Smart Grid Resilience: Concepts on dealing with Power Scarcity for decentralized Power Systems

Sadeeb Simon Ottenburger, Wolfgang Raskob

Introduction

A better understanding of upcoming technological transformations and their impact on critical infrastructure systems and security of supply is one of the main drivers of our research. The transformation of the classical power system into a smart decentralized power system is one of the most prominent and societally relevant examples of such transformations - the ongoing increase of automation and power consumption illustrates it's increasing importance accompanied by a simultaneously increase of vulnerabilities. Furthermore, a drastic change of power consumption, e.g. by an increased usage of electric vehicles, may result in unforeseen loads that cannot be managed by the utility provider e.g. in terms of demand side management. Therefore, our research deals with the following topics: Assessing the impact of different power and ICT- network structures on the resilience of urban systems. Development of new risk-based power distribution mechanisms dealing with power scarcity in order to avoid large-scale blackouts and improve security of supply (Ottenburger et al. 2018b; Ottenburger und Münzberg T. 2017). The methods that are used ground on modelling various critical infrastructures, power-, and ICT-infrastructures separately, but also new resilience measures. The key idea is to consider smart grid topology and power distribution mechanisms as model parameters. Thus, by varying these parameters for a specific region, e.g. an urban area, good structures and distribution mechanisms may be identified.

Urban Resilience and Power System

The concept of urban resilience encompasses various types of resilience dimensions such as the social, economic or physical infrastructure dimension (Cimellaro 2016). Critical infrastructure (CI) services such as the supply of electricity, drinking water, and health care provide vital services for the population, thus disruptions or failures of these services are hazardous and can lead to injuries or even losses of life, property damages, social and economic disruptions or environmental degradations. Therefore, CIs constitute a pivotal aspect in urban resilience considerations and establishing and implementing sophisticated continuity management concepts w.r.t. CIs can be regarded as one of the major building blocks for preserving or enhancing urban resilience. Most of the CIs like water supply, hospitals, pharmacies, and traffic- and transport systems rely on electricity - the circumstance of massive dependencies of other CIs to the electrical power entitles the electrical power grid to be considered as a *high ranked* CI. The generation and supply of electricity is currently about to undergo a fundamental transition (Farhangi 2010; Gungor et al. 2013). Due to the integration of smart meters, the consumers in the classical sense will have the eligibility to consume, produce and distribute electricity. The therefor necessary smart meters are electronic devices that monitor electricity consumptions and generations and allow two-way communications with other meters (Parhizi et al. 2015). However, to keep a stable electricity supply it is important that in-feed and consumption form an equilibrium. A smart grid construed as a complex and highly automated power distribution grid fundamentally relies on a rigorous multi-layered distribution management system in order to maintain grid performance and reliability. The architecture of a distribution management system allows a partitioning into several locally arranged and interconnected operation centers which themselves may be considered as local distribution management systems. A precise and secure operation of an energy management system of a smart grid, that operates - due to grid stability issues - automatically in real-time, heavily depends on the degree of accuracy of the transmitted quantities of interest.

For reasons of simplicity, in the remainder of this report infrastructures like companies, commercial buildings or households are included in the term CI.

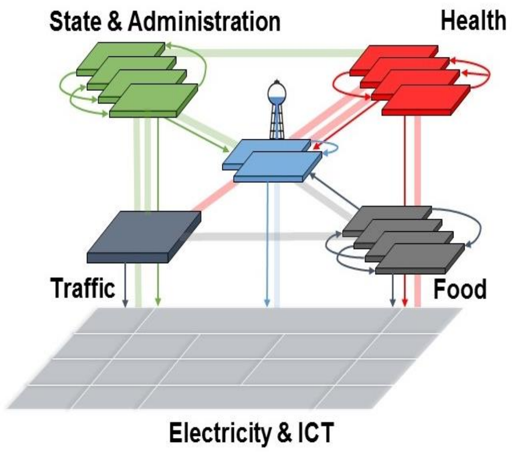

Fig. 1 Interdependent Critical Infrastructures

Vulnerabilities and Challenges of Future Power Systems

Many components of a smart grid are located not on the utility's premise and are therefore prone to physical damage. Since information technology systems are relatively short lived it is quite likely that outdated devices are still in service e.g. anti-virus software may be deprecated or hardware components may not comply with the latest requirements. Furthermore, the great number of devices are potential entry points for malicious cyber-attacks like malware spreading which may infect smart meters or other devices and can add or replace functions and disseminates, injecting false information by faking sensitive smart meter that can cause wrong decisions, and Denial-of-Service attacks by manipulating IP protocols that can delay, block or corrupt the transmission of information in order to make SG resources unavailable (Aloul et al. 2012).

