Why Your Power System Restoration Does Not Work and What the ICT System Can Do About It

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ABSTRACT

While long-term wide-range blackouts have been studied extensively from a power systems perspective, the role of ICT in the recovery of smart energy systems has not been investigated to the same extent. This paper presents a flexible blackstart service to restore a smart distribution system alongside an impaired ICT system. We formulate the problem of power grid restoration as a distributed optimization problem, taking into account distributed energy resources and remote-controllable switches as optimization variables and employ a multi-agent system to deliver an optimal island configuration. We define an integrated architecture for the interdependent power and ICT system and test our methodology on a realistic distribution system scenario with varying impaired ICT. The results show that the efficiency of the restoration is highly sensitive to the placement of emergency power supply and the coverage of ICT nodes.

CCS CONCEPTS

• **Hardware → Smart grid**; • **Computing methodologies → Multi-agent systems**; • **Computer systems organization → Reliability**.

KEYWORDS

distribution grid restoration, distributed optimization, multi-agent system, communication network restoration

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1 INTRODUCTION

Failures of large power plants, tripping of transmission lines or mistakes in grid operation can cause major blackouts in the transmission grid, leaving customers in the distribution grid without power [10]. Although there exist well-established concepts to blackstart the power system on transmission level [26], necessary repair work can increase the time until all customers are restored [20]. *Distributed Energy Resources (DERs)* can be used to extend existing top-down restoration approaches by intelligent automated restoration services in the distribution grid to restore critical loads and reduce the general outage time for customers. In this paper, we use the term *island grids* in context of local distribution system restoration to emphasize that we do not consider predefined grid areas, which would also work as a microgrid in normal operation, but rather the dynamic formation of local operational grid areas in case of a blackout.

To solve the highly combinatorial, non-linear, non-differentiable, constrained and multi-objective problem of distribution system restoration, *Multi Agent System (MAS)*-based heuristics are a rational choice [3, 21, 23]. While this problem has been extensively studied from the power engineering perspective, the majority of existing research only considers abstracted communication or omits communication constraints altogether [4, 24, 30]. An exception is the recent work in [19], where interdependencies between power and communication systems have been considered in the problem formulation. However, the focus is only on power system restoration and detailed coordination between DERs is not considered. Our approach provides a significant advantage by shifting the focus from isolated power system restoration to parallel power and Information and Communication Technologies (ICT) system restoration so as to achieve a *cascading restoration process*, where both systems assist each other [28]. In this paper, we focus on the development of the fully distributed blackstart algorithm and investigate the impact of ICT impairment on its performance.

Our contributions are as follows: We adapt the *Combinatorial Optimization Heuristic for Distributed Agents (COHDA)* algorithm to perform the restoration by adding remote-controlled power switches into the problem formalization [12]. COHDA is an established heuristic which offers robustness against message delays and a changing communication overlay and therefore, provides a good basis for the impaired ICT scenario. Using available ICT nodes,

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the agents successively form island grids with balanced generation and load in the distribution grid, thereby restoring additional ICT devices. We perform an evaluation on realistic simulation scenarios of interdependent power and communication systems and study different communication parameters to underline the influence of the degraded communication system on the island grid forming.

2 ICT-ENABLED POWER SYSTEM ARCHITECTURE

We consider a Medium Voltage (MV) grid after a wide-area blackout in the transmission grid. The topology represents a modern radial distribution grid with tie lines between feeders. DERs have a significant contribution to the energy generation with a high share of Renewable Energy Source (RES) like Photovoltaic (PV)-plants and wind turbines. Throughout the grid, several DERs are designed to be blackstart capable, for example by combining large wind- or PV-plants with battery storages and suitable grid-forming inverters and controllers [17, 25].

We assume the distribution grid to have a high level of automation to support the Distribution System Operator (DSO) in dealing with the increased complexity of future distribution grids. The generators and controllable devices (e.g. switches, electric vehicles, heatpumps) at Low Voltage (LV) and MV level are equipped with microcontroller-based *Intelligent Electronic Devices (IEDs)*, which are typically supplied with a battery which can last up to 30 hours. We assume that software agents of the MAS run on each available IED in order to collect the information for restoration service and aggregate it at the associated MV/LV substation.

