

Cascading failures in power grids

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Few people consider the complexity of power grid operation when they flip a switch to light a room. Power grids provide electricity to billions of individuals around the globe, often with higher than 99.9% reliability. Because the social structures in most developed countries rely on high-reliability electricity, massive social disruption can result when the power grid fails to deliver energy to customers—urban transportation systems grind to a halt, heating and cooling systems stop, computer systems shut down, and vital services like water, sewer, and communications quickly degrade. In some cases, blackouts can uncover major social unrest, as occurred in the 1977 New York City blackout, which led to widespread rioting and the arrest of more than 3,000 individuals.

In order to better understand how others perceive electrical blackouts, we asked students at the University of Vermont to share their blackout stories. The following are two particularly insightful responses:

I think many people are in the dark about blackouts, specifically regarding what to do when one happens and perhaps more importantly what not to do. I know as soon as the lights go out and the summer heat rises, the first thing that goes through my mind once the power comes back is to turn on my air conditioning

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and get back to work on my computer or resume whatever I was doing prior to the blackout—even if that means boosting up the power use. —Adam Gonzalez, Graduate Student, Psychology.

When I was a senior in high school, there was a tornado that hit Birmingham, Alabama, where I lived. The tornado went through my neighborhood, destroying houses, and happened to miss our house. My younger sister was home alone, and my mom and I could not get home that night. It was too dangerous to drive because of the storm, and there were trees that were blocking the entrance to our neighborhood. The next day, we got dropped off about a quarter mile from our house, which was as close as we could get because of the damage, and walked home. The whole neighborhood, and probably surrounding neighborhoods, did not have power for a few days. It made the experience of the storm even scarier not to have power, and it made it harder for people to get back to their normal routines, as well as recuperate from the damage. —Erin Marshall, graduate student, psychology.

While most in the electricity industry agree that blackouts will not go away in the near future, there are important steps that can be taken to mitigate blackout risk. In this article we describe some causes and consequences of large electricity system failures and describe two strategies that can reduce the size and cost of large blackouts, given appropriate engineering guidance.

Being left in the dark

Blackouts can result from many causes. Most large blackouts begin with natural disturbances, such as ice storms, hurricanes, tornadoes, and earthquakes (Fig. 1). About one third of large blackouts stem from nonnatural events such as human error, equipment failures, supply shortages, or even volitional attacks.

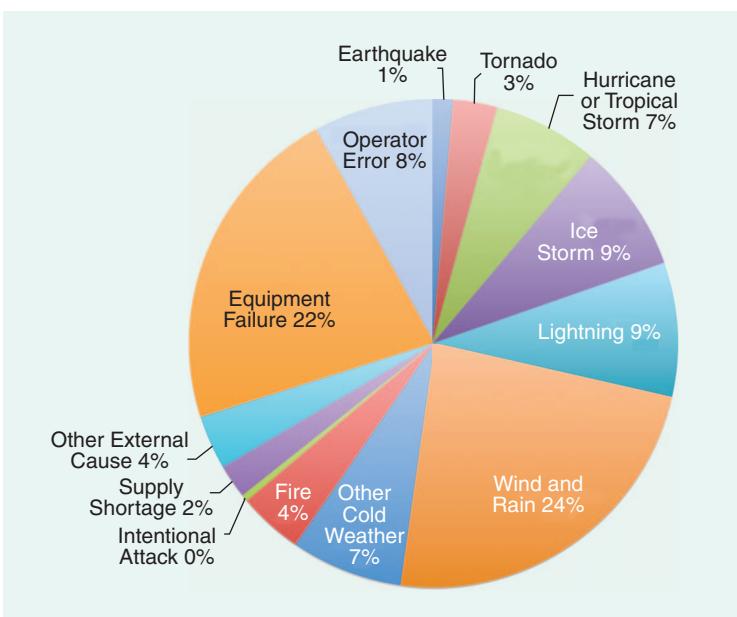


Fig. 1 Initial causes of blackouts affecting at least 50,000 customers between 1984 and 2006. Data from NERC records (www.nerc.com).

