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Actionable information from electric transmission grids to ensure their reliability and resilience

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Overall challenge

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extract actionable information from electric transmission grids to ensure their reliability and resilience.

Motivation

1. Most generation technologies, with the possible exceptions of distributed solar, fuel cells, and diesel-generator sets, are enabled by the transmission grid. The grid enables electricity to be produced at scale more cheaply away from the large loads where the source is available and so that it does not foul or disturb where most people live. The transmission grid is relatively flexible and allows the generation mix and location to change relatively easily. We can leverage the trillion dollar investment in the current grid and enhance it to help transform the nation's energy future.

2. Our industry, homes, government, and way of life all rely on a reliable and resilient transmission grid. Frequent widespread blackouts are completely unacceptable. Politicians understand the importance of reliable electricity, and the government will take action if reliability deteriorates. It is better to assess and mitigate blackout risk before reliability deteriorates.

3. The transmission grid has historically had fairly high reliability, with notable occasional exceptions that each cost our society billions of dollars. However, the past reasonably good overall performance is no guarantee as we transform the nation's energy systems. New technologies, sources, loads, patterns of use, and increasing use of electricity can also transform the grid reliability, and we need to be able to monitor and mitigate blackout risk as we move forward.

4. It is crucial for new generation, grid, and load technologies that the risks they pose for blackouts be assessed and mitigated. Any new technology that is fairly or unfairly blamed for blackouts will be discontinued or curtailed. It is much better to be able to assess and mitigate the risks before they are fully realized. The experimental approach of simply waiting to find out if there are repeated large blackouts or, alternatively, if we have wasted huge amounts of money on ineffective measures or unnecessary curtailment of new technologies is not desirable.

5. The state of the art in assessing blackout risk is that, while many practices and guidelines are reasonably thought to mitigate small blackouts, there is little quantitative risk-based analysis available that can, for example, balance risk and cost. Thus we can either pay far too much out of excessive caution, or incur excessive risk, and can regulate in an only vaguely effective manner. And large blackout risk, which is substantial, is a harder problem that is not well understood, much less analyzed. There is a problem with mitigating small blackouts is that many of the reasonable mitigations can inadvertently increase the risk of large blackouts. It is important to jointly mitigate the risks of small and large blackouts. We advocate taking practical steps towards monitoring and mitigating blackouts of all sizes, and we believe that such steps have become technically feasible.

The overall challenge is to extract actionable information from electric transmission grids to ensure their reliability and resilience. Although there is some useful overlap, we separate this challenge into three related challenges:

Challenge A: Extract actionable information from historical grid events

Challenge B: Extract actionable information from real time grid measurements.

Challenge C: Extract actionable information from grid simulations.

Before discussing examples of how each of these challenges can be addressed, we describe the cyberphysical systems nature of the challenges.

1. The electric transmission grid, even before any smart or smarter grid enhancements, is the largest and most important civilian cyberphysical system. It not only is continental in scale, with tens of thousands of heterogeneous physical components, it is systematically littered with sensing, communications, computing, actuators, and automatic and human controls at all time scales ranging from milliseconds to decades. The grid performs in a varying and stochastic environment in which quantities must be controlled between tight limits (an engineering equivalent of biological homeostatis) and protection and human operator actions routinely switch components in and out of the system. The flow of information is both analog via circuit laws (a large generator tripping in Georgia can be detected in Iowa), but also digital through sensing, communications, computing, and via about 100 control centers across North America. The cyberphysics of the smarter grid will be even more complicated.

2. The cyberphysical challenge is that the transmission grid is large, heterogeneous, and complicated. Many of the challenges of other cyberphysical systems, including human factors, appear in some aspect of the electrical grid. The staggering complexity of the grid cyberphysics puts a premium on the correct modeling assumptions for a given problem, deep analysis of the physics and engineering, and feasible solutions. That is, the complexity is such that there is no such thing as a comprehensive model for the power grid. However, there are grid models that are credible approximations for particular cyberphysical problems. Some of these grid models are well established for particular problems (e.g. slow voltage collapse, transient stability), and can be used to demonstrate and test ideas. The analysis, computation and simulation for realistic versions of these models almost always poses technical challenges ... these are hard problems requiring considerable sophistication drawn from multiple fields ... but the work is interesting and useful from theory, cyberphysical engineering, and computational points of view. Some other grid phenomena are less well understood (e.g. cascading, interarea oscillations, handling uncertainty), and a basic scientific understanding must be established and tested in order to be able to proceed towards computable engineering solutions. Direct experimentation with the transmission grid is usually impossible, but it is sometimes feasible to get access to system parameters, measurements, and operational conditions.