The primary challenge of the ICT system is to enable communication between IEDs in the presence of multi-level disturbances, arising from the unavailability of the power supply for the intermediate ICT nodes, such as routers and repeaters, and upper-level communication services, such as wide-area routing. We assume that public communication infrastructures are primary used at the distribution grid level. In this work, we consider 450MHz [29] and Long Term Evolution Advanced (LTE-A) networks as enablers of the distribution grid restoration. In order to guarantee packet routing during the power outage, LTE-A base stations can be enhanced to support self-backhauling at the access network level [8], hence continue providing end-to-end links between MV/LV substations during the whole restoration process. Flexible placement of the self-backhauling functions is possible by employing Network Function Virtualization (NFV) [27]. However, limited battery time [6] as well as switching from normal to self-backhauling operation can lead to degradation of the communication. In this work, we want to focus on the influence of size and availability of the cells on the restoration process.

We do not consider the challenges for stability that arise from operation of small grids, like low system inertia, high R/X ratio and limited short-circuit capacity [7]. Instead, we use a simplified model with steady-state simulations, that does not take into account aforementioned dynamic effects. The question of handling stability issues in microgrids is part of ongoing research and promising solutions have already been introduced, e.g. virtual synchronous machines [16].

3 PROBLEM FORMALIZATION

We formally describe the power grid model by creating a graph $G = (V, E)$ with MV power system nodes V and MV lines E. A node $v_i \in V$ can either be a single generator, a single load or a set of any number of both. It is therefore described as a tuple (G_i, L_i) with $G_i \cup L_i \neq \emptyset$; G_i being the set of generators and L_i the set of loads connected to v_i. We represent each generator j in G_i by a schedule $w_{ij}^{G} \in \mathbb{R}^q$ and correspondingly each load k in L_i by a schedule $w_{ik}^{L} \in \mathbb{R}^q$. Variable q marks the schedule's planning horizon, which always starts at the current timestep and extends to the future timestep defined by q. Following the passive sign convention, we assume loads to be modelled with positive consumption ($w_{ik}^{L} \geq 0$) and generators with negative generation ($w_{ij}^{G} \leq 0$). To start the restoration process and allow the creation of an island, there has to be at least one node with a blackstart capable unit, defined by $v_i^{bc} \in V$. Finally, we define the total set of switches S: A switch $s_i \in S$ is associated with one line $e_i \in E$ and has a state $s_i.state$ that can either be open (0) or closed (1).

We can now describe island grid $G_I = (V_I, E_I)$ as follows: After choosing a state $s_i.state \in \{0, 1\}$ for each $s_i \in S$ we update graph G by removing all edges $e_i \in E$ for which $s_i.state = 0$. The current island composition G_I is now a connected component of G: Since an island is always formed around a node v_i^{bc}, each node $v_i \in V$ that has a path to any v_i^{bc} is considered as part of V_I and therefore as part of the island. Consequently, all G_i and L_i of v_i are also part of the island. The complete distribution system restoration problem can now be defined by extending the problem description from COHDA, which was originally developed to solve a predictive scheduling problem for virtual power plants [13]:

$$\begin{aligned}
&\max \left(\sum_{i=1}^{|V_I|} \sum_{k=1}^{|L_i|} w_{ik}^{L} \right) && (1)\\
&\text{with } G_I = (V_I, E_I) \subseteq G = (V, E) \\
&\text{where } E = \{\{e_1, ..., e_x\} | e \in E, s_i.state = 1\} \\
&\qquad V_I = \{v_1, ... v_x \ | v \in V, v \text{ has path to a } v^{bc}\} \\
&\text{subject to } \left(\sum_{i=1}^{|V_I|} \sum_{k=1}^{|L_i|} w_{ik}^{L} \right) + \left(\sum_{i=1}^{|V_I|} \sum_{j=1}^{|G_i|} w_{ij}^{G} \right) = 0
\end{aligned}$$

The objective is to maximize the amount of restored load in the island G_I by choosing a state $s_i.state$ for each $s_i \in S$ while keeping generation and load in the island balanced. This balancing can be done by choosing a schedule w_{ij}^{G} for all generators in V_I to match the total load in V_I. A change of any $s_i.state$ potentially changes the composition of G_I and therefore changing the generators available for balancing. This results in two nested optimization problems: The maximization of load in V_I on upper level and on lower level the minimization of the difference between load and generation – represented as Euclidean distance between the aggregated load and generation vectors – for the current composition of V_I.

