Designing resilient and secure smart micro grids

Siavash Valipour

Abstract: The research presented in this extended abstract paper depicts a smart grid management framework which enables a decentralized and autonomous organization of the energy participants within these grids. Based on basic requirements for operating such systems, challenges and tasks are being discussed here as a basis for future research. The discussion encompasses both fields of electrical engineering and computer science. The presented grid coordination and energy transfer schemes are briefly regarded and openly discussed.

Keywords: Smart Grid, Micro Grid, Energy Network, Decentralized Power Sources

1 Introduction

The supply of energy is on a transition from a traditional, centralized “powerplant-to-consumer” tenet to an increasingly decentralized approach in countries like Germany, respecting renewable energy policies. In recent years, smart grids have been discussed to empower an IT-supported “smart” supply system, where an intelligent system manages energy produced and consumed within the grid. The energy participants of such grids are usually proposed to be organized in decentralized clusters. The idea behind smart micro grids (from now on: “smart grids”) is to produce and consume ideally renewable energy locally, i.e., near the source in order to decrease transportation losses and costs for infrastructure investments. Implementing such a grid management system requires knowledge from both electrical engineering and computer science and faces challenges such as grid reliability, security and resilience. The members of a micro grid consist of heterogeneous parties, that is, consumers, producers and storage systems which are equipped with smart-metering and control devices, providing bidirectional information and energy flows. Here, the classic household can act both as a consumer and as a producer at the same time, for example by having solar panels installed on the roof which supply parts of its immediate neighborhood. There exist many definitions and surveys depicting major differences between the smart grid and the traditional grid. A good insight view can be obtained in [Fa10], [Fa14], [HHM11], [Fa12b] and [Fa12a]. In this paper, we present our research on a formal, resilient and decentralized smart grid model. The overall goal of this proposed system consists of providing certain autarchy and self-management aspects in these dedicated networks. The term “resilience” aims here at a high degree of service availability, making the grid robust to failures and attacks. This presented research plan deals with selected integral topics related the smart grid’s performance and stability:

1 Technische Universität Darmstadt, TK, Hochschulstr. 10, 64289 Darmstadt, valipour@tk.tu-darmstadt.de
1. **Model**: Defining an applicable smart grid coordination model is needed. This particularly includes formal statements to form logical groups and subgroups within the decentralized network as well as defining goals.

2. **Coordination**: These groups need coordination, thus an underlying dynamic coordination model is required. This can be done by centralized/decentralized managers, called coordinators, who are elected by a leader election process.

3. **Prioritization**: In situations as in energy scarcity phases, a priority based energy distribution system seems favorable, e.g., classifying the needs of hospitals higher than households. We discuss such a proposed priority model.

## 2 Research Questions

Based on the smart grid model (SGM) and the available capabilities of the participants within the model, algorithms for energy management, emergency plans etc. can be defined.

### 2.1 The Model

In the literature, both Hashmi et al. and Fang et al. survey smart grid technologies and approaches in [HHM11] and [Fa12a], respectively. The German state funded project *Modellstadt Mannheim* [MV12] proposed a cell driven topology for the grid. As this model offers a rather fixed mapping of how devices and buildings are set up in this system, dynamic processes which arise during shortages are not being taken care of with the desired efficiency and thus leave room for improvement. Several non-exhaustive research tasks can be identified when designing our model: First, maximize the overall availability of energy to present consumers. Second, support island operation modes in a case of a (partly) blackout. Third, enable dynamic and demand-based allocation of energy. Fourth, support management and transfer of locally produced energy.

The future grid’s desired ability to separate itself from the greater network (island operation) requires new concepts and investments in communication-enabled electrical equipment. From an IT-based point of view, these islands need to be operated and coordinated according to the up-to-date parameters, e.g. sensor data, and constraints, e.g. line capacities. Two concepts are favored here, the hierarchical and the autonomous approach. The centralized, hierarchical approach where a central control station controls its local domain grid, allows grid operators a total supervision over the entire grid, but also creates a single point of failure. Given that the future grid’s stability will heavily depend on the reliability of the IT infrastructure, this approach should be questioned.

Otherwise, in an autonomous system, each part of the grid acts as self-regulatory systems where individual decisions and actions are based on locally available data and communication. The decentralized system takes electrical sensor data via communication as input in order to determine the current (self-)behavior of the local entity. Decisive units are presumed within the local grid need to retain its stability. This can be achieved by dynamic and adaptive promotion of normal grid stations (“buildings”) into a decisive station through
leader election, which will be further described later on. Our current and future research deals with investigating a well suited decentralized smart grid coordination model, aimed to be self-regulatory and resilient in terms of service availability.

