Hierarchical Distributed Consensus for Smart Grids

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Abstract: Reaching consensus in distributed systems is a topic with a long record of suggestions and discussions. One instance of such a distributed system is the emerging Internet-of-Energy: Thousands of Smart Grid service providers orchestrate a multitude of generators, consumers and storage capacity to keep the balance between supply and demand of electrical power. Centralized decision making struggles to fulfill recent requirements regarding robustness against communication outages. In the last decades, consensus research made great leaps towards resilience, elaborating distributed approaches like Paxos and many successor concepts, but has still research gaps in the direction of scalability and dynamicality of node participation. Our work builds upon the results of this recent research while taking a more topologically-driven perspective. We discuss two important innovations towards applicability in future Micro Grids: Clusters are formed to achieve parallelized consensus, acknowledging the grid topology and inter-dependability of Nano Grids. We describe a hierarchical scheme, where aggregation of the locally achieved consensus forms a higher level consensus. This way, we achieve loose coupling combined with partial order of events, implementing a hierarchically distributed global consensus.

Keywords: Smart Grids; Distributed Consensus; Clustering

1 Introduction

Power management in Smart Grids is developing from simple distribution grids towards a decentralized system with multiple domains of responsibility. One emerging challenge is the orchestration of a multitude of generators, so-called distributed energy resources (DER) and consumers, or intelligent energy devices (IED). The scheduling of power generation and consumption can either be represented as a vector of per-resource schedules [SPK19], or in an agent-based manner by peer-to-peer agreements, to pairwise match the schedules of DERs and IEDs [SIB20]. Volatile DERs such as PV panels increase the system's complexity, while mobile consumers such as electric vehicles lead to a more dynamic system. To avoid conflicts between the participating nodes, consensus on the partial order of events can ensure that the global system state is consistent. Including locality in the sense of electrical distance between DERs and IEDs [St19] is the logical continuation towards a mature distributed Smart Grid control scheme.

Micro Grids represent independent sections of the distribution grid. The concept of a self-organizing Micro Grid, where nodes can dynamically join and leave, poses important

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research topics, especially regarding security aspects when establishing consensus in such open networks [St18]. Refraining from centralized solutions for the coordination of power grids can increase resilience, but it does not solve all existing problems and also comes with additional requirements. From the distributed systems perspective, new challenges include fairness, as well as the three properties Consistency (C), liveness or availability (A) and partition-tolerance (P) from the CAP-Theorem [Br00]. Liveness refers to the requirement, that distributed algorithms are vulnerable to deadlocks and unexpected system states. These may be hard to detect and resolve, therefore a formal verification of the liveness is essential. Consistency describes the property that all claims from the system have to be valid and up-to-date. Together with partition-tolerance, which means that the system would continue working despite disconnected nodes, these requirements build the triangle of the CAP-theorem. It states, that it is not feasible to have all three properties C, A and P: If a partition occurs, any claim from the system might possibly be incorrect, because not all necessary information is available. It follows, that any distributed system has to prioritize between liveness (or availability), consistency and partition-tolerance [Br00].
Fairness refers to a system where every actor is eventually served, even if equal options are available. Applied to the Smart Grid context this means that when considering two equally suitable consumers, it is not acceptable to always skip the same [BFT11].

Future Smart Grids will not only be more decentralized, but are also expected to be more open to small business operators and flexible contracting of prosumers to contribute to dynamic Micro Grids. The Smart Meter Gateway roll-out increases the amount of IEDs for the grid management [URZ15]. This leads to challenges regarding:
Scalability. Well proven optimization software may turn out to be too slow and static to incorporate thousands of participants.
Blurred Borders between Transmission Grid and Distribution Grid. Traditionally, power is injected into the transmission grid and then distributed in a top-down manner via the distribution grid. This is now contradicted by the ubiquitous introduction of prosumers that both inject and consume power.

To address these challenges, our research elaborates on solutions to divide the Micro Grid into so-called Nano Grids: independent clusters that need to find a consensus regarding their balance of power demand and supply. The proposed consensus protocol aims to bridge the gap between the physical grid topology and the often-times grid-agnostic application layer, as depicted in Figure 1. The overall research topic therefore is, how such a distributed consensus can be organized.