The behaviour of uncontrollable loads is assumed to be known and described by one fixed schedule w_{ik}^{L}, whereas generators offer certain flexibilities from which different schedules w_{ij}^{G} can be created. One approach to handle the potentially large set of possible

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schedules and unit-specific constraints is the use of a decoder: Instead of having a complete set of schedules, the possible schedules are represented by a flexibility model, which can be used to map an optimal, but infeasible schedule to a feasible one in the search space [2].

4 RESTORATION ALGORITHM

The previously described problem is mapped to a MAS to achieve distributed problem solving. *Switch Agents* control the state for each switch and solve the upper level optimization problem (Equation 1). A Switch Agent is always an aggregator of one grid segment and represents all switches connecting this grid segment with neighbouring segments. *Unit Agents* monitor the consumption of loads or control the schedules of generators and focus on the lower level optimization problem by trying to minimize the difference between load and generation in the current island configuration. They can represent a single MV generation unit, a single MV load or an aggregation of LV generation/load.

Figure 1 illustrates the holonic structure of the MAS. A holon describes an element that is the whole and the part of a system at the same time – constituted by lower level holons, while also being a part of a higher level holon [9]. The different holons reflect two different structural aspects: The physical structure of the power system (each grid segment is represented by one level 1 holon with the connected elements being a part of the underlying level 0 holons) and the abstract structure of the nested optimization problem (upper and lower level).

The restoration algorithm now uses two interlaced COHDA-instances, as has been successfully demonstrated in [1], to solve this nested optimization problem. One negotiation consists of three steps, which are the same for both COHDA-instances. *(Perceive)*: When receiving a message, an agent integrates the new information into its current knowledge about the system, i.e. its *working memory*. *(Decide)*: Based on its current working memory, the agent makes its decision on the optimization variable it controls (w_i^G or $s_i.state$) and tries to find a better solution for its respective optimization problem. *(Act)*: Finally, an agent sends its updated working memory to all its neighbours. After *(Perceive)*, Switch Agents first send a target schedule to their Unit Agents to start an underlying negotiation. Using a flexible target schedule instead of trying to balance generation and load in each node allows the surplus generation to be used by neighbouring holons. Only after receiving the result, they continue with *(Decide)* and *(Act)*.

If an agent does not receive new information and is not able to improve its current best choice, it does not perform the final step *(Act)*. This behaviour eventually leads to the convergence and termination of the algorithm as described in detail in [12]. The number of exchanged messages of COHDA increases superlinearly with the number of agents, as in $O(n^{1.4})$ [14]. However, due to the holonic structure the number of agents in individual negotiations is limited to the number of MV nodes in one distribution grid. After each successful restoration step, further parts of the ICT system get restored, enabling more agents to participate in the next negotiation and, in turn, restore more parts of the power system. Therefore the repeated execution of the algorithm creates a cascading restoration process.

