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The AC Electrical Grid: Transitions into the Twenty-First Century

The electric power system infrastructure is at a crossroads in the twenty-first century. After one hundred years of development of Tesla and Westinghouse's synchronous alternating current (AC) generation and transportation systems, the grid has evolved into a complex system-of-systems upon which a nation's critical infrastructures heavily rely. Canada, for example, identifies 10 critical infrastructures: energy, communications, food, health, manufacturing, finance, water, transportation, safety, and government. Disruptions in this system, such as power blackouts, can have extensive and highly negative consequences.

Despite the complexity of the electrical grid, electricity has become ubiquitous to the point that, in modern societies, it is taken for granted. Prices have been reasonable, availability has not been a concern for the general population, service continuity has been excellent despite behind-the-scenes wars, and environmental effects have been largely ignored. Monopolistic ownership and technical prowess have made the grid "invisible" to the user.

In the twenty-first century this will be different. It will no longer be possible to ignore cost and environmental impact, and the continued availability of affordable electricity will no longer be a given. The twenty-first century will be defined by a higher level of public awareness, and the grid will become "one more concern." The traditional paternalistic grid will be broken down not by regulation, but by the need to use local energy resources, such as solar, wind, and other renewable resources. Distributed ownership of power generators, along with user awareness of consumption, will become the norm.

In this essay, then, I will discuss the history of the AC electrical grid, before examining possible changes to this system in the twenty-first century. I hope to show that, alongside and as a result of the changes mentioned above, Direct Current (DC) power generation and distribution can make a comeback, leading to a safer, more reliable, and more efficient electrical system.

Before we address the future, though, we should consider the past. How has the AC electrical grid come to occupy such a dominant position in our societies?

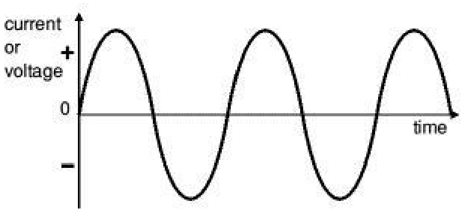

Figure 1: Alternating current (AC), where voltage, or current, is a sinusoidal value where waves oscillate.

Two characteristics of the AC grid of the twentieth century have been responsible for its rise and its ills. The alternating nature of AC waves makes it easy to change voltage levels using relatively inexpensive coupled-coil power transformers: this is the grid's major strength. Generating AC voltages using synchronous generators is straightforward. Doing so, however, leads to the requirement of synchronicity, which is the grid's major weakness.

To understand these two concepts, we need to understand the behavior of alternating current. In AC systems, voltages and currents are a sinusoidal wave (fig. 1), oscillating in North America at 60 Hertz (Hz) and in Europe at 50 Hz. In an AC grid, many oscillating waves must move synchronously in order for the grid to transmit electricity.

This oscillating nature of AC voltages and currents allows for the voltage levels to be changed; this in turn makes it easy to transport electricity over long distances from large generation centers to the consumer's location. Since power equals voltage times current, transforming the voltage to a high value decreases the value of the current and the size of the wire required to transport the electrical energy. In high-voltage systems, electrical power can therefore be transmitted efficiently over long distances using relatively thin wires. (This is not possible with DC electricity since coupled-coil transformers cannot change the DC voltage level.) After the energy is transmitted, the electricity can be brought down to low voltages for safe industrial and consumer use.

Nicola Tesla's concept of synchronous AC generators and William Stanley's power transformers were the disruptive technologies of the nineteenth century that boosted the development of long-distance electric power generation and distribution systems. The synchronous AC electrical system, with its capacity to transmit power over hundreds of kilometers, dominated Thomas Edison's DC electrical systems, which could transmit power over only a few kilometers.

While synchronous oscillation proved hugely beneficial, though, it meant that the electrical system was inherently fragile. In an AC electrical grid, the rotor angles of all major power generators must turn at the same speed. When, due to some disturbance, one AC generator speeds up or slows down too much with respect to the others, the associated part of the grid is cut off. Unless immediate remedial action is taken, the entire system may collapse.

Two factors hastened the expansion of the AC power grid throughout the twentieth century: economies of scale and a high demand for electricity.

Economies of scale allowed for the construction of large central generating stations. These generating stations yielded a high efficiency of transmission, higher profits for utility companies, and lower costs for consumers. By the 1930s, it had become economically advantageous to interconnect multiple generating plants over wide geographical regions to reduce the transmission requirements, share spinning reserves (the extra generating capacity that comes from increasing the power output of generators that are already connected to the power system), and improve system reliability. Today, the North American electrical grid is the largest in the world, with a capacity of about 830 Gigawatts (GW) and total assets of $1 trillion. The next largest grids are those of Europe (781 GW), China (391 GW), Japan (243 GW), Russia (216 GW), and India (131 GW). The North American grid comprises three major extensive interconnected areas: the Eastern, Western, and Texas systems. The Eastern and Western systems include Eastern and Western Canada, while the Western grid also includes the northern part of Mexico. Interconnected power grids constitute some of the most complex systems ever created. A generator in Alberta, for example, has to run in sync with a motor in Arizona.

