Power grid upgrades may cause blackouts, warns Braess's paradox

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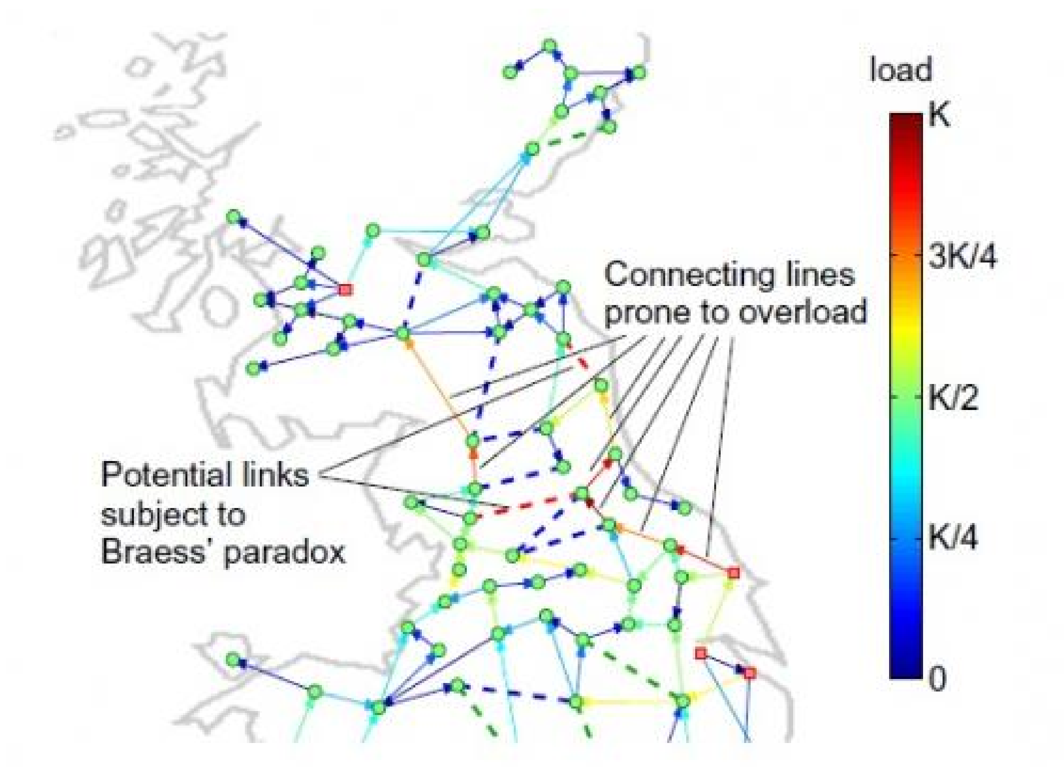

In this power grid model, the dashed lines represent potential new links at arbitrarily chosen locations. Two of these links (dashed red) are potentially subject to Braess's paradox and could destabilize grid operation. Braess's paradox can be caused by a nonlocal collective effect in which links in a nearby region are prone to overload. Credit: Witthaut and Timme. ©2012 IOP Publishing Ltd and Deutsche Physikalische Gesellschaft

(Phys.org)—In order to meet increasing energy demands, power companies have the option of adding new power lines to the existing grid. But in a new study, researchers have found that, contrary to common intuition, adding certain new power lines may cause power outages across the grid due to desynchronization. This finding is an example of Braess's paradox, which was originally discovered in traffic networks to show that adding a road to a congested traffic network may counterintuitively increase overall driving time. This study is the first time that Braess's paradox has been found in oscillator networks.

Dirk Witthaut and Marc Timme from the Network Dynamics Group at the Max Planck Institute for Dynamics and Self-Organization (MPIDS) and the University of Göttingen, both in Göttingen, Germany, have published a paper on Braess's paradox in electric power grids in a recent issue of the New Journal of Physics.

"Given the change of our energy supply from large, centralized power plants to many distributed sources of renewable energy, an extension of the power grid is inevitable," Timme told *Phys.org*. "However, upgrading the grid in an effective way is a complex task with lots of unexpected challenges. In our paper, we show that building new transmission lines does not automatically improve the performance of the grid. Instead, some possible lines can actually destabilize it. This finding is of technical as well as economic interest: building such an inappropriate line would actually have enormous costs, but reduce grid performance and stability."