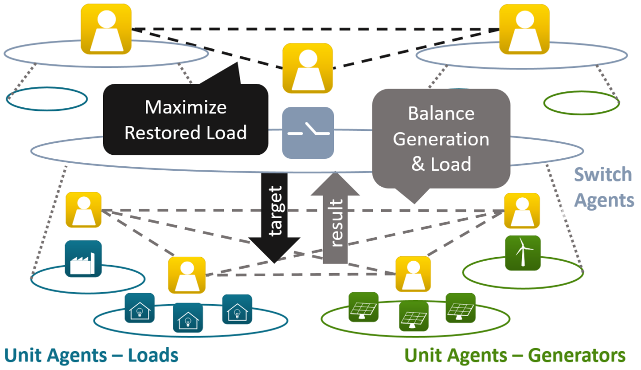


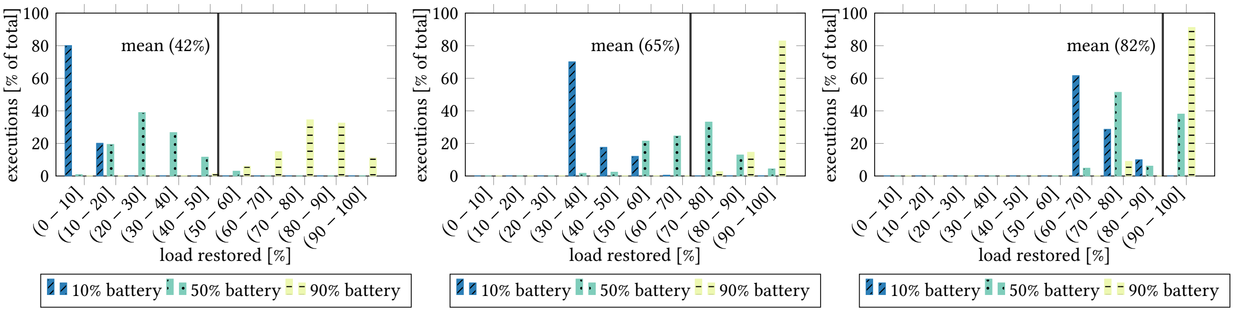
Figure 1: Holonic agent structure

5 EVALUATION

The goal of our evaluation is to assess the effects of ICT impairment on the solution quality of the restoration algorithm. The solution quality is here defined as a percentage of maximum load restored using the available generation capacity. We chose a SimBench MV scenario [18] as our fixed power system scenario, which offers increased flexibility in island formation with a switch on every line. We use the associated time series for the RES in the grid model as the maximum possible generation for each unit, which can be arbitrarily reduced if necessary to create optimal schedules. We assume the loads to be fixed according to the time series.

We then used a Box-Behnken-Design for the experimental setup to study the following two ICT factors: (1) the number of the available ICT nodes (in our setup with cellular access networks – base stations with battery supply) and (2) size of access network as cell size. According to [6], more than 30% of the batteries installed at the base stations might be in faulty, discharged or nearly-dead state. Therefore, we assume that a minimum level of degradation will always be present, choosing 90% of available battery backup as the highest possible value. On the other hand, we assume a minimum value of 10% of available batteries to enable basic restoration and 50% as the medium value to achieve uniform coverage of the response surface. To reflect the possible variety of initial scenarios, we place the batteries randomly at the base stations for each scenario and for each simulation run. This mandates the need for repeated simulation runs, therefore each scenario is executed as many times as necessary to reach a confidence value of ≤ 0.05 for the results. The values of cell sizes are chosen based on the power grid scenario as well as current state of the art. We consider the smallest cell size to be 2 km and the medium cell size is selected to be 6 km. We also consider large cell size as 10 km as per state of the art of Long Term Evolution (LTE) technology [15]. Larger cells provide also more overlapping behaviour, thus, power grid nodes can have access to several ICT nodes at the same time.

For executing the experiments, we developed a co-simulation setup, using the co-simulation platform *mosaik* [22]. We coupled *mango* [5] for the implementation of the MAS, *SimBench* [18] for the power grid and *NetworkX* [11] for the ICT system.



(a) 2 km cell size **(b) 6 km cell size** **(c) 10 km cell size**

Figure 2: Distribution of load restored per scenario execution for different numbers of batteries in different cell sizes

6 SIMULATION RESULTS

As a benchmark for the simulation results, we tested scenarios with 100% battery backup considering all three cell sizes, which always resulted in 100% of load restored. This implies that any degradation in load restoration observed henceforth is a consequence of impaired ICT.

