Survivability Schemes for the Power Distribution Network in the Smart Grid Era

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Abstract—The Smart Grid concept introduces an updated architecture and new elements to the traditional power grid. As a result, existing survivability schemes that have been designed with a centralized architecture in mind are either inefficient or no longer applicable. In this paper, we review several solutions that have been suggested in the literature in order to ensure the proper operation of the power distribution network within the Smart Grid context. Their applications range from decentralized voltage regulation, to blackout prevention, or quick restoration of supply in case a failure is unavoidable.

Keywords—smart grid, survivability, reliability, self-healing, restoration, reconfiguration, multi-agent systems, distribution systems, power distribution network, protection, microgrids

I. Introduction

The Smart Grid concept encapsulates the current ongoing efforts to modernize the ageing and unreliable conventional power grid into a flexible, more efficient power network that will (1) increase the reliability of electrical supply to the customers, (2) enhance the system performance and reduce transmission losses, (3) improve the resilience to disruptions, and (4) allow for automated maintenance and operation [15] [17].

The key component in this transformation is an information and communication technology infrastructure that enables the various entities within the network to communicate with each other in a fast and reliable way. This justifies the characterization of the Smart Grid as the Energy Internet [16] [18]. Besides a communication link, the modern grid relies on a vast number of sensors and actuators that are distributed throughout its transmission and distribution network; these “smart” agents monitor the health of the system on a constant basis and are able to automatically act upon a disturbance in order to prevent a failure, or minimize its impact if it’s unavoidable. Finally, distributed renewable energy generators help reduce transmission losses by bringing generation closer to consumption, while promoting the use of clean, low-carbon energy. These distributed generators give rise to an important concept within the Smart Grid domain, that of the microgrid. Microgrids are small-scale, medium/low voltage electric power systems that also house distributed storage units and loads, and cover a limited geographic area.

It is immediately obvious that the coordination and smooth operation of the Smart Grid is far
from an easy task. For instance, while renewable resources may supplement the generation capability and address environmental concerns, they also aggravate reliability due to their volatility [6]. New mechanisms and protocols are required that will ensure the proper function of the network and guarantee its reliability in case of system disturbances, while running in a non-hierarchical and completely decentralized way. This means that previous survivability frameworks that were designed with the conventional power grid in mind are either inefficient or no longer applicable.

In the next section, we review several schemes that have been devised for the Smart Grid's power distribution network and allow for efficient and fast response to contingencies and system disturbances. Each one covers a different application, ranging from decentralized voltage regulation, to blackout prevention, or quick restoration of supply in case a failure is unavoidable. In section III we conclude this brief review with our observations and remarks.

II. Power Network Survivability Schemes

An effective network voltage regulation is of paramount importance for the survivability of the power grid. As we've hinted in the introduction, this is a process that's becoming more complex due to the increasing penetration of distributed generation systems in electrical grids; since these generators rely on renewable energy sources, their power injections are random and may alter the voltage profiles on the network buses in a non-scheduled fashion. In order to tackle this problem, Loia & Vaccaro [11] suggest the deployment of smart controllers, with each regulating the voltage magnitude of a particular grid section. Their contribution lies in the completely decentralized way with which the controllers assess the state of the network. Each controller is equipped with a set of sensors, a radio, and an oscillator. The oscillator follows a strategy derived from the mathematics of populations of mutually coupled oscillators [12]. With a properly chosen control loop gain in the evolution model that describes their state, all the oscillators converge quickly (sub-second range) to the weighted average of the variables sensed by all the controllers in the grid. Equipped with this information and some fuzzy logic (Fuzzy Inference System [13]), each controller then regulates the reactive power flows injected by the local distributed generator into the electrical grid. Simulations performed on the IEEE 30-bus test system confirm that this fully decentralized, non-hierarchical architecture results in quick and effective voltage profile flattening and minization of power losses.

