Modeling the benefits (or detriments) of increased automation in electric power grid operations: Methodology and experiments

A review of current research conducted at Sandia National Laboratories suggests that automation represents a paradigm change in the way in which grid operators interact both with elements of the grid under their control and with field crews whose deployment and activity may be necessary for system restoration. Utilities need to consider a complex set of interdependencies, including human factors, and the risks and benefits, before deploying advanced automation.

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Abstract

Implementation of new technology by electric power utilities – whether it be new control systems, new hardware in the field designed to interact with control systems, or both – comes at a cost to the utility, including expenses for the equipment, and training for employees in its proper use. The benefits to the utility and to the utility’s customers are reductions in the duration of outages. From a utility’s perspective, the ability to show the value of such an investment is integral to making a legitimate rate case before a utility regulatory commission, allowing for cost reimbursement over time.

This paper reviews current research conducted at Sandia National Laboratories, with active support from industry partners, to develop and implement a methodology for measuring the benefits to the electric sector of installing and utilizing automation technology. A number of aspects of the research are discussed, including the review of previous system outages, development of an experimental design supported by scenarios of differing complexity and level of automation, implementation of this experimental design with utility operators to measure performance on the system, and modeling of system behaviors to capture the benefits of automation. Lessons learned from this development path will be discussed, along with paths forward.

1. Introduction

The continuing evolution of the electric grid brings with it many of the same challenges to utility operators as seen throughout the industry's history. From an industry dominated in its early years by small generating stations designed to serve local communities (Sulzberger, 2003), the grid evolved to one more centralized, taking advantage of economies of scale in a tightly regulated environment. In more recent years, its evolution has continued, as a restructured industry again reliant on the addition of smaller generation sources, much of it more cost-effective, distributed renewable energy (Sine & David, 2003). Improved data gathering and system control, designed to increase operator situational awareness and reduce system interruption time, have been utility objectives for decades (Amin & Stringer, 2008), and techniques once reserved for transmission systems, or for the distribution systems of large utilities, are increasingly finding their way into the control rooms of smaller, distribution-focused utilities (Northcote-Green & Wilson, 2013). The acquisition and use of technologies for advanced system situational awareness and control comes with two major questions that must be addressed. First, will these advanced systems reduce system disruption duration (for distribution utilities, this comes in the form of customer minutes interrupted, or CMI)? Second, can one, prior to investment, quantify the benefits to customers in terms of reduced CMI that can be used to provide regulators with a cost justification of the benefits to the utility and its customers of the equipment investment? Addressing each of these questions relies on an understanding of the human dimension in system control. While control systems developers and utilities aim for increased automation, the "human in the loop" maintains a presence, at minimum for observational system interaction, that must be considered (Muir, 1994). Interactions in systems create opportunities for systemic performance risk, whether it be interactions between automated systems and humans – who can be prone to doubt the output of an automated system (Muir, 1994) – or between humans and other humans - where misinterpretation can lead to erroneous decision-making (Baillieul & Antsaklis, 2007). Research at Sandia National Laboratories, with strategic industry partners, aims to address these questions within the construct of its Improving Grid Resilience through Informed Decision-making (IGRID) project. This work builds on Applied Cognitive Task Analysis work with utilities in Vermont that identified the value of field crews to situational awareness, and

suggested that the replacement of such interactions with automation might degrade situational awareness (Stevens-Adams, et al., 2015).

2. Research process

2.1 Developing partnerships

Sandia developed essential partnerships as part of the IGRID project. On the utility side, Sandia worked with Green Mountain Power (GMP), a Vermont-based utility with substantial efforts in grid modernization, including distributed energy resources, system awareness and control. On the control systems side, Sandia developed a relationship with Oracle, whose Network Management System (NMS) software can support automated outage restoration including fault location, isolation, and service restoration (FLISR) actions.