Owing to the random placement of batteries, the amount of restored load differs in each scenario execution. This effect is summarized in Figure 2, showing the distribution of results for different cell sizes. The black line marks the mean restored load of all simulations runs in all scenarios for the respective cell size. It can be observed that with a larger cell size and therefore higher amount of overlapping cells, the restoration process is more robust against base station unavailability. Figure 2c shows that in the 10 km cell size scenario, the spread for all levels of battery backup availability is relatively small with a minimum of $(60-70]\%$ and a maximum of $(90-100]\%$. The spread in the restored load is, however, larger for 2 km and 6 km cell size – not only for all levels of battery backup availability but also within one individual level. For example, Figure 2a shows that even with 90% available battery backup, the possible restored load varies between $(50-60]\%$ to $(90-100]\%$.

Figure 3 shows the effect of battery and cell size on restored load as well as the correlation between the two parameters. As expected, a higher amount of battery backup availability enables more load restoration. Likewise, with increasing cell size more load gets restored due to larger initial communication overlay and more cell overlapping. The highest mean restoration of 99% can be observed for the combination of both parameters' highest values, the 10 km cell size and 90% battery backup availability. It can also be seen that both factors can compensate each other: Scenarios with 2 km cell size and 90% battery provide equally good results as scenarios with 10 km cell size and 10% battery backup.

7 CONCLUSION AND FUTURE WORK

In this paper, we presented the power system restoration as a two-level optimization problem and applied a MAS for distributed problem solving, using the COHDA algorithm. We also proposed an ICT-enhanced power grid infrastructure, which supports the communication between the agents of the MAS. For the evaluation, we considered an interconnected ICT and power system with varying values of cell size and battery backup. The results show, that both parameters have an effect on the restored load but can also compensate each other.

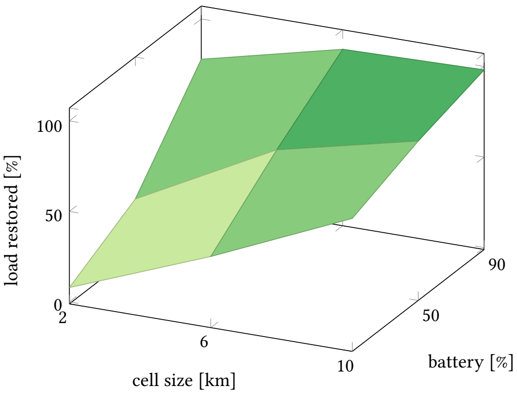


Figure 3: Surface plot for battery and cell size

This work motivates extensions along several directions. Our next step is to evaluate the scalability of the algorithm, considering the holon size as well as ICT impairment in terms of limited bandwidth and message losses. Following this, an intelligent ICT restoration algorithm will be designed, taking into account the architectural and Quality of Service (QoS) parameters of the ICT network and also identifying critical nodes that influence the efficiency of the restoration process. By prioritizing these nodes in the power system restoration, the cascading restoration process can be improved significantly. Finally, the robustness of the algorithm should be increased by considering unexpected events – such as not cleared faults in the grid – as well as uncertainties in the generation and load.

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See `http://www.net.fim.uni-passau.de/papers/Stark2021` for full reference details (BibTeX, XML).

REFERENCES

[1] Jörg Bremer and Sebastian Lehnhoff. 2017. Decentralized Coalition Formation with Agent-based Combinatorial Heuristics. *ADCAIJ: Advances in Distributed Computing and Artificial Intelligence Journal* 6 (09 2017), 29. https://doi.org/10.14201/ADCAIJ2017632944

[2] Joerg Bremer and Sebastian Lehnhoff. 2018. A Cascading Chi-shapes based Decoder for Constraint-handling in Distributed Energy Management. In *IJCCI*. 184–191. https://doi.org/10.5220/0006926101840191

[3] Chen Chen, Jianhui Wang, Feng Qiu, and Dongbo Zhao. 2015. Resilient distribution system by microgrids formation after natural disasters. *IEEE Transactions on smart grid* 7, 2 (2015), 958–966. https://doi.org/10.1109/TSG.2015.2429653

[4] Markus Eriksson, Mikel Armendariz, Oleg O Vasilenko, Arshad Saleem, and Lars Nordström. 2014. Multiagent-based distribution automation solution for self-healing grids. *IEEE Transactions on industrial electronics* 62, 4 (2014), 2620–2628. https://doi.org/10.1109/TIE.2014.2387098

[5] OFFIS e.V. 2020. *mango - Modular Python Agent Framework*. https://gitlab.com/mango-agents/mango Accessed: 2021-05-18.