The expansion of the electric grid in the twentieth century was accompanied by a steady increase in consumer demand for electricity. In 1905 only five percent of urban homes in the United States had electric lighting; by 1930 that number had increased to more than 90 percent (Nye, 2010). Abundant and affordable electricity shaped consumers' habits and expectations, with consumers expecting new products and improvements over older ones. From 1900 to 1970, consumers' demand for electricity in industrialized countries doubled approximately every 10 years. Electricity improved the quality of life for the population with its conveniences, such as electric lighting, heating, refrigeration, air conditioning, household appliances, and electronic devices. Despite its achievements, the electric power grid has been showing significant signs of aging for the last decade and may be approaching its limit in meeting the electricity needs of the twenty-first century. Heavy investments by utility companies have focused on supplying consumers' energy demands with little incentive to upgrade the grid's infrastructure. The result is an aging electric grid that is being operated closer to its limits and is increasingly unstable. One consequence has been the rising number of large-scale blackouts. As indicated, due to the synchronous nature of the grid, problems that develop in one region spread in a cascading manner to the rest of the interconnected grid unless the area that has the problem is isolated.

The 11 most severe, large-scale blackouts in history have occurred since 1998, with the most recent one in India in July 2012. The Indian blackout was the largest in history and affected over 620 million people for two days. In North America, the Northeast Blackout of 2003 lasted four days and affected 50 million people in the Northeastern and Midwestern United States and Ontario, Canada, with economic losses of about $6 billion.

Due to the strong dependence of critical national infrastructures on the power grid, when a blackout occurs, the other infrastructures can shut down within seconds. The impact of a major blackout of even a few hours is enormous and can result in disruptions in communication and transportation systems, heating, water supply, and other utilities.

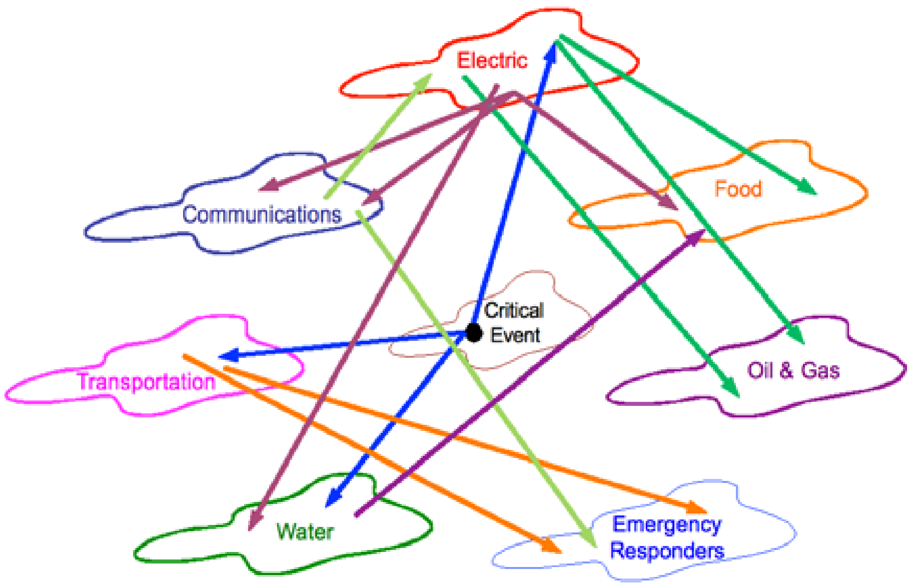

Figure 2: Critical Infrastructure Interdependencies

These, in turn, can affect emergency services and hospitals. The disruptive effects can ripple into everyday necessities, such as obtaining cash from ATMs or financial institutions and food supplies from supermarkets, to personal and social services, such as telephones and internet services. Where the interconnected power grid crosses national borders, more than one nation is affected. Since power supply systems are potential military targets, such as from terrorist groups, the power supply industry itself is a critical infrastructure.

The power industry has undergone two major changes in the past decades that increased the grid's risk of blackouts: deregulation and the emergence of independent power producers, including those generating renewable energy.

