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The China power grid: a network science perspective

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Power grid is a very large scale and highly non-linear dynamical system, and its stable and reliable operation poses a great challenge to scientists and engineers. As a complex dynamic network has a tendency of catastrophic failure, sophisticated analysis and control are required. In an interview with NSR, Professor Yusheng Xue, member of the Chinese Academy of Engineering, Honorary President of China's State Grid Electric Power Research Institute, talked about the economic impact, technical challenges, and future development of power grid in China.

POWER GRID DEVELOPMENT IN CHINA

NSR: Why is power grid an important and difficult problem?
Xue: As we all know, supply of electricity is critical to our daily life. Thus, a stable and smart power grid that avoids catastrophic power failure is vital to our society.

Power grid is a typical complex system, and there are many factors involved in its operation, including static and dynamic constraints. Furthermore, these factors are deeply intertwined, making things more complicated.

NSR: What is the status of power grid development in China?
Xue: To the end of 2013, China had 1.247 billion kW installation capacity of electricity generation, including 75.48 million networked wind power generation, which is leading the world. The growth of solar power generation in China is also the fastest in the world. China power grid is responsible for wide-area coordination of energy resources and long-distance transmission of clean energy, bearing great pressures in load balance and stability problems caused by large-scale uncertain intermittent electricity generation.

Today, China has become the only country in the world with comprehensive technologies for using ultra-high-voltage (UHV) power grids, with international standards. In the 8-year period, starting from 2013, the State Grid Corporation of China plans to build 'five latitude lines and five longitude lines' of UHV synchronous power grid with 27 UHVDC (UHV refers to ±800 kV or above for DC). Meanwhile, it will build smart power distribution networks that can accept and fuse renewable energy, and support charging networks of electric vehicles.

China now has advanced power systems protection and control technologies, with multiple defense lines for blackouts, holding excellent records of reliability. About 4/5 of state power networks have adopted the integrated framework for protecting power outage, accidents and disasters, which was established based on systems' stability theory and quantizing analysis developed in China.

Yusheng Xue, Honorary President of China's State Grid Electric Power Research Institute *(Courtesy of Yusheng Xue)*

NSR: What is the role big data and complex networks play in the power grid?
Xue: The grid must keep a balance between electricity generation and consumption in real time, so as to reduce the risk of electricity congestion and to keep the synchrony among all generators online.

Theoretically, any disturbance will spread out in light speed over the whole power grid nationwide. Correspondingly, both qualitative and quantitative analyses are urgently needed, while optimizing the feed-forward and feed-back controls for stability.

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The power grid system can be described by dynamical equations containing a huge number of trigonometric and magnetic saturation functions. The protection relay and system protection require logic equations to describe. Moreover, the grid topology and the dimensions of different type of equations can be changed during the dynamics. Consequently, to analyze and control a large-scale power grid, many complex factors have to be considered altogether, and complex network theory and techniques are obviously very important and useful.

Commercial software made in China can be used to analyze a complex power network of more than 10 000 nodes (with more than 1000 generators) and more than 30 000 edges. It should be noted, furthermore, that every generator node here requires two to seven dynamical equations and two algebraic equations to describe; every load node requires one dynamical and two algebraic equations to do so. Furthermore, if the power distribution models of lower than 35 kW are also considered, it will increase the network dimension by one order. The big data faced by such a power network with real-time monitoring is difficult to imagine, especially with disturbances that could trigger a huge amount of dynamic responses. More crucially, all the data-mining and decision-making have to be carried out and completed online, including early risk warning, real-time optimization of operation, and so on.

DEFENSE AGAINST ATTACKS

NSR: Could you comment on the reliability, stability, and robustness of the power grid against attacks and disasters?

Xue: In the power grid, there exist complex dynamics of various time scales: electromagnetic transients in milliseconds, synchronous instability in less than one second, low-frequency oscillations in tens of seconds, thermo-instability in minutes, as well as static voltage and frequency instability in tens of minutes. They constitute the diversity of stability constraints on the power grid. The current available online analysis technology is not powerful enough to handle the dominos effect on the grid, not to mention the quantitative analysis and optimal control in handling the network synchronous stability. In addition, renewable energy and electric vehicles introduce large-scale intermittency and uncertainties into the grid, which cannot be ignored.

China's power sector has gained significant progress in preventing blackouts caused by local failures, including stability quantification theory as well as stability control techniques, adaptive stability control and optimization methods, the establishment and improvement of the spatiotemporal coordination of security and stability of an integrated defense system, etc. Such a defense system periodically assesses the potential effects of faults on power system stability, performs risk alert, suggests prevention and control measures, and searches and renews the best decisions on emergency control according to the actual operating conditions.