With elevated concerns about terrorism, a number of recent media articles have discussed the potential for a cyber-attacker to initiate a blackout by hacking into computers. While there is continued need for improved cyber security, particularly as automation increases, to our knowledge, cyber attacks in North America have not yet resulted in large blackouts. Sometimes the initiating events for a blackout include a combination of human error and natural events. For example, contact between trees and power lines was an important cause of the 14 August 2003 North American

blackout. When transmission or distribution lines carry high currents, the I^2R heat losses cause the conductors to expand and drop closer to the ground. When trees or other vegetation are allowed to grow too close to high-voltage conductors, a high-current arc can form between the cable and the tree, which will be sensed by a relay, which will remove the line from service. The combination of natural occurrences, such as tree growth, and human causes, such as inadequate vegetation management, can increase blackout risk.

Disturbances can result in blackouts directly and indirectly. In some cases disturbances immediately interrupt electricity service. When a radial distribution line fails, customers will immediately lose electricity service because there is typically only one path between the high-voltage power grid and customers connected to the medium voltage distribution infrastructure (Fig. 2). Very large storms can interrupt hundreds of thousands or even millions of customers (Table 1) by damaging the distribution system. High-voltage transmission systems, however, are designed in a mesh configuration with multiple paths between generators and customers. The

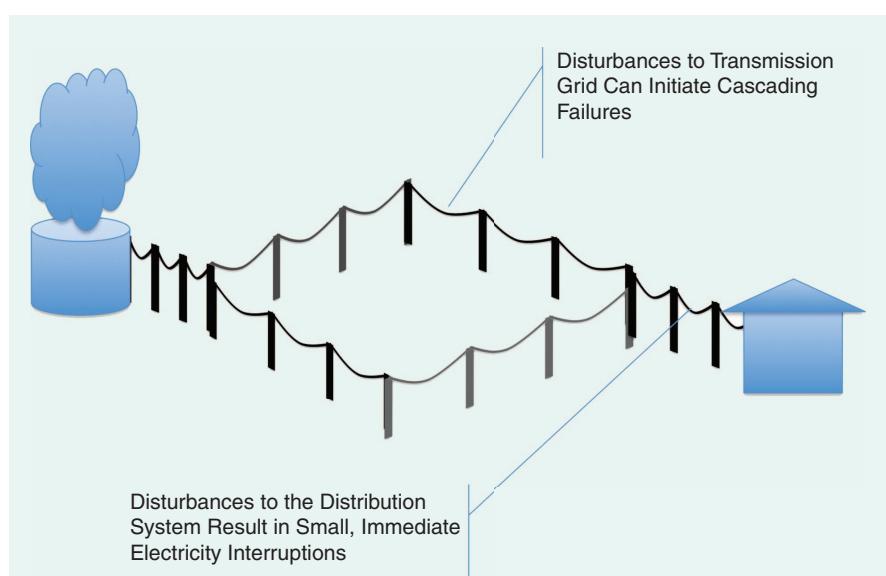


Fig. 2 Illustration of disturbances on radial distribution and networked transmission systems.

Table 1. The 15 largest North American blackouts and their causes, 1984-2006 (data from NERC).

Date	Location	MW	Customers	Primary cause
1 14-Aug-2003	Eastern U.S., Canada	57,669	15,330,850	Cascading failure
2 13-Mar-1989	Quebec, New York	19,400	<i>5,828,000</i>	Solar flare, cascade
3 18-Apr-1988	Eastern U.S., Canada	18,500	2,800,000	Ice storm
4 10-Aug-1996	Western U.S.	12,500	7,500,000	Cascading failure
5 18-Sep-2003	Southeastern U.S.	10,067	2,590,000	Hurricane Isabel
6 23-Oct-2005	Southeastern U.S.	10,000	3,200,000	Hurricane Wilma
7 27-Sep-1985	Southeastern U.S.	<i>9,956</i>	2,991,139	Hurricane Gloria
8 29-Aug-2005	Southeastern U.S.	9,652	1,091,057	Hurricane Katrina
9 29-Feb-1984	Western U.S.	7,901	3,159,559	Cascading failure
10 4-Dec-2002	Southeastern U.S.	7,200	1,140,000	Ice/wind/rain storm
11 10-Oct-1993	Western U.S.	7,130	<i>2,142,000</i>	Cascading failure
12 14-Dec-2002	Western U.S.	<i>6,990</i>	2,100,000	Winter storm
13 4-Sep-2004	Southeastern U.S.	<i>6,018</i>	1,807,881	Hurricane Frances
14 25-Sep-2004	Southeastern U.S.	6,000	1,700,000	Hurricane Jeanne
15 14-Sep-1999	Southeastern U.S.	5,525	1,660,000	Hurricane Floyd

