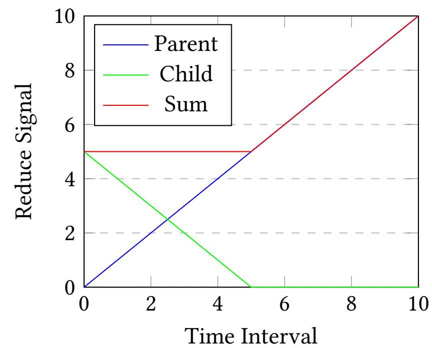


Fig. 7. Parent-Child Conflict

3.2 Step Down

Included in the original AIAD algorithm is an *initialreducePower (IRP)* variable. This was included to force the car chargers to drop their maximum output to a level that would reduce the consumption of the EV immediately upon receiving a control signal from the GridShield parent. Without this inclusion, a smart charger might reduce its maximum by 1A from 25A to 24A while the car is charging at 20A. This results from the fact that a smart charger may choose to charge at a lower setting than the maximum depending on user preferences. Thus, the IRP is necessary given the lack of ability to measure the output at the charger while only having control over the maximum charge rate. The result of which being that there would be no change in consumption until the control signal reached 6, reducing the max output of the charger to 19A. Such delays might be problematic as overloads would not be resolved in time as discussed in [10].

$$reduction = \begin{cases} reduceSignal + IRP, & \text{if } reduceSignal > 0 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

The problem observed comes when the control signal received at the charger from the GridShield parents reduces to 0. The *IRP* was often observed, by analyzing the values of variables during execution of a simulation, to add 32.2A to the reduction signal received following the formula in equation (2). Given this, a reduction from a control signal to 0 would cause a change in reduction from 33.2A to 0A. This lead to large spikes in overall consumption following a signal decrease to 0, which would immediately be followed by an increase in the control signal from parent controllers. In some cases this rapid change would produce instability, evidenced by non-resolving oscillations in the control signals and consumption levels.

The solution is to step down the *initialreducePower* by 1A for each interval that the signal remains at 0 rather than the immediate drop from 33.2A to 0A. This eliminates the spikes in consumption and the subsequent reactive signal increase from the parent controllers.

3.3 Delay In Parent Response

Within the AIAD algorithm, when an overload occurs in multiple lower level networks, such as at the LV network level, it is likely that this will also result in overload in the parent network, e.g. at the MV/LV or HV/MV transformers. When this happens the parent and child GridShield controllers will send control signals to reduce power consumption at the EV chargers. This leads to a doubling of the reduction as the parent signal is added to the child signals. In such a case, the reduction signal from the parent GridShield controller may not be necessary to eliminate the overload condition at both levels. Doubling would then cause an unnecessary reduction in the efficiency of the system.

When an overload is detected at a parent network level, instructions in the GridShield controller to wait until the next time interval, and reevaluate before sending a response as a control signal would allow the child controller the opportunity to correct the problem before the parent takes action. If the overload is not resolved at the parent level, the ten second delay (one time interval) would not be sufficient to lead to outage or damage. This delay is realized in code by tracking the previous two signals sent by the parent. The pseudo-code in Algorithm 3 shows how these values are used to determine what signal to send. In this way, if the overload condition neither increases nor stays the same over two time intervals, the parent controller will send the previous signal thereby not increasing the reduction. As such, if the electricity draw reduces, the parent controller will not act as the child has likely resolved the overload.

Algorithm 3 Parent Controller Delay

```
procedure DELAYPARENTINCREASE
    if currentSignal > previousSignal and previousSignal <= previousPreviousSignal then
        send currentSignal
    else
        send previousSignal
    end if
end procedure
```

The simulations executed to test this delay, comparing the performance of the delayed parent to the non-delayed parent controllers, show that the delay leads to substantial spikes above capacity as well as instability as shown by oscillations. This can be seen in the graphs of the total electricity draw in Fig. 8.