When applying such a systems-theoretic concept onto smart grids, new challenges arise as future work. We define this very formal model to incorporate all smart grid participants (electrical and information layer) into one framework. This encompasses buildings, devices, power stations, servers, lines and connections. The model strives to maintain an equilibrium between the produced and consumed amount of energy at all times as one of its goals. Available energy flexibilities on demand and producer side are considered as well as emergency situations and strategies. In cases of danger, e.g., parts of the grid being in exceptional states due to an electrical short circuit, detected malicious parts should be excluded from the larger entity so that a further instability of the grid is mitigated. The formal model is going to be designed for dealing with these issues by defining monitoring functions and polling sensors. The functions are evaluated regularly by the coordinator and a set of best practice rules and strategies, e.g. opening switches, throttling down consumers, activating generators etc. will be defined in order to mitigate potential risks and failures. For that, several constraints from the engineering perspective are not to be neglected: A “logically” separated building might still be physically connected to the grid and thus influence the area. Solutions for this matter might be remote controllable switches and “electricity gateways” installed at the house connector level. These gateway devices are envisioned as supply influx delimiters, installed in the house’s basement and connected to the grid’s communication network as well as the main supply line. If the gateway receives an order from a coordinating authority to limit its demand, it is assumed this device will do so by ensuring that consumers within that building are switched off or kept on standby until the total consumption is below the threshold. This allows the coordinator to actively conduct the grid operation given scenarios. The model’s concept is to be proven by theorems while its abstracted feasibility is meant to be evaluated and researched on by simulation.

2.2 Leader Election

There are a wide variety of efficient leader algorithms (LEAs) mentioned in the literature. The bully algorithm described by Garcia-Molina in [GM82] along with its sped up versions by Lee et al. [LC02] as well as by Arghavani et al. [AAH11] are to name among others. The algorithm by Yu et al. [Yu09] describes a more electricity-grid-fitting approach where each system starts off by assessing a self-evaluating process based on criteria such as computing and communication capacities. Then these values are propagated and a vote for the leader is conducted. In these models, when the current leader fails, the approach is to simply conduct a new election, triggered by anyone noticing the failure. While the number of reelections is reduced in improved versions, the idea of a complete reelections appears to be excessive, as all other nodes except of the leader may still be online. Also, denial-of-service attackers easily could exploit this behavior. An apparent idea is the application of a “leader / deputy leader” system which could enable quick substitution in case of failure. As the coordinator is the key player in our grid model, it is essential to consider the resilient nature of our model also when designing a LEA. It is assumed, that a failing
coordinator triggers the participants into an emergency mode and limits consumption of energy to a minimum in order to – if possible – avoid major outages and instabilities until a new coordinator is found. An adversary could be interested in inserting unauthorized, or manipulating existing, machines in the network and try to promote himself as a new coordinator to conduct his malicious intents. He could also deliberately disturb the election process preventing mutual consent and keeping the grid in under-resourced exceptional state. The integrity of the LEA is therefore of utmost importance.

Our own, very preliminary and shortened approach focuses on a LEA based on a multi-step voting scheme. It is assumed, that the participants \( \Pi \) are able to communicate with each other. The crucial part is depicted as follows: First, each participant willing to participate in the election process will do an self-assessment regarding its own leader qualifications. The assessment algorithm might consider the machine’s available computational resources, its communication capacities, its physical location in the grid, its machine type and so forth. All of these factors are weighted by the algorithm. The assessment values are then propagated to everyone in election. These received values are then multiplied by a trust factor \( t_i \in [0..1] \), where each participant has stored such a dynamic factor for every other participant’s unique ID \( i \in \Pi \). The participant with the highest result is then openly voted by multicast. As the voting is open, the participants will accept the participant with the highest vote-count as the new leader.

Trust values are stored individually on non-volatile memory and set to a standard value initially, but change dynamically over periods of time, due to the participants’ individual experience with that leader in the past. If, for example, a leader was noticed for keeping up the grid only for short periods of time, or if the supply under that coordinator was regularly sub-optimal, then the assigned trust value for that particular leader might decrease. We expect to come up with such tailored LEA. The method will be evaluated formally by assessing the number of messages sent in cases where a leader is needed or fails.

### 2.3 Priority Model

Available capacities and consumption-needs in the local grid are part of the energy balance which should remain equated. In times where the demand exceeds the supply, active energy management is proposed to keep the grid operational.