In [1] the authors try to tackle the problem of insufficient energy generation in microgrids, whether this is due to equipment failure or the intermittent nature of renewable energy resources. In case a microgrid's locally generated and stored energy fails to meet the demand, it may operate in grid-connected mode and receive additional energy from the public utility grid. The goal, however, is to decrease the dependence from the grid. With that in mind, the authors consider the formation of microgrid clusters, where a microgrid that produces more energy than its current needs, may supply electricity to another microgrid that faces the prospect of a blackout. The resulting formation provides complete robustness under single-failure conditions, and partial robustness under multi-failure conditions. It also enables the maximization of renewable energy utilization and, through this electricity trading among communities, provides incentives for increased energy production. The clusters are identified with the help of an Integer Linear Programming (ILP) model, where the objective function aims to
minimize the number of microgrids per cluster in an effort to increase the cluster manageability. Since the energy generation and demand values that are inputted in the model come from several hours ahead predictions, the overlay topology has to be recalculated on a periodical basis and therefore constitutes a dynamic graph. Once the ILP model is solved and the clusters have been identified, a nearest neighbor heuristic is run on each cluster to find a Hamiltonian cycle. The end result is a multiple disconnected ring topology. Simulation results showed a significant reduction in the microgrids’ dependence from the utility grid, with power imported from it only during the most heavily loaded peak periods. The simulation also confirmed the robustness of this design scheme in terms of survivability with several concurrent failures actually recoverable, without affecting the rest of the microgrid network.

The authors in [5] argue that ensuring the smooth operation of a microgrid in the Smart Grid context is a complex matter, particularly when it is running in islanded mode. Most distribution systems in the traditional power grid are operated in radial mode, and the protection systems in place today have been designed for radial operation. However the integration of distributed energy resources in the Smart Grid means we are now dealing with bidirectional flows in certain feeders; furthermore, when a microgrid operates in islanded mode the levels of the fault currents change significantly. Traditional survivability schemes are therefore inadequate, and a replacement is needed that can adapt to the microgrid’s operation mode, be it grid-connected or islanded. Sortomme et al. suggest the deployment of digital distribution feeder relays on the end of each distribution line for instantaneous differential protection and increased robustness. According to their proposal, each relay, which is programmable and has fiber optic and Ethernet ports, measures absolute current at 16 (or more) samples per cycle and transmits these measurements to the relay on the other side of the line, using the communication infrastructure of the Smart Grid. Transmission of this data takes place quite quickly (<0.1ms for distances under 18 miles). If the absolute values of the two samples are above the tripping threshold, a tripping signal activates the switching signal and opens the circuit. If the switching device fails, a backup trip signal is sent to the adjacent (i.e. next) relay on the same bus with a delay between 0.3s and 0.6s, assuming the measured differential current continues to exceed the tripping threshold. If the relay, or the communication link fails, all connected relays are immediately aware of the failure because of the lack of incoming data. This triggers an alarm to the distribution center in order to restore the failure, and places the operating relays in comparative voltage protection mode.

![Figure 1](image)

*Figure 1*

Conceptual representation of the proposed protection scheme [5]

Extensive simulations performed on an 18-bus distribution system showed that this protection scheme was able to quickly detect and clear line-to-line and line-to-ground faults, including high impedance faults which are not uncommon in distribution systems, and which several
Microgrid survivability schemes fail to detect [7] [8]. The authors also suggest a less costly scheme that works similarly to their original proposal; instead of deploying expensive relays on each line tap in the distribution system, the buses can be equipped with cheaper sensor units that use the Smart Grid’s communication infrastructure to transmit data to the substation. A central controller in the substation monitors the current and voltage differences observed by the sensors and remotely operates the switching devices.