Besides the increase of susceptibility on the cyber-physical component level, and despite the current and upcoming advancements and progresses in cyber security technologies, the vulnerability of the future power system itself and hence the probability of CI systems suffering from power outage grow, if there won't exist appropriate power continuity management strategies w.r.t. CIs. Another issue that should not be underestimated are drastic increases in power consumption that cannot be handled by demand side management techniques solely, e.g. e-vehicles and charging behavior.

Our research is pursuing the following objective: Developing new approaches to operationalize risk-based concepts to foster the developments of new strategies for CI protection by exploiting topological design options for smart grids and by proposing a risk-based smart grid control mechanism that is embedded in an energy management system.

Criticality and Degrees of Freedom

In view of net neutrality, this work perceives criticality as a risk-comparing framework, which we split up into different subcategories. The type of the power shortage scenario, the different relevancies of CIs and the timely varying demands for critical services determine the possibly timely varying so-called *global criticality* of CIs in an urban area. *Global criticality* of a CI can be considered as a function depending on relevancies of all other CIs, global system variables and the CI's *local criticality*, where *local criticality* is a function describing the critical state of a CI, reflecting its internal state, current and expected demand, current and expected fulfillment of demand etc. *Global criticality* and *local criticality* are of course power shortage scenario dependent. In the case of normal performance states of CIs and no occurring or expected power shortage, *global criticality* reflects the different relevancies of CIs compared to each other - these values are called *initial criticality* of CIs - for more details we refer to (Ottenburger et al. 2018b; Münzberg und Ottenburger 2018).

Operationalizing criticality should start in the phase of designing grid extensions or developments both from the ICT- but also from the physical power infrastructure perspective. This work especially focuses on two topological degrees of freedom in the design of smart grids. One topological degree of freedom refers to decomposition of a smart grid into so-called microgrids which may be disconnected from the overall smart grid and operate autonomously in island mode. A smart grid subdivided into microgrids has the potential to restrict cascading effects and hence to be less vulnerable against disruptions. Cascading effects due to dysfunctionalities of certain components or propagation of malware throughout a smart grid might be prevented by disconnecting the affected microgrids from the overall smart grid. Although having isolated disturbed or dysfunctional microgrids from the smart grid of a city, CI dependencies may cause issues in other parts and reduce the resilience of the city as a whole. Another topological degree of freedom refers to different configuration options w.r.t. smart grid components, e.g. overlaying network structures to provide redundancies within a microgrid.

Obviously, the network topology of a smart grid has significant effects on urban resilience particularly referring to the adequate provision of vital services of CIs. Taking *initial criticality* into account during the smart grid design phase can be regarded as a first proactive measure in the sense of preparedness. The rationale of applying *initial criticality* could be to distribute CIs with high *initial criticality* on different microgrids, avoiding a concentration of highly relevant CIs in one microgrid, or to build redundancies for CIs with high *initial criticality*. An elaborated topology of smart grids increases urban resilience.

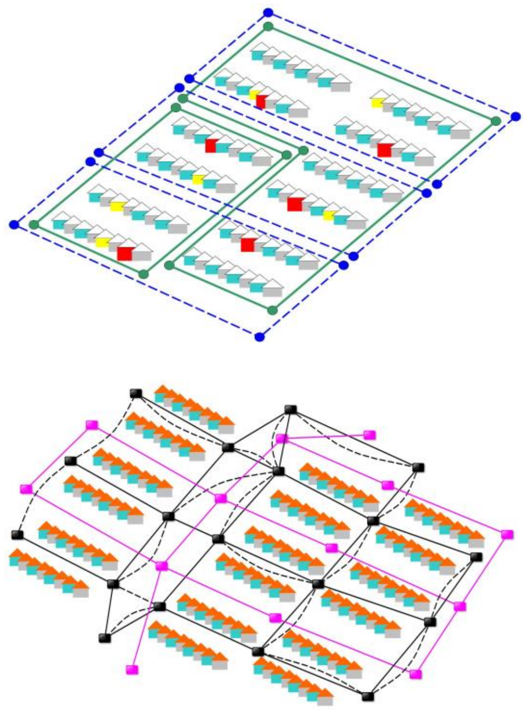

Fig. 2 Topological degrees of freedom: decomposition into microgrids and configuration of components

Resilience Measure: Supply Index

Advanced Metering Infrastructures (AMIs) including smart meters allow fine-grained power distribution management strategies that go beyond the classical strategies like rolling blackouts. A main task is to develop resilient and fair power distribution strategies in times of power shortage by exploiting the advantages of an AMI and smart meters. Therefore, new resilience metrics, measuring security of supply that complement known measures like SAIDI (System Average Interruption Duration Index) are developed.