The deregulation of the electric power industry, in North America and most other industrialized countries, has contributed to an increase in power blackouts due to the lack of incentives to maintain a robust grid. Prior to deregulation, the power supply industry operated as a vertically-integrated monopoly that was responsible for all operations of the grid. Deregulation resulted in the separation of the system's tasks of generation, transmission, and distribution into individual economic entities, and, in the process, introduced new participants, such as independent power providers (IPPs), transmission companies (TRANSCOs), retailers, integrated energy companies (combining IPPs and retailers), and independent system operators (ISOs). After deregulation, there were few incentives to invest in a reliable and robust system, despite the large increase in electricity demand. For example, between 1990 and 2004 in the US, transmission transactions increased 400 percent, but the high-voltage transmission system expanded by only 2.8 percent. When utility companies stopped being monopolies after deregulation, independent system operators (ISOs) were given the task of overseeing the synchronized operation of the grid as a whole system. However, these ISOs could not directly control the operation of the internal systems of the individual companies.

The US Energy Information Administration projects a 53 percent increase in the global demand for energy between 2008 and 2035, accompanied by a projected CO_2 emissions increase of 35 percent. Electricity will be in very high demand in the future, particularly since information and communications technologies are highly dependent on it, and new technologies aimed at reducing fossil fuel consumption, such as electric vehicles, are based on electrical energy.

Unless the growth of alternative sources (solar, wind, biomass, etc.) is accelerated, traditional sources such as coal, natural gas, hydro, and nuclear power will remain the main drivers for large electricity generating plants in the next half-century, at least to maintain the existing base load. Coal and natural gas produce high amounts of greenhouse gas (GHG) emissions, of the order of 500 to 1,000 grams poer kilowatt hour (kWh) of electricity produced. This level of GHG emissions will continue to contribute significantly to extreme climate changes, which, in turn, threaten ecology and place human welfare at risk. Hydro energy is clean but can have a considerable impact on the surrounding eco-system. Nuclear energy does not contribute to GHG emissions, but presents serious safety concerns, such as the problem of nuclear waste.

Renewable energy sources, such as solar, wind, biomass, tidal, and geothermal, constitute valid alternatives to effectively reduce GHG emissions as well as political and economic dependence on fossil fuel supplies. However, the intermittence of renewable energy sources like wind or solar makes the supply less reliable.

Huge investments in power supply infrastructure will be needed in the near future to create smarter grids that can handle the technical challenges of volatile renewable energy sources. The technical problem of interfacing with the AC grid can be solved with power electronics, and the problem of dispatching electricity in the right quantities on demand can be solved with storage strategies. However, the existing aging grid is reaching its limits very rapidly, and these efforts may be insufficient.

The existing paradigm, based on a mostly AC system, consists of large generating stations located hundreds of kilometers away from the many small loads that are served. The new paradigm, based on distributed renewable energy sources, will consist of many small generators connected to the main grid through DC to AC power electronic interfaces.

Since about 80 percent of home loads can be more efficiently fed with direct current, DC grids will emerge that will connect local DC renewable generation to load districts. Considerable energy savings can be achieved by distributing DC current to homes. For example, electronic devices, such as computers, televisions, and mobile phones use DC for their internal operation. Currently, a power supply that converts AC to DC is used inside personal computers, with an energy loss in the conversion process of 20–40 percent. These losses would be avoided with DC distribution systems, in addition to the savings in the cost of providing AC to DC interfaces for each of the DC devices.

After a century of AC-dominated power generation and transmission, pioneered by Tesla and Westinghouse, DC power generation and distribution, pioneered by Edison, will make a comeback. Since local small generation facilities will have multiple owners, the new energy self-sufficiency paradigm will result in a more democratic energy infrastructure. During this much-needed move towards renewable energy sources, the existing AC grid will continue to play an important role in facilitating the transition towards new technologies. Where the main grid is accessible, it will also be used for storage and backup functions.

Abundant energy is not on the decline. The sun, wind, tides, waves, and heat in the interior of the earth will last for as long as the planet lasts. In 2010, the world population was 7 billion. Despite a century of investment in electric power systems, there are still 1.6 billion people without access to electricity. Rural electrification in scarcely populated towns is very expensive, with centralized generation great distances away. Local, autonomous DC systems that utilize local renewable energy sources can enable the growth of such rural communities.

In terms of sustainable economic development, the new paradigm of locally generated renewable energy can be the first step towards creating prosperous communities that use locally available energy resources to create local economies. Perhaps this change of paradigm in the way electricity is produced—small-scale and locally versus large-scale and centrally—can also lead to a shift from large concentrated population centers with highly wasteful and inefficient use of resources, to self-sufficient local communities that integrate energy and other resources with ecological, economic, and human variables, as well as to the sustainability of the planet and improved quality of life.

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