This three-way partnership was designed so that each party would provide expertise in certain areas, while aiming for objectives beneficial to each party. GMP's objectives for the partnership were geared around increasing their confidence in new technologies prior to deployment, demonstrating the impact of new technologies on grid performance to better understand the return on investment, and improving operator training and effectiveness. Oracle's objectives included having operator feedback on their NMS software, quantifying the benefits of automation, with a long-term objective driven from these points of improving their market share. Sandia's objectives for the partnership focused on the collection of experimental data, using GMP operators working on a version of the Oracle NMS, to better ascertain the effects of use of the NMS in various levels of automation on restoration of the grid from outages.

2.2 Designing an analysis framework

Sandia created an analytic framework designed to meet the above objectives and to collect data on the interactions between operator and automation, including overall operator performance and behaviors with and without automation. Sandia, GMP, and Oracle team members worked in concert to develop elements of an analysis framework. This framework entailed data collection from a series of experiments conducted by Sandia utilizing the Oracle NMS, into which a portion of the GMP system was modeled, with GMP operators serving as test subjects. These experiments were designed to cover a range of outage events seen on the GMP system. The purpose of the data collection was to see if adding automation to the system (in the form of automated FLISR devices, which can automatically reroute power when an outage occurs) led to a reduction in CMI. Sandia extrapolated this from applying the experimental data onto historical

response data, to estimate the benefits of NMS and FLISR in a way that is demonstrable. Multiple elements of this process are worth exploring in more detail.

2.3 Data analysis and scenario construction

The team agreed to study a portion of the GMP grid, which GMP had already identified as a test bed for the rollout of FLISR technology. Sandia reviewed historical outage data for this portion of the GMP network to identify potential causes of disruptions, and to use the historical data as a basis for building outage scenarios of varying complexity. With GMP's help, Sandia created five scenarios, all of which were vetted and refined by former GMP operators to clarify interactions, and make the scenario process as close as possible to actual processes under a disruption, including alarms, phone calls from external parties, and other elements beyond the NMS interface.

Performing a detailed analysis of the scenarios as they were developed allowed for the development of a work breakdown structure (WBS) capturing the interchanges between the operator and external parties in detail, including the originator and receiver of the communication or action, the means of communication or action, and the content of the communication or action. The WBS was beneficial in three ways:

- First, in error correction of the scenarios (e.g., identifying inconsistencies in switching or identification of assets used in the scenario);
- Second, in identifying the elements of each scenario that should be timed (e.g., the time from receipt of an alarm to awareness of its' cause and dispatch of a crew to the scene) during the course of the experiment; and
- Third, identifying elements of each scenario for which timing would be neither operator-response dependent nor predictable (e.g., the time for a repair crew to reach a location once dispatched, the time for a repair crew to exact a repair once provided a switching plan).

The latter category was valuable in scenario execution within the experiment, as it created opportunities for acceleration of the scenario far beyond real timing, allowing for more scenarios to be explored (and more data gathered) in a shorter period of time. For those elements for which timing was deemed to be important, these were often grouped. For example, a timed sequence might involve the operator opening three reclosers, closing three others, and placing the first three breakers on non-reclose so that repairs can be done to a circuit within the now-opened are of the system. Capturing this group of events as a group places less importance on the order and more on the fact that the group of events is completed. Grouping occurred because the sequencing of individual tasks within the sequence could vary. Grouping also occurred so as to

make certain that the method of data capture (discussed in Section 2.5) was consistent at the beginning and end of the sequence.

In addition, the scenarios provided a likely path, as determined by highly experience operators, for operators to follow, serving therefore as a de facto baseline of operator performance, though (as we shall see) the scenario script does not prevent actions beyond the expected path from being pursued.

2.4 Interface construction

Oracle, in turn, used geospatial data provided by GMP to model this portion of the GMP network in their NMS software environment, and developed and delivered a training program to instruct GMP operators on its use.