Examples of Challenges

Challenge A: Extract actionable information from historical grid events

Example: Cascading outages can be thought of as an initial outage followed by propagation to a series of following outages. While there is a substantial body of risk analysis that can quantify the chance of the initial outage, it is only recently feasible to quantify the tendency for the outages to propagate. To mitigate cascading one should consider ways to reduce both the initial outages and their propagation. Indeed, the average amount of propagation can be understood as describing the grid's resilience: in a resilient grid, regardless of the initial outages, there will little propagation of outages following the initial outage.

Recent work [1] has shown that the average amount of propagation can be estimated from standard utility data about transmission line outages that is reported to the government (this is the data in the TADS Transmission Availability Data System). Then the average amount of propagation can be used to quantify the effect of cascading, and in particular, estimate the distribution of the total number of outages given some initial outages. This procedure can estimate the probability of the rare, larger cascades from about one year of TADS data in a large utility. This procedure uses a high-level probabilistic branching process model of cascading that has been validated for this purpose.

The key fact enabling this work is that BPA makes detailed TADS data available for research by publishing it on its website.

This initial success in counting line outages would seem to open the door to more elaborate analyses and challenges:

- Quantifying the cascading load shed
- Establishing outage propagation as a practical metric of grid resilience.
- Find identifying factors contributing to the cascade propagation, formulating notions of causes of cascading, devising mitigation strategies that reduce the propagation, and computing how these mitigations affect the risk of small and large blackouts.
- Processing multiple observed quantities (vector data) to get more data to estimate propagation and estimate the cascading risk. The multiple quantities can be weighted and summed to form a scalar that quantifies the cascading. It is important to find out how much each quantity should be weighted to make this scalar a meaningful metric.
- All the previous items focus on quantifying the statistics of blackout size. These can be complemented by exploring the statistics of how the cascade spreads. How cascades spread determine the likelihood of the cascade remaining a local problem or crossing state or utility boundaries.

This example suggests the following more general conclusions:

- Researcher access to examples of detailed data sets is crucial.
- Much historical data is now gathered and stored in electronic form. The cyberphysical challenge is to do the modeling and analysis to be able to process the data to add value and extract useful information.

- The ability to construct and validate simple mathematical models that summarize and explain some aspect of the complicated cyberphysical processes is a key part of the research. The parameters of these models often provide the most useful and insightful metrics of performance.

Challenge B: Extract actionable information from real time grid measurements

Example: Interarea oscillations are the slow oscillations of about 1 Hz that can arise spontaneously in the power grid. For example Northwest Canada can swing slowly against Arizona at about 0.7 Hz. Such oscillations can damage equipment and interfere with system controls, and have been involved in some blackouts. Synchrophasor measurements of power grids can now be communicated to central location at a control center and then signal processing can track the frequency and damping of interarea oscillations. This is a success of cyberphysical monitoring of the grid (and of government support of technology R&D).

But what should the operators do when an oscillation mode of the power system is insufficiently damped? Power system operators at control centers are already swamped with information, and they want sound advice about what to do about a problem, not just indication of a problem. For example, they could redispatch generation (increase power at one generator and decrease power at another), if they knew which pair of generators would be most effective in suppressing the oscillation. The main barriers to solving this are lack of fundamental understanding of the oscillations, and the difficulty of accurately modeling the entire grid dynamics, including load dynamics, in real time.

One solution is to advance the theory of suppressing grid oscillations and further rely on the synchrophasor measurements to track the "shape" of the oscillations to measure in real time the salient parts of the dynamics. With support from a current NSF CPS grant, we have derived new theory for calculating from measurements the sensitivity of oscillations to generator redispatch [2], and we are now proceeding towards applying the theory as a practical mitigation of oscillations.

Example: Synchrophasors can measure the angles of voltage phasors at locations all across the grid. Subtracting the angles measured at two locations gives a real-time measure of angle difference. It is well known that the angle difference gets larger when the system is stressed, but its use as an index of stress is limited because the angle difference responds to events all over the grid, and it is hard to set actionable thresholds for the angle difference. That is, a high angle difference indicates high stress, but does not indicate the source of the stress or its severity, or what to do about it. However, choosing an area of the power system, measuring the angles of voltages all around the border of the area, and combining the angles with the correct weighting can give an "angle difference across the area" that measures the stress across the area. The new "angle across an area" obeys circuit laws and can be modified so that it only responds to events inside the area [3], thus distinguishing where the events causing increased stress happened. The correct weights come from new circuit theory [4], and the applications to measuring stress [5] and also indicating margin to voltage collapse blackouts are now being worked out.