Italics indicate an estimated value, based on a U.S. average of 300 customers per megawatt.

ditional current, a cascade of component outages can begin. To prevent sequences like this, reliability regulations, such as those established by the North American Electric Reliability Corporation (NERC), require that operators manage power grids such that no single component failure will result in customer interruptions. Thus, single component outages do not generally result in a loss of service to customers. However, a set of two or more nearly simultaneous outages can initiate cascading failures. As 50 million North Americans (about 15 million electricity customers) who lost power on 14 August 2003 can attest, cascading failures can produce very large blackouts and tremendous social disorder. Fig. 3 illustrates a cascading failure in a small power grid model.

Disasterous consequences

Due to the vast number of services that require electricity, large blackouts can have disastrous consequences, particularly in urban settings. The consequences of the 14 August 2003 blackout illustrate this well. When the cascading failure hit New York City, traffic lights and subway trains failed immediately. Both are vital to the flow of traffic in and out the city. As a result, thousands of people were forced to abandon their cars, walk through subway tubes, and walk off the island. Mobs of commuters were reported to have stormed empty buses and refused to let them pass. In large buildings across the city, hundreds of people were stuck in elevators. According to *The New York Times*, “By 9:30 p.m., the New York Marriot Marquis Hotel in Times Square resembled a refuge camp.” Even air traffic suffered. Since Laguardia International Airport could not restore power for passenger screening, air traffic throughout the country was delayed. Numerous commercial losses resulted from the blackout as well. Metal fabrication plants sustained multimillion dollar losses when metals hardened inside of machinery. Grocery stores in the affected area discarded massive amounts of refrigerated food.

Shortly after these immediate consequences hit, the blackout began to affect vital city services. Water and sewer pumps across the eastern United States failed, putting stress on those systems. One New York City pump station spilled millions of gallons of sewage. With heavy rains on 15 August, untreated sewage flowed into waterways in

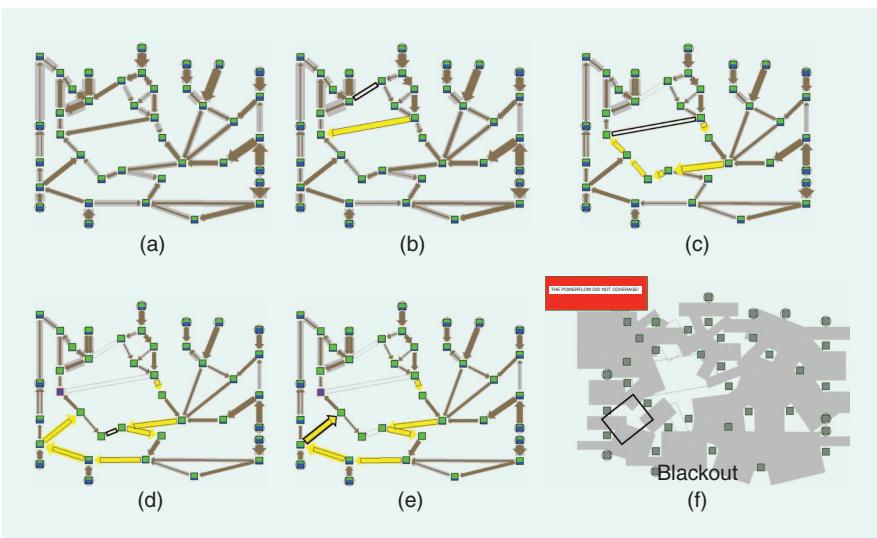


Fig. 3 Illustration of a cascading failure in a small system. The thickness of the lines indicates current flow, and the blue-green threshold at the nodes indicates voltages. In (a), the system is operated at a stressed (insecure) state, but no transmission lines are overloaded. In (b) a transmission line fails causing an overload (yellow). In (c) the overloaded line fails causing three subsequent overloads. In (d) a branch outage cuts off the only remaining parallel path between the right and left portions of the network. In (e) the final branch outage results in (f) a voltage collapse and blackout.

flow of current in these mesh systems is dictated by Kirchhoff's current and voltage laws. When one path is removed

from the network, current shifts nearly instantaneously to parallel paths. If a parallel component cannot handle the addi-

Detroit and Cleveland. Four million Detroit water customers were asked to boil their water due to a risk of contamination between the sewer and water systems.