We propose a priority scheme which allows to decide on which buildings to supply first. For example, a hospital might appear more important to supply with scarce energy than a normal household. Horsmanheimo et al. show by a formal proof the theoretic property of such a priority grid model in [Ho14]. However, given that there is only limited energy available, one might argue that a coffee machine inside the hospital might appear less important to supply than a refrigerator inside a standard household. Therefore, we extend prevalent priority models from “building-only” over the domain of smart devices. We assume for this priority model, that devices are partitioned into device priority classes inside the smart home, according to their type. Furthermore, the coordinator knows all its connected consumers, their priorities and the consumer’s aggregated energy-need bound to
device priority classes. It is also assumed that adversaries are able to change neither the building priority nor device priorities on their own nor replay requests to the coordinator in order to gain benefits or disturb the grid. The installed and operational energy gateway devices allow the coordinator to actively scale the energy influx into buildings.

The “importance” of incoming energy requests is obtained by adding (or multiplying) the device’s priority (class) to the requesting building’s priority. Therefore, the consumer’s request consists of the device class and the energy amount. Now, energy is dealt out by the coordinator from the (in numbers) lowest priority class to the highest. We formally introduce thus a set of $B := \{1, \ldots, n\}$ different building priorities and $D := \{1, \ldots, m\}$ device classes and $m, n \in \mathbb{N}$. An example follows: the refrigerator (device priority $d_k \in D$) in a kiosk (building priority $b_k \in B$) is in the “total priority class” $p = d_k + b_k$. The coordinator would first try to serve its micro grid all other priority requests smaller in numbers than $p$ unless surplus energy is available for $p$.

Nevertheless, a few tasks persist: First, which entities and devices should be assigned priorities? It is expected that regulating authorities will have to decide on this. Second, seek methods to reduce priority propagation and processing complexity. Third, how much better is the priority system in scarcity operation mode? We expect to publish simulated results in near future by comparing our priority model to a non-prioritized / FIFO model.

3 First Results

We conducted a grid simulation to find potentials in decentralized and autonomous supply. In the traditional grid system, a failing transformer station would drive the subnet behind the transformer offline (blackout) even though local generators might be available and could potentially operate parts of the grid. Under given assumptions described in our paper currently under submission, two models of decentralized energy supply were evaluated in randomly generated, real-world based scenarios: The first model operates with respect to a fixed cellular model with low dynamics. Here, the island mode, i.e., a connected component of the smart grid graph, is operational when all provisioned participants behind a failing local substation transformer are technically available, can communicate and have available producers and consumers present. The improved model allows operation even when only sub-components of the grid are found to be available. Our simulation ran 10,000 passes with randomly generated sub-grids which are based on parameters obtained from a real-world site in a medium-sized German city. Our results show that the proposed dynamic island approach can supply an average fraction of 22.08% of the sub-grids when the substation transformer fails. This encourages deeper research in this field.

The proposed priority model was also tested in similar grid topologies with randomized priorities. The simulation showed the theoretical feasibility of our model, by correctly preferring priority consumers over others, while at the same time still respecting production and line capacities. As such a model appears to not be implemented elsewhere, it is to determine appropriate ranges of priorities for both buildings and devices in order to assert reasonable and just consumer partitioning during scarcity-plagued operations.
4 Conclusion

Smart grids are future models of electricity distribution empowering the renewable energy transition. We propose a model which facilitates a decentralized way of operation of these grids. The objective behind our approach is enabling a more resilient and autonomous up-keeping of future grids. We investigate the application of evolving smart grids, which allow us to form dynamic clusters and allocate energy where needed. As an assumption, a smart energy gateway device is introduced which ensures the regulated use of authorized amounts of energy only. This allows active micro grid management by a coordinating entity. By incorporating an adapted leader election process into the bootstrap process of our model, we expect to enhance the grid’s resilience in exceptional cases. Additionally, a proposed priority model enables the dissemination of scarce energy with preference until the grid has recovered.

ACKNOWLEDGEMENTS The work in this paper was performed in the context of the PolyEnergyNet project and partially funded by the Germany Federal Ministry for Economic Affairs and Energy (BMWi) under grant no. “0325737E”. The author assumes responsibility for the content.

References


[Ho14] Horsmanheimo, S; Kamali, M; Kolehmainen, M; Neovius, M; Petre, L; Rönkkö, M; Sandvik, P: On proving recoverability of smart electrical grids. NFM, 8430 LNCS:77–91, 2014.

