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COMPLEX NETWORKS

Synchronization and your morning coffee

Networks as complex as national power grids must be stable enough to maintain synchrony in order to function. Understanding how this stability is achieved forms the focus of a new study that holds promise for improving grid performance.

Ian Dobson

Your nation's electrical grid is humming along at either 50 or 60 Hz, you get up in the morning and switch on the coffee maker — and yet all the lights on your block keep burning. Although optimally contemplated after the caffeine kicks in, this miracle of technology and physics relies on the electrical grid maintaining synchrony: barring extreme events, all of the shafts of the generators in the grid are spinning together in a stable state. Turning on the coffee maker (or even hundreds of coffee makers) perturbs the grid, but the stability damps the perturbation and allows the grid to maintain its operation at almost exactly 50 or 60 Hz. Conditions for stability are of great interest not only for network science, but also for their potential to improve the engineering design and operation of electrical grids. Now, writing in *Nature Physics*, Adilson Motter and colleagues have derived new mathematical conditions for grid stability [1].

Roughly speaking, a physicist can think of the grid as hundreds or thousands of oscillators coupled together by a large (up to continental-scale) network comprising transmission lines. The oscillator at each node of the grid represents an electrical generator. The generators are rotating together in synchrony, and the deviations of the angles of the generator shafts behave like the angles of pendulums. The electrical coupling of the generators through the grid is nonlinear, and any disturbance makes the generator shaft angles swing a bit relative to one another all over the grid. When the system is stable, the deviations damp down and perfect synchrony is restored. However, in some combinations of disturbance and operating conditions, synchrony can be lost as one group of generators speeds up relative to the others. This in turn causes large, potentially destructive power flows, so that parts of the grid automatically shut down to prevent damage. If enough of the grid shuts down, we experience a blackout.

Coupled nonlinear oscillators have been studied ever since Christopher Huygens observed synchronized ticking of mechanical clocks hung on the same wall in the seventeenth century. Recently there has been much interest in the emergence of synchrony in oscillators coupled via a network. For example, the Kuramoto model, which describes a regular and homogeneous network of coupled oscillators, permits elegant analytic conditions identifying the point at which they lose synchrony [2] Although the oscillators each have their own natural frequency, if the network coupling is sufficiently strong, the network synchronizes to a common frequency and all the oscillators swing together.

It turns out that the conditions for synchrony of electrical power grids, which have been known and applied in electrical engineering for the last century, are similar to those for Kuramoto oscillators. Indeed, power grids can be regarded as a nonhomogeneous generalization of Kuramoto oscillators, and the point at which they lose synchrony can be computed by extending the corresponding Kuramoto conditions [3].

These parallels between scientific theory and engineering practice are exciting, but researchers face substantial challenges in passing from the ideal models of physics and network science to the engineering models representing power grids. Ideal models are designed to show the essential characteristics of synchrony phenomena in an elegant analytical way — whereas engineering models must approximate the formidable intricacies and complications of the power grid. The grid is a specific arrangement of aluminum, copper, steel and control systems optimized to transport electricity cheaply and reliably from all the particular places and ways it is produced to all the sites at which it is consumed. As a consequence, even approximate mathematical models of one aspect of the power grid are heterogeneous, messy and difficult to analyse — even with the help of caffeine. Researchers are continually seeking compromises between sufficiently accurate approximate modeling of these complexities for the purpose at hand and analytic and computational tractability.

Active control systems of generators that maintain the generator outputs, together with the physics of the fixed hardware of the generators, influence their individual tendency to damp perturbations. The new analytic results of Motter *et al.* [1], together with those of another recent study [3], show how the network connections between all the generators via the transmission lines interact with their individual dampings to produce a stable and synchronized state. This opens up the possibilities for research to adjust the design of control systems to forestall problems of loss of stable synchrony in some operating conditions. It is generally cheaper to redesign controls than it is to limit power transfers in the grid. Limiting power transfers tends to increase the amount of power taken from more expensive or less environmentally favorable sources.

A direct experiment to verify that grid stability is being maintained is not difficult to perform — simply check that your coffee maker turns on in the morning! However, to reliably maintain this condition every day in an evolving and complicated electrical grid is a continuing challenge. It is not simply a matter of repeating the analyses and engineering of the past, because the grid is being transformed to accommodate significant amounts of highly variable sources such as wind and solar energy. The new sources, as they are currently controlled, also tend to contribute less to damping perturbations. Thus the transformation to a more sustainable energy system generally holds great promise but also poses specific challenges for maintaining synchrony.

The grid is both a playground for physical and mathematical phenomena and a critical infrastructure that underpins our way of life. The recent advances in bridging the scientific and engineering realizations of network synchrony have already yielded some analytic conditions for synchrony, and the hope is that these analyses can yield improvements to maintain grid stability, keep the lights on — and continue to optimize the brewing of coffee in the morning.

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