Telecommunication infrastructures also suffer immediate damage after a blackout. While most telecommunication systems, such as cell phone towers, have backup batteries, allowing service to continue for hours after the initial power loss, longer blackouts can lead to service failures. If the blackout lasts longer than the design time for the energy storage system, or backup power supply equipment are not sufficiently maintained, communications failures can propagate to other services that rely on telecommunications, such as stock markets or emergency responders.

Since blackouts affect customers in many different ways, it is difficult to precisely quantify the costs associated with large blackouts. The direct costs, such as commercial and industrial product losses, can be roughly tabulated, but indirect costs, such as the health risks associated with persons walking through subway tunnels, are more difficult to estimate. Thus it is often easier to measure blackout impact in terms of more measurable quantities, such as the number of customers affected, the number of megawatts of demand removed from the system, the number of transmission line or generator failures, and/or the duration of the event in hours. Given the duration and the size in MW, we can estimate the total amount of unserved energy (megawatt hours), which arguably most closely correlates to blackout cost.

NERC collects data from member reports on blackouts that affect at least 50,000 customers or 300 MW of load. Reports for the years from 1984 to 2006 are available from NERC. From these data the frequency of large blackouts does not appear to be decreasing in time. While technology and policy improvements have facilitated major reliability improvements in other network systems, such as air traffic control, these changes

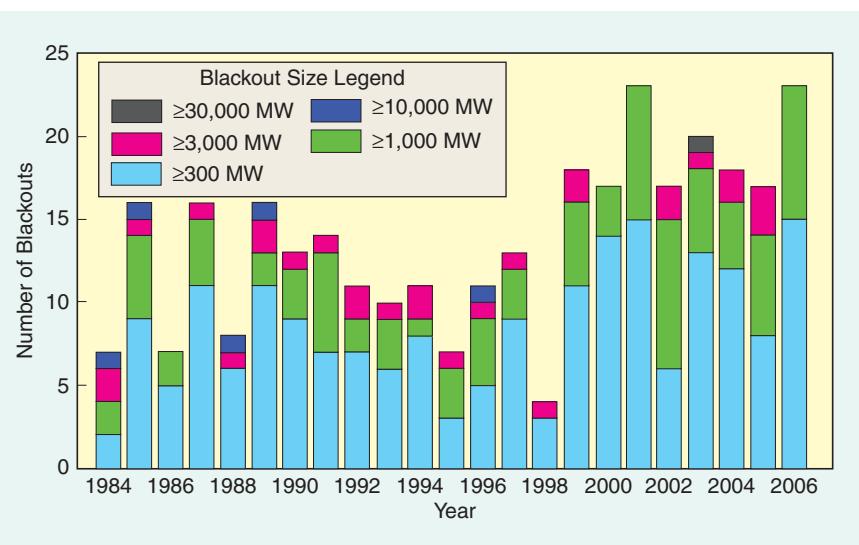


Fig. 4 The number of large blackouts in North American for 1984–2006 (data from NERC).

have not resulted in an observable decrease in the frequency of large blackouts (Fig. 4).

Another trend that emerges from these data is the surprisingly high frequency of very large blackouts. Whereas in many engineering systems, exponential statistics like the Weibull and Gaussian distributions work well in describing random processes related to reliability, these statistics do not work well in predicting

blackout sizes. A power-law probability distribution fits the data well:

$$\Pr(x \geq X) = \left(\frac{x_{\min}}{X}\right)^k, \forall X \geq x_{\min}. \quad (1)$$

Power-law probability distributions exist in a number of other systems including the relative wealth of individuals (Zipf's law), the damage caused by hurricanes, and the “1/f noise,” that is found in many systems including cosmic background radiation and micro-electronic circuits. Fig. 5 shows the probability distribution of blackout sizes in North America. The superiority of the power-law fit is clear.