[6] Xiaoyi Fan, Feng Wang, and Jiangchuan Liu. 2016. On Backup Battery Data in Base Stations of Mobile Networks: Measurement, Analysis, and Optimization. In *Proceedings of the 25th ACM International on Conference on Information and Knowledge Management* (Indianapolis, Indiana, USA) *(CIKM '16)*. Association for Computing Machinery, New York, NY, USA, 1513–1522. https://doi.org/10.1145/2983323.2983734

[7] Mostafa Farrokhabadi, Claudio A Cañizares, John W Simpson-Porco, Ehsan Nasr, Lingling Fan, Patricio A Mendoza-Araya, Reinaldo Tonkoski, Ujjwol Tamrakar, Nikos Hatziargyriou, Dimitris Lagos, et al. 2019. Microgrid stability definitions, analysis, and examples. *IEEE Transactions on Power Systems* 35, 1 (2019), 13–29. https://doi.org/10.1109/TPWRS.2019.2925703

[8] Romain Favraud, Chia-Yu Chang, and Navid Nikaein. 2018. Autonomous Self-Backhauled LTE Mesh Network With QoS Guarantee. *IEEE Access* 6 (2018), 4083–4117. https://doi.org/10.1109/ACCESS.2018.2794333

[9] Adriano Ferreira, Ângela Ferreira, Olivier Cardin, and Paulo Leitão. 2015. Extension of holonic paradigm to smart grids. *15th IFAC Symposium on Information Control Problems in Manufacturing* 48, 3 (2015), 1099–1104. https://doi.org/10.1016/j.ifacol.2015.06.230

[10] Hassan Haes Alhelou, Mohamad Esmail Hamedani-Golshan, Takawira Cuthbert Njenda, and Pierluigi Siano. 2019. A survey on power system blackout and cascading events: Research motivations and challenges. *Energies* 12, 4 (2019), 682. https://doi.org/10.3390/en12040682

[11] Aric Hagberg, Dan Schult, and Pieter Swart. 2020. *NetworkX Reference*. https://networkx.org/documentation/stable/_downloads/networkx_reference.pdf Accessed: 2021-05-18.

[12] Christian Hinrichs, Sebastian Lehnhoff, and Michael Sonnenschein. 2013. COHDA: A combinatorial optimization heuristic for distributed agents. In *International Conference on Agents and Artificial Intelligence*. Springer, 23–39. https://doi.org/10.1007/978-3-662-44440-5_2

[13] Christian Hinrichs, Sebastian Lehnhoff, and Michael Sonnenschein. 2014. A Decentralized Heuristic for Multiple-Choice Combinatorial Optimization Problems. *Operations Research Proceedings 2012*. https://doi.org/10.1007/978-3-319-00795-3_43

[14] Christian Hinrichs and Michael Sonnenschein. 2017. A distributed combinatorial optimisation heuristic for the scheduling of energy resources represented by self-interested agents. *International Journal of Bio-Inspired Computation* 10, 2 (2017), 69–78. https://doi.org/10.1504/IJBIC.2017.085895

[15] Harri Holma and Antti Toskala. 2011. *LTE for UMTS: Evolution to LTE-advanced*. John Wiley & Sons, New York, NY, USA.