4 EVALUATION

The results in this section are based on a model of an MV network containing 50 LV sub-networks. The model was generated by the program described in section 2. Fig. 9 shows a graph of the networks with some relevant specifications. The graph includes a depiction of the hierarchy of the networks as used in the simulations. Each node represented can be used as a GridShield controller. The leaf nodes of the graph, i.e. the houses and connected EVs, were left off for brevity. As shown, the model contains 11 MV/LV Transformers, each with its own subset of LV Networks.

4.1 Simulation Configuration

Table 1 shows a list of the possible configurations of the hierarchy of GridShield controllers to be used in simulation. For each configuration in the list, simulations were executed using both the AIAD and AIMD protocols from [10]. Additionally a simulation with no GridShield controllers was executed as a base case for comparison purposes. Further, each of those simulations was executed a second time using the attack vector described in [10]. Each simulation was executed to represent a 24 hour time period beginning midday at 12:00 on Jan 30. EV charging schedules and household baseloads used by DEMKit are generated by the Artificial Load Profile Generator (ALPG) [3]. The eighty household profiles generated in the previous research [10] were reused and randomly applied to the 1913 houses in the simulations for this research.

Table 1. GridShield Configurations

Configuration ID	GS Hierarchy
MV	MV Transformer - Chargers
MV-LVT	MV Trans - LV Trans - Chargers
MV-LVN	MV Trans - LV Networks - Chargers
MV-LVT-LVN	MV Trans - LV Trans - LV Networks - Chargers

4.2 Stability

The stability of the GridShield system can be evaluated based on principles commonly used in electrical control systems. A graph of the power output as well as the control signals sent by the GridShield control units will show continued, uncontrolled oscillation if the system is unstable. A stable system may oscillate upon changes in the power or signal, but will stabilize in a short time as shown in an end to the oscillations. This is designated as an under damped system as depicted in Fig. 10b with the red line as the desired performance level and the blue line as the actual performance. A critically damped system quickly achieves stability, while controlling the power output according to the prescribed capacities, without oscillations as depicted in Fig. 10a. As such, this is generally considered the ideal configuration [9].

Within GridShield, the parameter that most relates to the stability of the system is the *Upper Restore Limit*. This is the point at which the electricity draw at a GridShield controller has declined sufficiently so that the control signal can be reduced. In other words, when a control signal is greater than 0 and the electricity draw decreases