Mitigation debate

Large power grids are an amalgamation of thousands of generators, hundreds of thousands of transmission lines, and millions of electricity consumers. Because the generators are, for the most part, synchronous machines, they must rotate in almost perfect synchronism to keep the frequency of the electrical power at the rated frequency (60 Hz in most of the Americas and 50 Hz in Europe and most of Asia and Africa). To keep the grid in synchronism, and to keep the state of the system within operating

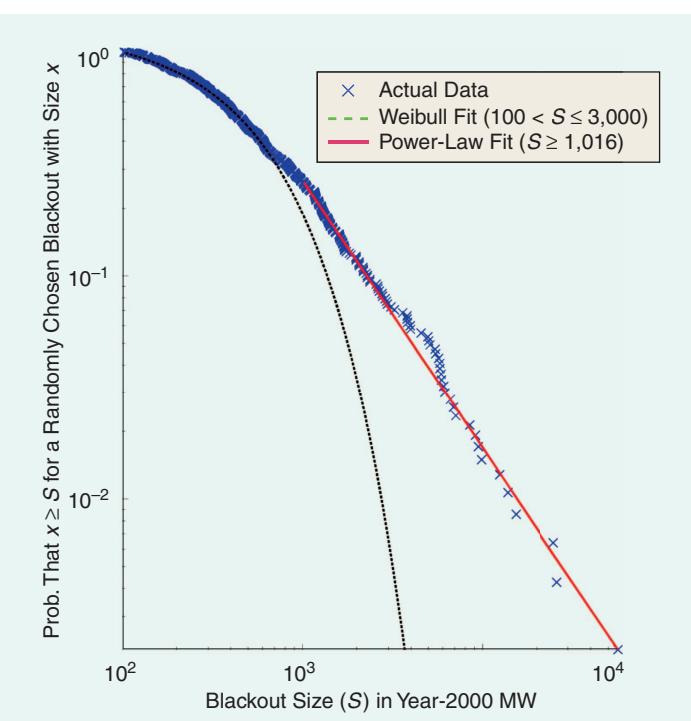


Fig. 5 The cumulative probability distribution of blackout sizes in North America (1984–2006, data from NERC) follows a power-law distribution. Large blackouts are much more frequent than one would predict from exponential statistics.

limits (thermal, mechanical and electrical), thousands of organizations and millions of human and electromechanical agents work around the clock to control the grid. Unlike with an airplane, a car, or even most municipal water distribution systems, no single organization supervises a large power grid. Instead power grids are complex systems, from which we get relatively reliable electricity service with very little centralized control.

The challenge for engineers seeking to mitigate blackout risk is to develop strategies that reduce existing risks without creating new risks that are worse than the old ones. Because of the myriad of unknowns in power grid operations, it is very difficult to find strategies that can verifiably meet this goal. In fact, Carreras et al. have shown that some strategies that would appear to have obvious reliability benefits, such as building new construction, would not result in long-term reliability improvements. Therefore in what follows we describe two strategies that solve a more tractable problem: that of reducing blackout size and cost. For both of these strategies we can show, using simple models of power grids, that it is possible to substantially reduce the cost of most cascading failure scenarios. The first strategy is survivability, a concept borrowed from the computer security literature and first proposed for power grids by Talukdar et al. The second strategy is what we call “Reciprocally Altruistic Control Agents” as proposed by Hines and Talukdar. The following two sections describe these strategies in more detail.

Survivability

While it would be comforting to know that we could prevent all future large blackouts, the power system is too complex to know that any technology or policy change will eliminate blackouts. The high voltage lines in the continental United States span a staggering 157,000 miles. The grid includes tens of thousands of nodes. It is economically infeasible to harden every mile of the transmission system and every transmission node against all natural and un-natural disturbances. Hurricanes, ice storms, earthquakes, and even the occasional attacker will occasionally damage the grid. Given the interconnected nature of the system, this damage will occasionally lead to at least some disruption of electricity service to customers.

However this does not mean that vital services must continue to fail on a regular basis. Computer science literature has come to some agreement that computer systems will occasionally be penetrated by hackers. Rather than resorting to despair, vital IT systems are designed to “survive” occasional interruptions through redundancy and careful network design. Similar principles are used in the design of military technology and strategy. While it is not possible to build invulnerable power grids, we can certainly ensure that vital services that require electricity can survive a failure in the power grid. Carefully chosen investments in battery technology and distributed or backup generators can ensure that critical services such as hospitals, traffic signals, urban mass transit, and water and sewer systems continue to fulfill their missions without support from the power grid.

