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High-Voltage Transformers – The Power Grid's Achilles Heel

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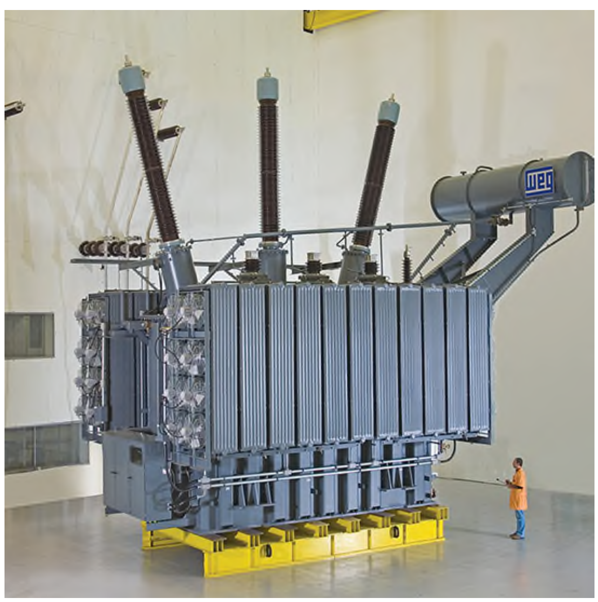
The U.S. power grid is extraordinarily reliable. It comprises a nationally connected network of power substations that can be rapidly reconfigured to substitute power for any substation that fails. Consequently, we seldom experience power failures that last for more than a few minutes. Occasionally, our power may be out for a few hours while repairs take place. These outages are generally caused by faults in the "last mile," such as a tree falling on power lines.

Outages that last days or weeks are highly unusual, though they do happen. In late October 2012, Super Storm Sandy knocked out power to over 8,000,000 residents for two weeks or more. The Great Northeast Blackout occurred in August 2003. It took out power for most of the Northeastern United States and a large portion of neighboring Canada. Some areas were dark for a week or more. Ironically, this blackout was caused by a high-voltage transmission line sagging on a hot day into an untrimmed tree.[1]

The worst-case scenario is an event that causes the destruction of an extra-high-voltage (EHV) transformer. These transformers are monstrous and vary in their characteristics. Thus, spares are not available readily. It can take months to manufacture an EHV transformer; and because of its size, it can take weeks to transport it to the substation needing the replacement. It is therefore imperative that power from other sources be rerouted to the affected area so that the length of the power outage can be contained.



[1] The Great Northeast Blackout and the $6 Billion Software Bug, *Availability Digest*; March 2007.
http://www.availabilitydigest.com/private/0203/northeast_blackout.pdf

Fortunately, a recent initiative by the power industry has led to the design of a smaller transformer that can be combined with others of a similar size to replace a large EHV transformer. These transformers can be premanufactured and located near sensitive power substations as spares. If a large EHV transformer should be disabled, it can be replaced in days rather than in months.

The Unthinkable – A Year-Long Power Outage

What would happen if the entire United States (or a major portion of it) lost power for a year or more? Ted Koppel explores this disaster in his book, "Lights Out."[2] He paints a picture of absolute desolation. Batteries would lose power, and we would lose our flashlights, cell phones, and portable radios. Emergency generators would provide pockets of light until fuel ran dry. Gasoline stations could not pump fuel when their tanks ran dry, even if they had generators. There would be no running water, without which there would be no disposal capabilities for human waste. Supermarket and pharmacy shelves would empty. Home-care patients reliant on ventilators and other medical equipment would die. Some officials estimate that only one in ten people would survive a year without power – and without food or water.

Worst of all, there are no government plans to handle such an emergency. The federal government and most state and local governments have plans to handle limited power outages that last for a few days or even for a few weeks. However, there are no plans in place for a year-long power outage. Interestingly, Koppel points out that the Mormons are in the best position to weather such a disaster. Their faith calls for stocking supplies to handle any disaster. Their organizational structure provides a strong top-down hierarchy that ensures there are ample central supplies that can be distributed to their people in the event of a long catastrophe. But would these supplies withstand armed assault from others in need?

In his interviews with top emergency officials, including those from FEMA (the U.S. Federal Emergency Management Agency) and DHS (the U.S. Department of Homeland Security), Koppel discovered the general attitude to be that such an outage could not happen; and if it did, they had no idea as to how to prepare for it.

Could Such an Outage Occur?

But could such a catastrophe occur? It has been estimated by some officials that the disabling of as few as nine critical substations could take out power to the majority of the United States. Koppel points out three possible scenarios for a massive power outage lasting a year or more:

Cyber Attacks

The United States is powered by three major power grids – a western grid, an eastern grid, and a grid largely centered around Texas. Computerized SCADA (Supervisory Control and Data Acquisition) systems manage the distribution of power between and within these grids, ensuring local needs are met even when portions of one or more grids are down.

These systems coordinate with each other via Internet connections. However, the SCADA systems were designed decades ago and do not include the security measures necessary to protect them from hackers.[3] We already know that malware exists in these systems to interrogate the interconnectivity of the grid, a first step for a hacker to determine how to attack them.

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2 Lights Out, *Ted Koppel*, *Crown Publishers*; 2015.
Available on Kindle.