2.5 Experiment execution

After running a number of field tests to clarify scenario elements, NMS interactions, and data collection, Sandia conducted a series of experiments running individual operators through the five scenarios, designed to capture different degrees of scenario difficulty and automation. Difficulty of the scenario was defined using the work breakdown structure (described above) and was based on the number of steps required to return the system to a state in which all customers have power (note that this does not mean full system restoration). Scenarios with automation included guidance within the NMS on a preferred path for use of FLISR-enabled controls, while scenarios lacking automation had no guidance from the NMS. In each scenario, operators were presented with an initial “ground truth” of the system prior to any disruptive event within the scenario, including weather, time of year, and crew availability. The operator was instructed to restore the outages they encountered as safely and efficiently as possible.

Data on the timing of particular actions (both human – human and human – machine interactions) was captured using several methods: stopwatch for human-to-human interactions; screen capture software for general interactions with the NMS software environment; and NMS timing data for actions recorded by the NMS in the scenario. Two individuals observed the experiments and coordinated the tracking of each action taken by the operator. They recorded times where appropriate, identified inconsistencies with the planned scenario actions, and corrected the path of the scenario when diversions occurred. Additionally, a post-experiment interview was conducted with each operator, to review decisions made during each of the scenarios and to assist the observers in clarifying the operator’s decision-making process.

3. Preliminary findings

Data analysis from the experiments is ongoing. Nonetheless, some observations can be made based on the data collection effort that are helpful to outlining future activities.

3.1 Expertise, speed and accuracy

Researchers proposed that experienced operators, defined in other research as part of this overall effort (Stevens-Adams & Hannigan, 2016), would perform tasks faster and with greater accuracy than non-experts. In the collected data, the most experienced operator was slowest at completing the tasks. Post-exercise interviews did not clarify whether this was due to the operator being measured and deliberate in his actions, or due to a lack of proficiency and confidence with the system on which the operator had recently been trained.

3.2 Situational awareness and critical thinking

Researchers postulated that operator situational awareness would decline both as the scenarios became more complex and as the NMS provided FLISR solutions. The experimental data collected suggests this may be the case for the use of the NMS system. Given the instructions provided, to “restore the outages they encountered as safely and efficiently as possible,” many operators appeared to be racing to achieve a solution as fast as possible. This strongly implies reduced situational awareness in decision-making on the part of the operators.

Observed behavior of operators also revealed that some operators take actions outside of the expert-suggested path to restoration. Some operators opened and closed switches in the system to try and identify the location of disruptions within the scenarios. When this happened, the simulated system responded as the real-world system would, avoiding actions that might lead to cascading outages through system protection devices. This raises several questions for utility operations planners:

- Will these protective devices work every time on a utility’s system as intended?
- Will these protective devices work subject to their being used more frequently than their design basis?

Answers to these questions are important to understanding whether risk to both utility equipment as well as consumer equipment and utility- and consumer-owned distributed generation resources from further consequence changes as the result of operator behaviors of this type.

These findings lead directly into the next finding.

3.3 Consistency of action

Within the experiments, the sequence of procedures expected from each of the operators was inconsistent at best, likely reflecting different perceptions of the system and the way an operator should interact with it and with other elements of the operational team (e.g., field crews). These actions, combined with some of those identified above, suggest that steps to create a more rigorous and consistent training procedure for the way operators interact with control systems and field crews, may be of value.

3.4 Trust in automation

Post-experiment interviews with operators suggest that automation provides value, and is seen as the future of grid operations. But most suggested in these interviews that trust in automation would be an issue. That was seen in the actions taken in the FLISR-driven scenarios. In most cases, the FLISR solution was seen, but not acted on; rather, the operator used it as a guide for a manual operation. This behavior may change with time, but it suggests that confidence in the products of the automated system will evolve rather than be in place to begin.

4. Gaps identified in this research

Several gaps in knowledge were identified in conducting this research, one of which led to an interesting finding that deserves further consideration.