Although the defense system has coverage of 4/5 provincial power networks in China, it is still insufficient to prevent severe external disasters, such as ice coating and lightning. There are problems and deficiencies in many areas, including the integration with environmental information and geographic information system, multiple defense lines for the information system, capability of effective responses to massive disturbances, adaptation and prevention capability in handling emergency control, and task coordination. Moreover, the current system cannot ineffectively deal with extremely complex power outage patterns caused by natural disasters today.

To better protect the power grid from severe damages, we must prevent all high-risk accidents of low probability. The traditional approach of collecting data from inside of the power system should be extended to the natural environment, so that the defense front can be moved to wider boarders. Also, the time scale of effective warning should be extended from minutes to hours, so as to provide sufficient time for the system to react.

Moreover, the warning target should be extended from single instant risk to groups with frequent cascading failures. Furthermore, optimal coordinated control decision-making should be extended from the normal operation mode to the worst scenario, and the typical passive defense strategies should be changed to active defense approaches. With all these measures in place, we will be able to gain a secure and safe coordination and control over the whole power grid, thereby avoiding the emergence of serious disasters. Today, we are working very hard towards this goal.

ABSORBING THE CUT-EDGE RESEARCH

NSR: Does current research on complex networks help to predict or prevent large-scale power blackouts?

Xue: Power grid has all the characteristics of complex systems, and has a large number of basic elements which interact with one another extensively, with open and complex multi-layer dynamics.

Researchers in the area of power networks apply complexity theory and use the evolving structures to describe the overall integrated behavioral patterns and laws, study the underlying principles of blackouts, evaluate the global fragility of the grid, predict the trends of evolution, and so on. Many researchers have verified the power law of the size scale versus the occurrence probability, but there is certainly room for further improvements in such research.

As a complex network, power grid has the characteristics of large-scale topologies and complex dynamics. Researchers in the area of power grid tend to use small-world and scale-free models rather than complete random networks to study the grid robustness against various attacks and cascading failures.

The above-discussed complexity theory and methods qualitatively investigate cascading failures from a global point of view. It has proactive impacts on the study of the power grid, especially in recommending useful strategies and plans when facing high uncertainties of many seemingly small and subtle events. Regarding the operation and control of large-scale power networks, however, it is necessary to perform quantitative analysis

that takes into account fault scenarios and the physical laws of power flows and transient dynamics. I believe that by combining complexity theory with the traditional modeling and simulation methods for the power grid, integrating the global coordination and the reductionism, and extending the understanding of cascading failures and large-scale blackouts will significantly benefit the future development of power disaster prediction, prevention, and control.

CHALLENGES AHEAD

NSR: What are the major challenges in research and development of power grids worldwide?

Xue: On the one hand, power industry consumes approximately 1/3 of the fossil energy and produces about 40% of CO_2 emissions worldwide, thus responsible for the major energy and environmental issues today. On the other hand, electricity is an efficient carrier of renewable energy, therefore is the driver for sustainable energy development. Therefore, the task of power research and development is to maximize the advantages of electric energy transmission to better support strategic decisions on energy security, environmental protection (especially emission reduction), so as to reduce air pollution that causes fogs and hazes.

Smart grid is such a mission that includes reliable, affordable, open, and user-friendly energy development and utilization, which can be either large-scale and massively distributed bases in far distances or small-scale but widely distributed sources, supporting various energy demands from electric vehicles, energy conservation, and market participation, etc. This is a multi-sector and multi-disciplinary system, contributing to uncertainty analysis, risk management, and research on system security and economic coordination.

There are also new developments that could be useful in reducing power consumption and saving spare capacity, including economical and effective massive storage of electricity, multi-DC transmission and large-scale AC/DC mixed-mode power networks, and wide applications of power electronic equipment. Effective operation and control of different types of inverter-based generations that can improve intermittent renewable energy (such as wind electricity and solar power) with accurate estimation of electric vehicle charges could also be very useful.

> “Power supply reliability must be a harmonic cooperation of power grid, primary energy network, financial systems, communication network, and so on.
>
> —Yusheng Xue”

NSR: Finally, what are future research directions that may link power grids and network science?

Xue: So far, the boundary conditions for grid analysis, namely the operating conditions and the disturbances, are given based on off-line experiences, therefore cannot be set realistically according to the evolutionary trends of external non-electrical systems. This not only limits the advancing of early-warning time, but also limits the adaptive ability of pre-decision about the external environment.

Thus, future network analysis needs to consider energy and environment as a whole rather than as separate entities. A physically secure power system can be unreliable to provide power supplies due to the restrictions on emission, primary energy, and power market. Therefore, preventing large-scale blackouts requires a harmonic coordination of many factors, including energy resources, financial systems, communication networks, transportation and goods supply networks, and so on. This is a topic on complex dynamic systems covering multi-vector networks.

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