Smart meter can be considered as an interface between a prosumer, e.g. a household, and the outer smart grid structure. An AMI that utilizes advanced smart meter technologies, allowing complex communication with distribution management system entities, enables a CI to transfer its current *local criticality* into the distribution management system. The distribution management system, being aware of all the *initial criticality* values, the relevancies of all other CIs, global system variables etc., is able to compute the current *global criticality* for each CI (Ottenburger et al. 2018b). In the case of a power shortage, caused by dark doldrums or cyber-attacks, a system knowledge about a *global criticality* distribution can be used for identifying optimal power distribution mechanisms. Therefore, a so-called Supply Index (SI) is applied: Let $i \in I$ be an infrastructure, and $c_i \in [0,1]$ the global criticality of i:

$\boldsymbol{SI} = \sum_{i \in I} \widetilde{c_i}\, q_i(SP_i)$, where $\widetilde{c_i} = \frac{c_i}{\sum_{j \in I} c_j}$, is the weighted global criticality and q_i a certain linear function measuring the quality of supply (Ottenburger et al. 2018a).

The spectrum of optimal power distribution mechanisms that are applicable strongly depends on the topology of smart grids or in other words smart grid topology determines the range of possible optimal power distribution techniques and massively influences urban resilience. During a power shortage, optimal power flows or power distribution policies should target at distributing electricity in such a way that the severity of the impact of a possible decrease of the overall performance of all CIs in an urban area is *minimum*. In enhanced power distribution policies, where *global criticality* is applied, rolling black outs in terms of dynamically connecting different microgrids with each other, might also be an option.

Results

The Smart Grid Resilience Framework

In an ongoing interdisciplinary research project (Raskob et al. 2015) UNF is collaborating with the Institute for Program Structures and Data Organization (IPD), the Institute for Industrial Production (IIP) and the Institute for Automation and Applied Informatics (IAI). The aim of this project is to develop a framework for simulating CIs against certain disruption scenarios and to perform systemic resilience assessments of regions of urban scale by mainly focusing on power shortage scenarios. Power scarcity may result from severe weather events, cyber-attacks, exceptional dark doldrums, or extreme loads.

A main feature of this framework is to use network topologies and power flow algorithms as model parameters that can be varied. The framework has a modularized structure: There is a power module, an ICT-module, and a CI-module, that simulates various CIs from the health sector and the water supply (Raskob et al. 2015; Münzberg T. et al. 2018).

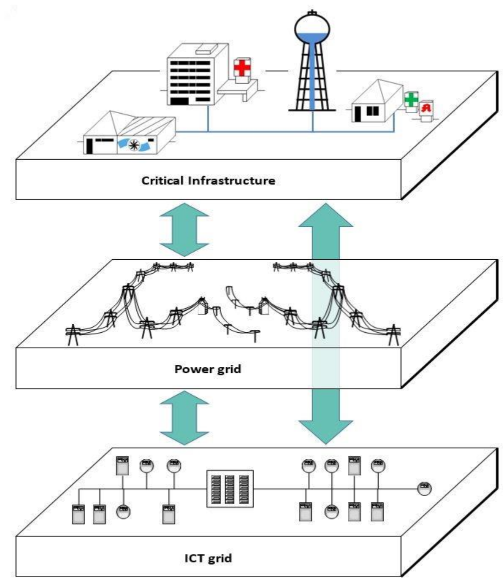

Fig. 3 Modular Structure of the Smart Grid Resilience Framework

In each of these modules, different disruptions/damages of infrastructures can be modelled separately and adjusted within a generic disruption framework. By applying the SI, the resilience of physical and ICT-network structures and power distribution strategies can be assessed. The nature of this framework is quite generic and could principally be applied to any urban area. Currently, the medium voltage distribution grid of Karlsruhe is modelled as the base physical power infrastructures upon which grid extensions models, as possible future scenarios, are further developed.

Optimal Power Flow applying *SI* and evolutionary Algorithms

As mentioned in the previous section, the Smart Grid Resilience Framework uses network topologies and power flow algorithms as model parameters that can be varied. First concepts on resilient power flow mechanisms were developed:

An infrastructure i may possess process flexibility or coping capacities that allow to specify a *power demand flexibility interval* $[P^i_{D,min}, P^i_{D,max}]$, where $P^i_{D,max}$ is the power demand for *normal process* mode and $P^i_{D,min}$ the power demand for at least running *some essential sub-processes.* There might be an infrastructure i that has criticality equal to 1 - in this case i has no power flexibility and thus demands a certain power value P^i_D.