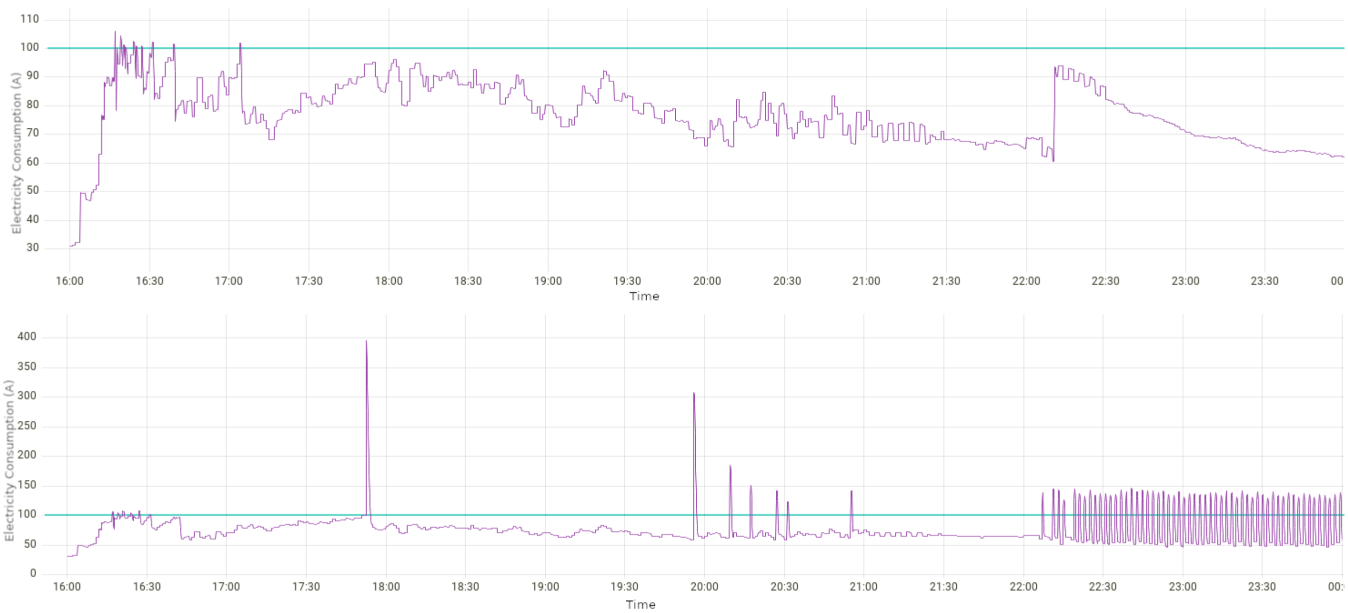


Fig. 8. Top: Without Delay Bottom: With Delay

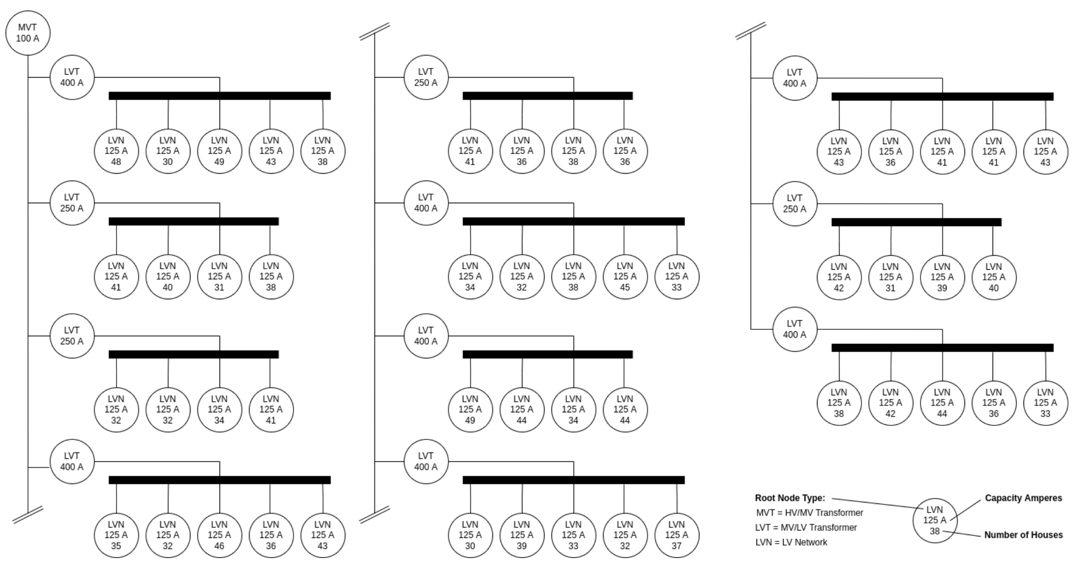
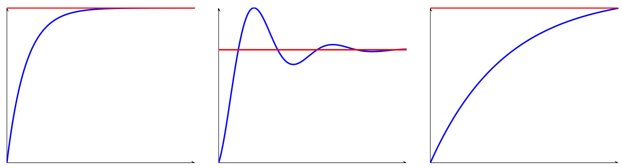


Fig. 9. Simulation Network

to the predefined *Upper Restore Limit*, the GridShield controller will reduce its control signal by one step, effectively allowing more electricity to be drawn at the car chargers. If the *Upper Restore Limit* is set too high, the system will decrease control too soon resulting in a quick jump in the draw that will exceed the capacity of the network. This is then followed by an increase in the control signal pushing the electricity draw back down below the capacity, likely to or near to the *Upper Restore Limit*. That cycle may then repeat producing the oscillations that, if they fail to resolve, denote an unstable system.