Mitigating cascading failures in a power network is an incredibly difficult task, primarily for two reasons: (1) these random events are characterized by complex discrete and continuous dynamics, and (2) while the goal is to find a good solution for the system as a whole, power systems are —as we noted— inherently decentralized. The distributed intelligence that is now available in the Smart Grid in the shape of “smart” sensors and actuators opens up the window for decentralized control approaches to this so-called Emergency Control Problem (ECP). Formally, the ECP calls for a minimization of (1) the costs associated with mitigating control actions, and (2) the risk of interrupted service that could result from future dependent failures. A decentralized solution —now feasible thanks to the Smart Grid— should offer increased robustness and decreased communications bandwidth compared to a centralized approach; the main issue though is decomposing the ECP in a way that facilitates high-speed, highly-coordinated, real-time decision making. According to Hines & Talukdar [3], the key is to get the agents in an area to exchange information with their neighbors before making a real-time decision that ultimately benefits the entire system. In order to do so, the notion of reciprocal altruism is adopted: an agent acting altruistically considers the goals of other agents when making local decisions, even if this is not beneficial to its own goals; in reciprocal altruism, agents consider the goals of some other agents, while assuming that these agents will act reciprocally.

Specifically, in the framework suggested in the paper, one agent is placed at each bus in the power network and is responsible for all the decision and state variables directly associated with its bus (load, generator set points, voltages, currents). Each agent is aware of the initial structure of the network, since this has been provided to it off-line by the system operator. It then chooses a set of local and extended neighbors, defined as the set of agents that can be reached by traveling over no more than r or e links in the power grid respectively (r<e). When the network runs, each agent forms a linear state prediction function for each of its local state variables using the power-flow Jacobian, and exchanges this information with its neighbors at varying rates; at least once per second with the local neighbors, and once per day to once per week with the extended neighbors. Every agent effectively maintains a model of the entire network and uses default data to make up for data that it cannot collect from its neighbors. It is with this information and the notion of reciprocal altruism in place, that each agent makes decisions. Simulations, performed in 10 permutations of the IEEE 300 bus power network, proved that the design can solve the ECP problem efficiently. As expected, the average blackout size decreased as the size of the local neighbor set increased (the set of extended neighbors had a fixed size during the experiments); this change however comes with increasing bandwidth requirements.

In case a power failure or blackout is unavoidable, Samarakoon, et al. [10] suggest a method to quickly restore supply to the distribution network, thanks to locally installed agents and the information obtained from domestic smart meters. In the traditional power
network, we have accurate load profiles only for the feeders originating from grid substations, thanks to the installed SCADA (Supervisory Control and Data Acquisition) systems. This is not the case though for loads connected to LV transformers in the distribution network. The smart meters that are installed in the domestic sector in an ever-increasing rate allow for the quick and periodical exchange of information between them and concentrators installed at each LV transformer. (The concentrators should also keep the meters’ internal real clocks in sync so that all reported measurements are synchronized.) The authors suggest the deployment of agents on the distribution network that query the resident concentrator’s database periodically and store the load profile of the distribution network in memory. When the primary supply fails, certain loads inevitably experience outages. The agents then check their database for the current load profile; when the affected loads are typically such that the secondary supply or backup generators have enough capacity to accommodate them, the agents close the circuit and restore the supply. When the total load is about to exceed the secondary supply’s capacity, the agent disconnect the loads in the affected area, except maybe the critical ones, assuming the topology allows this. This goes on until the primary supply is restored and the network is restored to its initial configuration.

III. Conclusion

The schemes that we covered in the previous section showcase a number of ways with which we can ensure the proper operation of the power distribution network in the Smart Grid era. We referred to how smart controllers coordinate in order to regulate the voltage profile of the network [11], mitigate cascading failures [3] or quickly restore supply to an area affected by a power outage [10]. We've also examined how microgrids group into clusters so that they can trade energy with each other in order to avoid a blackout [1], or how they can benefit from instantaneous differential protection thanks to digital distribution feeder relays [4].

It should be noted that we are still in the early stages of the power grid’s transformation, so these designs merely give us a hint of the high degree of reliability and survivability possible in within the Smart Grid context. The lack of papers that suggest tangible solutions and are accompanied by actual (simulation or experiment) results—as opposed to abstract frameworks [14] and architectures—is indicative of that.

It is certain that, as the modernization of the power grid progresses, more advanced frameworks will come along and will provide improved resilience, by making better use of all the benefits the Smart Grid infrastructure has to offer.

References


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