3 Can Hackers Take Down Our Power Grid?, *Availability Digest*; January 2016.
http://www.availabilitydigest.com/public_articles/1101/power_grid_hacks.pdf

A sophisticated hacking attack could cause circuit breakers and other control equipment to be reconfigured so as to damage substation equipment. Normal operating displays would be presented to the system operators to prevent them from seeing the attack.

Physical Attacks

There have been cases of deliberate physical attacks on power substations. Typically, saboteurs using high-powered rifles or submachine guns fire at transformers and other substation equipment to disable the substation. If a transformer is damaged by weapons fire, its cooling oil leaks out of the holes and destroys the transformer. The transformer has to be replaced.

In one attack on the PG&E Metcalf Transmission Substation in April 2013, gunmen fired on seventeen high-voltage transformers, destroying most of them.[4] 52,000 gallons of oil were spilled.

Electromagnetic Pulse

A high-altitude (200 miles or so) nuclear explosion creates a massive electromagnetic pulse (EMP) that will result in damaging voltage and current surges in a power grid.[5] An EMP pulse over the United States easily will destroy many large transformers throughout the country. Rogue nations such as North Korea are nearing the potential to launch such attacks.

The electrical substations of most military installations are protected from EMP pulses via Faraday cages, a thin mesh of conducting material.[6] The cost to protect the substations of the nation's power grid with Faraday cages is minimal, but as yet this has not been undertaken.

A Simulated Attack Proves Disastrous

Recently, the North American Electric Reliability Corporation (NERC) led a simulated attack on the U.S. power grid.[7] NERC injected computer viruses into grid control systems, simulated bombed transformers and substations, and knocked out dozens of power lines. DDoS (Distribute Denial of Service) attacks were also made on several control computers. The tests involved 210 U.S. utility companies as well as Mexican and Canadian companies that are part of the U.S. power grid.

Though no actual operating equipment was affected, the simulated result was not good. Control computers tore the system apart. DHS's National Cybersecurity and Communications Integration Center specialists took calls from electric industry technicians all over the country to assist them in recovering from cyberattacks. Hundreds of major transformers and transmission lines were damaged or destroyed in simulation. Tens of millions of Americans were left without power.

The viruses injected into the control computers kept technicians in the control centers from knowing the status of critical equipment, requiring the dispatching of several trucks with linemen to investigate. In many cases, attempts by the linemen to enter power facilities were stymied by police officers who had locked down locations because of shooters.

The Weak Link – Large High-Voltage Transformers

It is clear that the weak link in restoring power from a major attack on our electric grid are the large extra-high-voltage (EHV) transformers. Though they comprise only 3% of the total number of transformers in the grid, they carry 70% of the power. Most of them are custom-designed for a particular substation. Therefore, it is impractical to manufacture spares for the EHV transformers in each substation.

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[4] Metcalf sniper attack, *Wikipedia*.
[5] Nuclear electromagnetic pulse, *Wikipedia*.
[6] Faraday cage, *Wikipedia*.
[7] Are Our Power Grids Vulnerable?, *Availability Digest*; December 2013.
http://www.availabilitydigest.com/public_articles/0812/power_grid_vulnerable.pdf

If such a transformer is damaged, it can take months to produce a replacement. Added to that is the problem of getting the transformer to the substation site. The transformers are so heavy that they must be carried on special twelve-axle trailers. They cannot be moved until each state through which they have to transit has certified that the bridges, roads, and tunnels can bear the weight and provide the clearance to accommodate them. Just the movement from the factory to the substation can add weeks to the replacement time.

Most of the EHV transformers were originally moved to the substations via rail. However, that was decades ago. In many cases, the rail lines no longer exist or are not serviceable.

Thus, if a major attack should take out a large number of EHV transformers in the U.S. power grid, it could be months before electric service is restored to all users. The apocalypse described by Koppel in his book will have happened. Electricity to most of the nation could be unavailable for months.

RecX to the Rescue

What is needed for EHV transformers is a rapid replacement strategy with universal spares. A consortium led by the U.S. Department of Homeland Security launched a Rapid Recovery Transformer (RecX) program. The goal was to develop a conventional, oil-filled transformer that easily could be transportable and quickly installable within one week. The result was a single-phase transformer that allowed multiple units to be coupled together to provide three-phase power of whatever capacity was needed to replace a failed EHV transformer. The single transformers were economical enough to be manufactured in quantity and stored near critical substations as spares. They were small enough so that they could be transported easily.[8]

A trial was run with the RecX transformers in March 2012. A trio of single-phase 345/134-kv transformers were disassembled, loaded into specially designed trailers, transported more than 900 miles, and reassembled to replace an existing three-phase EHV transformer. The entire operation was completed in less than five and a half days. The RecX prototype spare is still in operation and is working as originally planned.

Summary

Currently, the U.S. Department of Energy is preparing to submit to the U.S. Congress a plan requesting the creation of a strategic reserve of spare RecX transformers. The plan will include the total number of transformers and the total megawatts required as well as the strategic locations for transformer storage.

As a side note, a system dubbed AssetShield is being introduced to protect large power transformers and other substation equipment from ballistic attacks. AssetShield is an impact protection system that reduces the kinetic energy of bullets to the point that they will not damage equipment.

[8] RecX: Prototype spare transformer sets the stage for substation recovery, *Electric Energy Online*; November/December 2015.