The key problem with adding certain lines is desynchronization. As the researchers explain, synchronization is essential in many networks such as electric power grids in order to ensure stability. In a power grid, synchronization means that every piece of equipment that generates or consumes power must oscillate at the same frequency (50 Hz in Europe; 60 Hz in the US). If the phase-locked synchronization is destroyed, the grid becomes unstable and power outages can occur.

At first glance, it would seem that adding new transmission lines to the grid should maintain the synchronization and stability of the network. And, on average, the researchers indeed found that additional links do maintain stable operation. However, they also found that certain specific additional links can decrease the total grid capacity, which can decrease or even destroy synchronization in the entire grid. By the same token, removing certain links may increase stability, just like removing certain roads can counterintuitively decrease vehicle congestion.

The underlying mechanism of the phenomenon for power grids is somewhat different than it is for traffic networks. In traffic networks, Braess's paradox arises due to a suboptimal Nash equilibrium, in which no driver can benefit by changing their strategy while the other drivers keep theirs unchanged. As a result, the individual "selfish" strategy of each driver prevents everyone from reaching their destination sooner.

In the power grid scenario, on the other hand, the paradox originates due to what the researchers call "geometric frustration." Adding a new link creates new cycles, along which all phase differences must add up to multiples of 2π to make all the phases well-defined. When a new link doesn't satisfy this condition, it doesn't synchronize with the other oscillators and the grid loses its phase-locked steady state. Witthaut explained the underlying mechanism using an analogy of a motor and generator:

"Consider an electric motor powered by a generator," he said. "Both rotate with 50 or 60 Hz with a fixed difference between their rotation angles. That means: The angle or phase of the generator will always be slightly larger than that of the motor. Just like two analog clocks, one going slow by a fixed time. This phase difference determines the power flow between the generator and motor and vice versa. The transmission line thus gives rise to a constraint for the phase difference of the generator and motor.

"Now consider a complex network of generators and motors. A stable operation of the power grid corresponds to a synchronous state of the generators and motors: They rotate with exactly the same frequency and fixed phase differences. Building a new transmission line introduces new possible pathways to distribute the electric power, reducing the ohmic losses, which is a desired effect. But at the same time, the new transmission line introduces *a new constraint* for the phases of the generators/motors it connects. In certain situations this constraint is too much – the power grid cannot satisfy all the constraints and becomes unstable.

"A similar phenomenon is known in the physics of magnets, where it is called geometric frustration. Anti-ferromagnetic interactions tend to make all nearby magnetic moments anti-parallel, thus also introducing constraints for the alignment of the magnetic moments. In a 'frustrated' magnet, the geometry is such that all these constraints cannot be satisfied simultaneously – just as in an oscillator network subject to Braess's paradox."

Geometric frustration occurs in most, but not all, complex networks. The researchers found that geometric frustration is more likely to occur in new power lines that are located in regions of a network where many of the existing power lines are already heavily loaded. Overloaded lines are, in general, more likely to lose synchrony and cause a power outage. By closely studying a network's topological features, it should be possible to predict the effects of adding a new link at a certain location, and avoid potentially costly power outages.

The results of this study can be viewed together with the findings of another recent study the researchers collaborated on, which demonstrated that decentralized power generation supports self-organized synchronization. This is because decentralization decreases the risk of heavily loaded lines. The finding is good news for the transition to distributed renewable energy sources, which are decentralized by nature.

"In a second article published in *Physical Review Letters*, we have analyzed how structure affects synchronization in a complex power grid," Timme said. "In particular, we have studied how replacing a few large, centralized power plants with many small distributed sources affects the stability of the grid. We have found three major effects: First, synchronization is easier to realize in a distributed power grid. More precisely, one needs less transmission capacity to ensure a stable synchronous operation. Second, a distributed grid is more vulnerable to dynamic perturbations, i.e., fluctuations of the power consumption. However, third, it is more robust to structural perturbations, in particular the breakdown of single transmission lines."

More information: Dirk Witthaut and Marc Timme. "Braess's paradox in oscillator networks, desynchronization and power outage." *New Journal of Physics* 14 083036 (2012). dx.doi.org/10.1088/1367-2630/14/8/083036

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