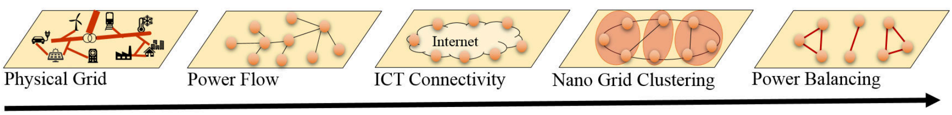

Fig. 1: The architectural layers from the physical power lines up to actual Smart Grid services like power balancing.

2 Related Work

Paxos [La98] requires all nodes to be included in the vote and a majority of them to answer and agree. On the other hand, Egalitarian Paxos (EPaxos) relaxes the guarantees, acknowledging that there are many possible orderings that meet the requirements of distributed computing: Commutative requests can be processed out-of-order [MAK13].

RAFT decouples leader-election and state-machine-replication to achieve an easy-to-understand solution for distributed consensus with a strong focus on leadership [OO14]. In Flexible Paxos (FPaxos), the interdependency between the two stages of leader election and log replication is investigated separately, allowing to further reduce quorum sizes [HMS16].

We identify a research gap when it comes to distributed consensus with the focus on topology requirements and awareness for the locality of event orderings. One important approach in this direction is Canopus [RWK17], which achieves some of the postulated requirements: Distributed Hierarchical Consensus. However in contrast to Canopus, we favor liveness, availability and failsafe partition-tolerance over global consistency [Br00], in order to maintain stable micro grids in case of grid separation.

3 Hierarchical Aggregated Consensus

We investigate consensus variants that allow us to maintain a global consensus on the partial ordering of decentralized events. Criteria are on one hand the computational, storage and message overhead. On the other hand, resilience against denial-of-service attacks, both targeted and random-target, will be investigated. The proposed scheme extends classical consensus by three concepts: Clustering, Hierarchical Aggregation and Pairwise Agreement.

Clustering We refer to local consensus regarding the classical consensus within one Nano Grid. When the participating nodes are arranged according their grid distances in the actual electrical power system, this defines the relative neighborhood between them [St19]. Nodes are dynamically organized with respect to their topological locality into a high-degree tree-structure, which we will call clusters. This way it is possible to solve critical grid states locally.

Hierarchical Aggregation Classical consensus that aims to agree on a single value or schedule for the whole system. The hierarchical distribution grid topology, as shown in Fig. 2, serves as the basis for clustering: Smart Meters aggregate IEDs, street energy management systems aggregate Smart Meters and so on up to the connection power to the transmission grid at a power transformer. In this model, we require consensus in two dimensions, namely on each hierarchy level and between the different layers.

Pairwise Agreement Announcing capabilities in a broadcast manner and then reaching pairwise agreements is an approach that can work completely without leaders and has proven to deliver reasonable results even for inter-cluster consensus [SIB20]. The application of

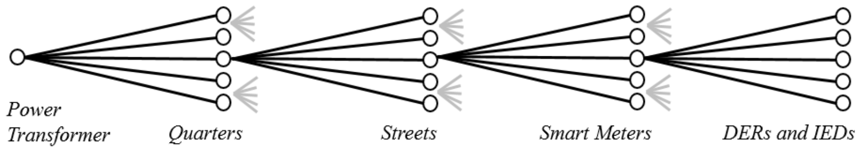

Fig. 2: Schematic hierarchy of the distribution grid and the coordinating Micro Grid.

balancing power between generators and consumers leads to the insight, that the approval of unaffected grid participants is generally not required. Analogous to EPaxos, where an a priori transactions dependency definition is required [MAK13], we are describing concurrent consensus of unrelated events from a grid-topological perspective.

Taking into account the related work of distributed consensus (cf. Section 2) and the suggested new approach, the ongoing research aims to answer the following three research questions:

RQ 1: How can pairwise agreement between nodes be parallelized into a generalized distributed hierarchical consensus protocol? Is pairwise agreement the best local consensus strategy?