While it is not possible to build invulnerable power grids, we can certainly ensure that vital services that require electricity can survive a failure in the power grid.

For example, consider traffic lights. Many city governments are currently replacing high-power incandescent bulbs with low-power LED signals. Given a relatively small investment in battery backup systems along critical traffic pathways, high-traffic corridors could continue to regulate traffic for hours after the start of a blackout.

In a study in the city of Pittsburgh, as a part of a capstone project course, students at Carnegie Mellon University found that some critical infrastructures like hospitals and air traffic control systems are already well protected with backup power systems. By working through the procedure outlined by Talukdar et al., some systems, such as traffic lights, were identified that warrant additional investment. We found that with relatively small investments to build a more redundant electricity supply system, with both centralized and decentralized electric energy

sources, the most important services can survive most blackouts, thus dramatically reducing the social costs of electricity interruptions.

Reciprocal altruism

While eliminating cascading failures is infeasible, it is possible to find a set of stress-mitigating control actions that would have dramatically reduced the size of most historical cascading failures. If the power grid could autonomously choose and execute these stress-mitigating control actions, we could reduce the size of most cascading failure sequences. Power system engineers have been working to develop grid control schemes of this sort for years. A wide variety of centralized control schemes (generally known as “Remedial Action Schemes” or “Special Protection Schemes”) exist in the research literature and in electricity industry practice. The problem is that power engineers have historically designed the power grid with decentralized, autonomous controllers, like relays, for good reasons. For one, as mentioned before, power grids are not operated by a single operator, but by hundreds, or even thousands, of cooperating, and in some cases competing, organizations. It is often difficult to get centralized schemes to perform well within this patchwork of operators. Also, centralized schemes are necessarily limited by the time it takes to gather state information, process this information into control decisions, and return the actions to the actuators in the field. Even in grids with a relatively advanced IT infrastructure, it can take tens of seconds or even minutes to gather measurement data and estimate the state of the network. Decentralized control agents are not necessarily limited by these delays. We thus propose a decentralized strategy, which we refer to as “reciprocal altruism.”

To understand the rational for reciprocal altruism it is useful to look at the existing system of decentralized control, which keeps power grids operating relatively well on a second-by-second basis. Generators inject electric energy into the transmission system, which delivers the energy to the medium voltage distribution system, which in turn delivers the energy to customers. Relays are located at every node in the network, monitoring for signs of stress that could damage equipment. When the stress exceeds locally monitored thresholds, the relays remove equipment from service. When stress is high throughout the network,

this process shifts stress to other locations in the grid and can initiate a cascade. The relays do exactly as they are designed to do, but they are designed to be rather selfish. They make decisions based only on local information and goals, without considering how this decision will affect the system as a whole. A superior approach would be for the control agents (relays) to consider how their local actions might affect their neighbors before taking action. In other words, we would like the agents to be a bit more altruistic.

Reciprocal altruism is common in biological systems. One of the best-studied examples is that of vampire bats. Vampire bats cannot survive more than one or two days without eating. When two bats go out hunting, and one is not successful, the successful bat will often regurgitate food to the unsuccessful one, even if there is no direct familial relationship between the two bats. There is no immediate genetic benefit for this sort of altruism, but biologists have found that this behavior can be explained by looking at the way that this behavior is reciprocal. The bats know that their neighbors will respond likewise if they are cooperative and share food. Inspired by this biological example, we propose that control agents for a power grid could be designed to be a bit more reciprocally altruistic.

To design reciprocally altruistic agents for power grids, we place one control agent at each node in a model of a power grid and then allow these agents to share information and goals with their “neighbors.” In our model each agent has two sets of neighbors. Consider “Agent a” in Fig. 6. Agent a exchanges measurement information very frequently, perhaps once per second, with its local neighbors. Its second set of neighbors extends further out into the grid and includes all of the agents that could help agent a with problems within its local neighborhood, such as extreme over-current on a transmission line, that could potentially lead to a cascading failure. At each time step (approximately once per second) Agent a runs a local optimization problem, using a method called model predictive control, to decide on