[16] Thongchart Kerdphol, Masayuki Watanabe, Yasunori Mitani, Dirk Turschner, and Hans-Peter Beck. 2020. Stability Assessment of Multiple Virtual Synchronous Machines for Microgrid Frequency Stabilization. In *2020 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 1–5. https://doi.org/10.1109/PESGM41954.2020.9281491

[17] A Korai, J Denecke, JL Rueda Torres, and E Rakhshani. 2019. New control approach for blackstart capability of full converter wind turbines with direct voltage control. In *2019 IEEE Milan PowerTech*. IEEE, 1–6. https://doi.org/10.1109/PTC.2019.8810684

[18] Steffen Meinecke, Nils Bornhorst, Lars-Peter Lauven, Jan-Hendrik Menke, Martin Braun, Simon Drauz, Christian Spalthoff, Dennis Cronbach, Tanja Kneiske, Annika Klettke, Julian Sprey, Tobias van Leeuwen, Albert Moser, Džanan Sarajlić, Chris Kittl, and Christian Rehtanz. 2020. *SimBench Documentation - Documentation Version EN-1.0.0*. https://simbench.de/wp-content/uploads/2020/01/simbench_documentation_en_1.0.0.pdf.

[19] Martin Pietsch, Anja Klein, and Florian Steinke. 2020. Merging Microgrids for Optimal Distribution Grid Restoration under Explicit Communication Constraints. In *2020 Resilience Week (RWS)*. IEEE, 48–54. https://doi.org/10.1109/RWS50334.2020.9241251

[20] Claudia Quester, Dagmar Sommer, and Claus Verstegen. 2014. *Störungen im Stromnetz und Notstromfälle in Kernkraftwerken in den Jahren 2003 bis 2012.* Technical Report.

[21] Ebrahim Rokrok, Miadreza Shafie-khah, Pierluigi Siano, and João PS Catalão. 2017. A decentralized multi-agent-based approach for low voltage microgrid restoration. *Energies* 10, 10 (2017), 1491. https://doi.org/10.3390/en10101491

[22] Steffen Schütte, Stefan Scherfke, and Martin Tröschel. 2011. Mosaik: A framework for modular simulation of active components in smart grids. In *2011 IEEE First International Workshop on Smart Grid Modeling and Simulation (SGMS)*. IEEE, 55–60. https://doi.org/10.1109/SGMS.2011.6089027

[23] Anurag Sharma, Dipti Srinivasan, and Anupam Trivedi. 2016. A decentralized multi-agent approach for service restoration in uncertain environment. *IEEE Transactions on Smart Grid* 9, 4 (2016), 3394–3405. https://doi.org/10.1109/PESGM.2018.8586526

[24] Anurag Sharma, Anupam Trivedi, and Dipti Srinivasan. 2018. Multi-stage restoration strategy for service restoration in distribution systems considering outage duration uncertainty. *IET Generation, Transmission & Distribution* 12, 19 (2018), 4319–4326. https://doi.org/10.1049/iet-gtd.2018.5915

[25] Christoph Strunck, Marvin Albrecht, Gerhard Meindl, and Christian Rehtanz. 2019. A Study on the Black Start Process of a real Distribution Network with CHP plants and BESS. *EPJ Web of Conferences* 217 (01 2019), 01015. https://doi.org/10.1051/epjconf/201921701015

[26] Union for the Co-ordination of Transmission of Electricity (UCTE). 2010. P5 - Policy 5: Emergency Operations. In *UCTE Operation Handbook*. UCTE, 1–46.

[27] Anna Volkova. 2019. Blackout Recovery: Resilient NFV-enabled ICT Infrastructure for the Smart Grid. In *Abstracts from the 8th DACH+ Conference on Energy Informatics*. Springer, Salzburg, Austria, 73–76. https://doi.org/10.1186/s42162-019-0098-7

[28] Anna Volkova, Sanja Stark, Hermann de Meer, Sebastian Lehnhoff, and Joerg Bremer. 2019. Towards a blackout-resilient smart grid architecture. In *International ETG-Congress 2019; ETG Symposium*. VDE, 1–6.

[29] Matthias Wissner, Bernd Sörries, and Wolfgang Zander. 2020. Die 450 MHz-Frequenz als Wegbereiter der Energiewende. *Zeitschrift für Energiewirtschaft* 44, 3 (2020), 163–175. https://doi.org/10.1007/s12398-020-00280-y

[30] Aboelsood Zidan and Ehab F El-Saadany. 2012. A cooperative multiagent framework for self-healing mechanisms in distribution systems. *IEEE transactions on smart grid* 3, 3 (2012), 1525–1539. https://doi.org/10.1109/TSG.2012.2198247