If the *Upper Restore Limit* is set too low the result will be that the system does not allow an increase in draw at the chargers when it could, causing the system to take more time to reach the desired performance level. This is designated as an over damped system as depicted in Fig. 10c. This increases the difference between the power used to charge the EV had GridShield not reduced the draw (assuming that the grid was capable of handling the demand without



(a) Critically Damped (b) Under Damped (c) Over Damped

Fig. 10

overload). This metric is known as the *Energy Not Served* and will be explained further in section 4.3.

Finding the optimal *Upper Restore Limit* requires running many simulations with a parameter sweep of the *Upper Restore Limit* values and assessing the results to find the point where the system is said to be critically damped. Through this testing, it was found that an *Upper Restore Limit* set equal to 62% of the capacity of the network, most often presents as a critically damped system without oscillation. Set to 62.5%, the system will likely oscillate, but is able to restore stasis. Thus, 62% of capacity is likely the optimal setting.

4.3 Performance

Performance of the GridShield system can be analyzed through two metrics, the Euclidean distance of excessive power (EDEP) and the energy not served (ENS) as mentioned in section 4.2, both in continuation of the previous research in [10]. The EDEP, taken at the root of the network, is a measurement of the duration and severity of overloads experienced $||max(0, P_{root} - P_{root}^{(max)})||2$. The EDEP is used as a measurement of the efficacy of the GridShield. The ENS, $\frac{P_{base} - P_{sim}}{n}$, measured in kilowatt hours per EV over the duration of the simulation, as compared to the base case, represents the efficiency of the system as well as the pain to the users. Table 2 shows the results of the simulations regarding these metrics.

Based on this data, the AIAD protocol applied with GridShield controllers at the HV/MV transformer as well as at the MV/LV transformers gives the best performance with a 12.6% overall reduction in power served compared to the base case, represented by the ENS, and a 78% reduction in overload events. The AIAD protocol with GridShield controllers at the HV/MV transformer, MV/LV transformers and at the LV networks is a close second with a 13.7% reduction in power served and a 77.5% reduction in overload events. Additionally, it is important to note that no overloads recorded in GridShield simulations for this paper were of sufficient severity or duration as to be likely to cause damage or outage. This includes all hierarchical GridShield configurations as well as the simulations including the attack vector described in previous research [10].

5 CONCLUSION

This paper presented a program for the generation of multi-layered electrical grid network models for use in DEMKit simulations. This generator significantly reduces the time involved in model creation. As such, running many, varied simulations for testing and validating GridShield implementations, as well as other projects, becomes more practical.

Table 2. Results of Simulations

Protocol	GS Hierarchy	EDEP	ENS
(No GS)	Base Case	13859.82	-
AIAD	MV	98.13	4.311
AIAD	MV-LVT	30.45	3.780
AIAD	MV-LVN	37.96	3.741
AIAD	MV-LVT-LVN	31.19	4.130
AIMD	MV	56.41	0.001
AIMD	MV-LVT	61.18	0.199
AIMD	MV-LVN	74.68	0.199
AIMD	MV-LVT-LVN	82.16	0.448

Simulations using the model generated for this research paper show that GridShield can be used in a hierarchical implementation. With some modification, the hierarchical GridShield controllers were able to communicate with their child controllers, thereby passing down the reduction signals to resolve and avoid overload conditions.

Stability was achieved through an optimal *Upper Restore Limit* set to 62% of the network capacity. This, coupled with the AIAD algorithm lead to successful simulation runs. The MV-LVT and MV-LVT-LVN GridShield configurations resulted in approximately 13% reduction in energy served while reducing the instance of capacity violations by 78%. While further parameter tuning could improve these metrics, the efficacy of the hierarchical approach is shown to be appropriate.

Though the MV-LVT and MV-LVT-LVN configurations perform similarly, further research should be done to verify that the MV-LVT configuration does not result in increased overload conditions on the LVN level should the distribution of EVs be less consistent across the various LVNs. Additionally, these protocols could be further tested over a wide variety of simulation configurations with detailed analysis of the performance at individual layers.

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