4.1 Adequate sample size

Working with GMP on this effort was wonderfully productive in terms of developing a sound experimental design and testing procedure, including our scenario-based methodology, but the small size of the utility, and the number of operators, both experienced and non-experienced, meant that the data collected has limited value from a statistical analysis perspective. Identifying a utility with the proper number of operators to satisfy basic statistical limitations on collected data is a priority for future Sandia research.

4.2 Errors in experiment execution

As with other experiments, this one was not without technical flaws. But the flaws seen in this case proved to be illustrative, revealing an interesting interaction between the NMS and the operator. In reviewing the data, for example, we saw that in one case, the NMS for the scenario in question had provided an erroneous FLISR option, associated with one of the other scenarios, with switching at a location completely unrelated to the outage posed. The operator chose to follow the erroneous FLISR option, trusting the automated input provided. It took the operator

several minutes to notice the difference, correct the system changes made following the FLISR option, and begin analyzing the system to restore based on the system fault.

This raises natural questions regarding the accuracy of information received by the operator via the NMS, of the underlying confidence and surety required by the operator in this information, and the potential for malicious actors or error in code deployment to lead to such errors, which have the potential to create disruptive events. This is a growing concern with the expansion of distributed generation assets connected to distribution utility systems, and of the need for these combined systems to operate without concern for erroneous reporting of this type. The researchers suspect there may be operators who are both unfamiliar with and overly trusting of automation. The presence of such a cohort suggests further study to inform training programs.

5. Conclusion

Our research team developed and tested an experimental framework, to examine the ways in which operators interact with a network management system on which they are newly trained. Observations from those experiments suggest that automation represents a paradigm change in the way in which grid operators interact both with elements of the grid under their control and with field crews whose deployment and activity may be necessary for system restoration.

Utilities need to consider a complex set of interdependencies, including human factors, and the risks/benefits before deploying advanced automation. As our research suggests, understanding operator-machine interactions is critical to the effective deployment of new technologies. More research is needed to understand operator performance at the distribution level in order to use this framework to make a legitimate rate case.

Operators also showed two extrema of trust in automated results: They either worked independent of the automation, or blindly followed the automatically (machine?) generated solution, even when the proposed solution was erroneous. The latter of these is a potential concern for threat vectors to automated control systems, and an opportunity to expand training. The research as presented provides for multiple avenues of further exploration. The methodology, as described, can be readily applied to other utilities, and for other disruption challenges.

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References

- Amin, M., & Stringer, J. (2008). The Electric Power Grid: Today and Tomorrow. *MRS Bulletin*, 33(4), 399-407.
- Baillieul, J., & Antsaklis, P. J. (2007). Control and Communication Challenges in Networked Real-Time Systems. *Proc. of the IEEE*, 95(1), 9-28.
- Muir, B. M. (1994). Trust in automation: Part I. Theoretical issues in the study of trust and human intervention in automated systems. *Ergonomics*, 37(11), 1905-1922.
- Northcotte-Green, J., & Wilson, R. (2013). *Control and Automation of Electrical Power Distribution Systems*. Boca Raton, FL: CRC Press.
- Sine, W. D., & David, R. J. (2003). Environmental jolts, institutional change, and the creation of entrepreneurial opportunity in the US electric power industry. *Research Policy*, 32(2), 185-207.
- Stevens-Adams, S., & Hannigan, F. (2016). Defining Expertise in the Electric Grid Control Room. In S. M. Cetiner, P. Fechtelkottter, & M. Legatt, *Advances in Human Factors in Energy: Oil, Gas, Nuclear and Electric Power Industries* (pp. 69-77). Springer International Publishing.
- Stevens-Adams, S., Cole, K., Haass, M., Warrender, C., Jeffers, R., Burnham, L., & Forsythe, C. (2015). Situation awareness and automation in the electric grid control room. *Procedia Manufacturing*, 3, 5277-5284.
- Sulzberger, C. L. (2003). Triumph of AC: From Pearl Street to Niagara. *IEEE Power and Energy Magazine*, 99(3), 64-67.