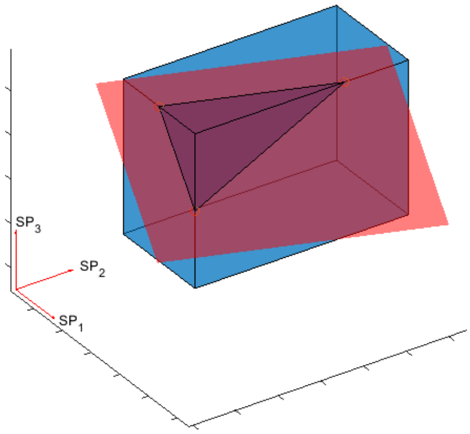

Fig. 5 75 % - scenario-hyperplane: power value vectors within the truncated power demand cube are potential solutions of the resilient optimal power flow

In the case of power shortage, e.g. only 75% of the normal power demand of all infrastructures is available, new resilient power distribution strategies in the energy management system of a smart grid are thinkable in order to avoid total blackouts - nevertheless, new distribution algorithms should not violate non-discrimination.

Before applying these new concepts on our distribution grid model of Karlsruhe, they are

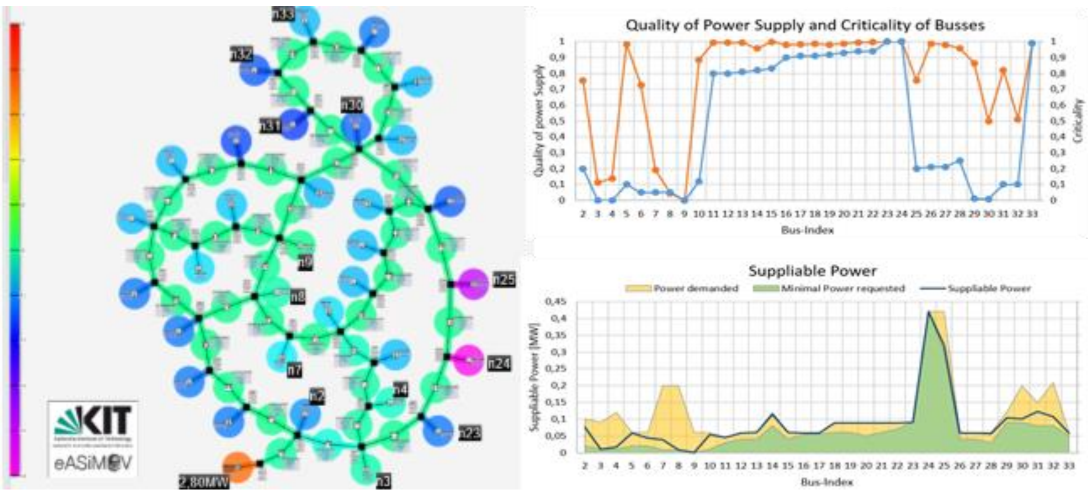

Fig. 4 First results of criticality based optimal power flows on the IEEE33 bus system for stationary load states

validated against simpler grid models e.g. standard IEEE-models:

For stationary load states optimal power flows on the IEEE33 bus system were calculated in a joint project with IAI - genetic algorithms were applied, in order to maximize SI while respecting fair distribution (Ottenburger et al. 2018a). Conclusively, the way we applied genetic algorithms can be considered as a possibility to specify the corresponding parameter in the Smart Grid Resilience Framework.

Summary

The ongoing transition of the power distribution system towards Smart Grids bears the chance to conceptually integrate principles of crisis prevention and management into power control mechanisms. Following this aspiration global criticality considered as a dynamic feature of CIs is a promising attribute that helps to bridge Smart Grids resilience and urban resilience in a sensible way. In cases of power shortages, where first, secondary, and tertiary controls are not able to stabilize the whole grid, global criticality as a further criterion can be applied for controlling the power flow in a Smart Grid in an urban resilient way and thus contribute to enhancing urban Continuity Management (CM).

The proposed simulation framework, allowing the variation of parameters like Smart Grid topology and power distribution mechanisms, can be applied to specific urban systems. Simulation studies against power disruption scenarios that are considered to be plausible for that particular urban system can be conducted. The outcomes of these studies would be

- an analytical view on Smart Grid infrastructure planning in terms of a selection of urban resilient Smart Grid design options and
- appropriate power distribution strategies or algorithms to deal with power shortage scenarios; these strategies or algorithms could be implemented in the Energy Management System (EMS) of a Smart Grid.

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