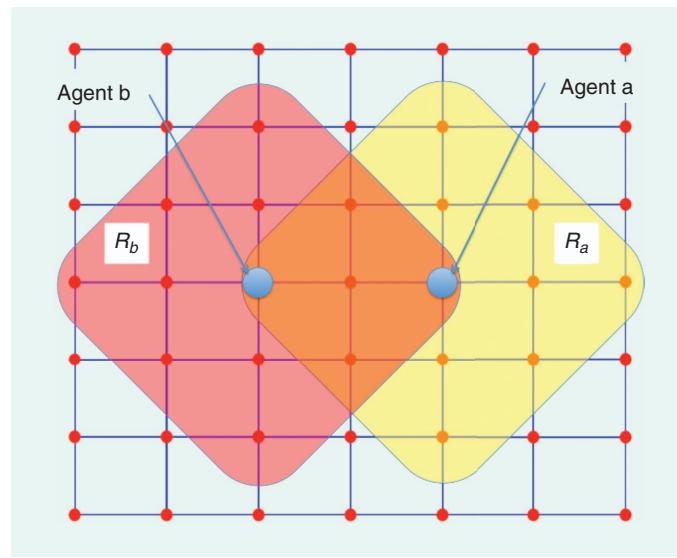


Fig. 6 An illustration of the overlapping neighborhoods of two agents in a power grid. R_a is the local neighborhood for Agent a.

Conclusion

Power grids are complex dynamical systems, and because of this complexity it is unlikely that we will completely eliminate blackouts. However, there are things that can be done to reduce the average size and cost of these blackouts. In this article we described two strategies that hold substantial promise for reducing the size and cost of blackouts. Both “reciprocal altruism” and “survivability” respect the necessarily decentralized nature of power grids. Both strategies can be implemented within the context of the existing physical infrastructure of the power grids,

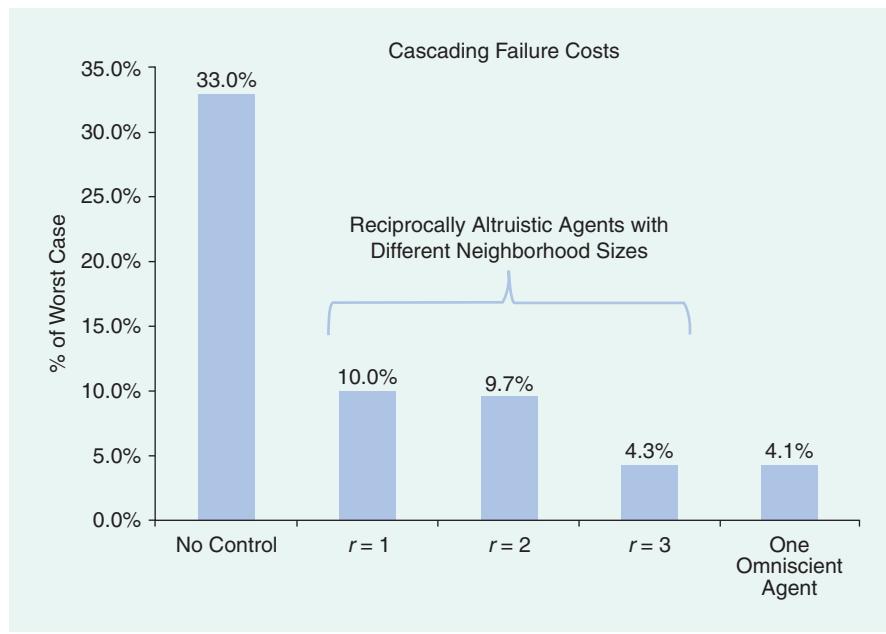


Fig. 7 Average blackout costs, after 100 simulations of reciprocally altruistic control agents for 5 different scenarios. As the amount of altruism (the size of the agents’ neighborhoods, r) increases the quality of the results approaches what we would get from a single agent with perfect knowledge of the power grid.

a set of actions. After negotiating with its neighbors, Agent a executes any control actions that need to be taken locally, such as shedding load, switching capacitors on or off, or changing generator set points, and then returns to collecting data and sharing it with its neighbors. By considering not only local goals, but also the goals of its neighbors, the agents are able to dramatically reduce the average size of set of simulated cascading failures (Fig. 7).

which is important because dramatic changes to the physical infrastructure are prohibitively expensive. However, additional engineering and innovation will be needed to bring strategies such as these to implementation and to create power grids with smaller, less costly blackouts.

Read more about it

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