RQ 2: How can the parallel agreement then be aggregated into a global state while maintaining fail-safe partition tolerance?

RQ 3: What kind of schedule description and aggregation satisfies the requirements of this Smart Grid balancing scheme, for deriving a global consensus state from concurrent sub-consensus?

When composing hierarchical layers of consensus, nonetheless it is still highly relevant to achieve local in-cluster consensus in a reliable manner. We are evaluating the suitability of the following alternatives to pairwise agreement:

Hierarchical Decision by Elected Leader: Hierarchical decision trees have the main advantage that they resemble the existing structures of power grids, both from the historical experiences as well as the topological reality of distribution grids.

Distributed Ledger: Using distributed ledger technologies has the attribute that all messages are stored for further inspection. Unlike Paxos variants, all nodes have to contribute to the message verification [SPK19]. The main disadvantages are the increased computing and storage requirements that may exceed the capabilities of small devices.

Power of Two: The concept of the Power of Two [Mi01] uses smartly randomized load balancing. The suitability of this concept for hierarchical systems is of special interest, since it leads to a convergence to close-to-optimal solutions while radically reducing the amount of messages that are required to find a consensus.

4 Outlook

In our future work we will elaborate on explicit clustering schemes. Thereby we want to describe an adaptable clustering scheme, such that the affiliation of nodes to clusters can be re-negotiated and the hierarchical structure of superordinate clusters may also shift, in order to respond to environmental influences, such as variations in wind speed, solar radiation or any other factor, which influence the capabilities of the DERs.

We also plan to look into continuous schemes that operate beyond single consensus rounds and are able to re-iterate towards changing optimal solution and clusterings. The distribution grid is structured hierarchically, but the transmission grid can be seen as a planar graph, as visualized in Fig. 3. Therefore we plan additional research towards the difference between hierarchical consensus and consensus in clusters within a flat neighborhood.

Regarding resilience against electrical Denial-of-Service attacks, we will elaborate on availability of power itself: e.g. an attack by synchronously switching on thousands of high-wattage IoT devices. We are looking into schemes that prevent the grid from experiencing cascading failures.

Machine-to-machine validation of identities and their positions in the grid topology will be a hard requirement to support the ongoing transition. In order to achieve valid consensus between authorized participants, the proposed scheme needs to provide protection against identity theft as well as Sybil attacks [NNM13].

Further, we identify two kinds of False-Data-Injection attacks that need to be addressed. First, since the aggregating nodes pose as gate-keepers between the various clusters, they are especially vulnerable to attacks on data integrity. Second, consuming or generating participants may act differently than announced. This is beyond the scope of communication integrity and thereby especially difficult to address.

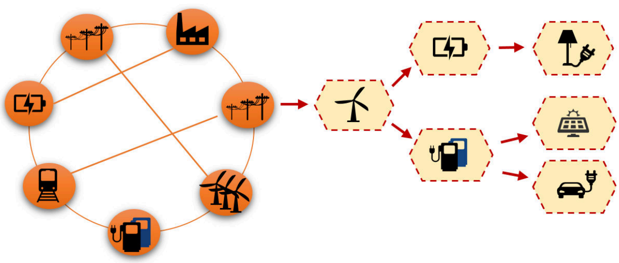

Fig. 3: The transmission grid on the left has a meshed structure whereas the distribution grid is structured hierarchically.

5 Conclusion

We elaborate on the use of hierarchical consensus schemes for Smart Grids, acknowledging both the mostly tree-like topology of the power grid, as well as the interdependency between power flow and the control infrastructure. Implementing a clustering scheme for Micro Grids, we can achieve fast consensus by directly communicating to an dynamically defined, interference-free subset of neighboring nodes and over the hierarchical composition of such clusters. We investigate which distributed consensus schemes are suitable to combine the advantages of parallelization of responsibility with strong respect to the locality of the electrical grid when achieving consensus within self-organizing Micro Grids including power suppliers and consumers.

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