These examples suggest the following more general conclusion:

- The limiting factor in extracting actionable information from large cyberphysical systems is often lack of basic theory that explains the physics of phenomenon being controlled and can compute the action to be taken based on the cyberphysical measurements. That is, physical and mathematical analysis of cyberphysical engineering systems is crucial to add value to measurements by showing how to process measurements into actionable information.

Challenge C: Extract actionable information from grid simulations.

There is much work to be done processing simulated grid data that is parallel to the data processing of challenges A and B, and that can be approached in a similar way, but here we focus on a way of simulating the effects of engineering upgrading the grid for evolving cyberphysical systems, and how to extract useful information from these simulations. It is of great interest to find ways to represent the effect of humans doing engineering on cyberphysical systems and responding to the socio-technical and economic drivers that in practice shape our critical infrastructures.

Example: After a blackout, there are always strong efforts to mitigate the causes of that blackout by upgrading the power grid components and upgrading the operating and planning rules. There are strong socio-economic forces driving this upgrading by engineers in response to the blackouts. Over the years, the grid slowly evolves as blackouts recur and the loading of the grid changes. This can be seen as a feedback that improves reliability after a blackout and does more minimal upgrades if there are no major blackouts for a while. The simulation upgrades the parts of the grid that were involved into the last blackout. In any case, it is clear that over the long term, this "engineering feedback" strongly shapes the reliability of the grid. It is possible to represent the effects of this engineering feedback in a grid simulation that simulates both cascading blackouts and the engineering responses to those blackouts [6]. The evolving system is a complex system in that the system reacts to readjust its own reliability when there a blackout. The evolving system settles down to a "steady state" with stationary statistics and a characteristic pattern of blackouts in which there is a heavy tail of extreme blackouts. Indeed the observed patterns of historical blackout size on the Western grid of Norh America can be reproduced by the simulation [7]. The feedback process of the evolving power grid is similar to a process of self-organizing to near a critical state in which blackouts of all sizes (up to the maximum size blackout of the entire grid) occur.

Now to apply the simulation to assess, say, the effect of more distributed generation on the grid, or more micro grids, one needs not only to run the simulation, but also to have metrics to assess and understand the simulation results. There are some indications about how to proceed: metrics related to average propagation in cascading explained in Challenge A can be applied, and there should be some way to detect the closeness of the system to the critical state in which blackouts of all sizes occur. The key is to better understand the complex system physics in order to be able to define useful metrics. The metrics, in turn, can then be used for mitigating the blackout risk. This mitigation can take into account mitigating both small and large blackouts as well as assessing the long term effect of the mitigation. That is, there is an immediate effect of any mitigation, but the system continues to evolve, and an initial advantage from the mitigation may change over the long term as the grid readjusts its reliability as a complex system. The goal is to be able to select mitigations that are effective both immediately and in the long term as the grid evolves.

This example suggests the following more general conclusions:

- Instead of directly representing the (difficult to characterize) internal details of humans engineering the cyberphysical system in response to societal and economic imperatives, it may be possible to represent the *effects* of the humans engineering the system.... in this case upgrading the parts of the system that failed.
- Developing basic understanding of the physics of the cyberphysical system is the key step towards meaningful metrics and engineering results.
- Ideas from other disciplines may sometimes be essential, in this case complex system theories of self-organized criticality from statistical physics. The work so far has been done by a team of engineers and physicists.

References

[1] I. Dobson, Estimating the propagation and extent of cascading line outages from utility data with a branching process, *IEEE Transactions on Power Systems*, vol. 27, no. 4, November 2012, pp. 2146-2155.

[2] S. Mendoza-Armenta, I. Dobson, A formula for damping interarea oscillations with generator redispatch, IREP Symposium: Bulk Power System Dynamics and Control-IX, Rethymon, Greece, August 2013.

[3] H. Sehwail, I. Dobson, Applying synchrophasor computations to a specific area, *IEEE Transactions on Power Systems*, vol. 28, no. 3, August 2013, pp. 3503-3504.

[4] I. Dobson, Voltages across an area of a network, *IEEE Transactions on Power Systems*, vol. 27, no. 2, May 2012, pp. 993-1002.

[5] A. Darvishi, I. Dobson, A. Oi, C. Nakazawa, Area angles monitor area stress by responding to line outages, NAPS North American Power Symposium, Manhattan KS USA, September 2013.

[6] I. Dobson, B.A. Carreras, V.E. Lynch, D.E. Newman, Complex systems analysis of series of blackouts: cascading failure, critical points, and self-organization, *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 17, 026103, June 2007.

[7] B.A. Carreras, D.E. Newman, I. Dobson, N.S. Degala, Validating OPA with WECC data, Forty-sixth Hawaii International Conference on System Sciences, Maui, Hawaii, January 2013.