A Second Look: For Power Systems, Geography Doesn't Matter, But Electrical Structure Does

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In a national grid, where should a new power generating plant be built? In a competive electricity market, why do wholesale prices for electricity vary between regions? Such innocent questions are often met with rather involved technical and economic answers. How can a more accessible understanding of power grids be articulated, suitable even for a non technical audience? This article discusses one potentially helpful step in this direction: drawing power network diagrams in an electrically meaningful way, rather than using geographic maps that can obscure their inherent structure.

1 Introduction

"Graphical excellence is that which gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space." - Edward Tufte

In basic engineering terms, it is not challenging to write down the equations that govern how electrical power flows through a grid. These equations have been well-understood for decades. However, their seeming simplicity is in some ways illusory, not least because they can only be solved with recourse to iterative techniques. For instance, with modern power system analysis software, one can rapidly calculate the voltage at every bus in even a large grid (a *bus* is a node, or junction, where power lines connect together) Likewise, the amount of power flowing in each line can also be readily calculated. However, these loadflow techniques give *answers* rather than *explanations*. The underlying processes that determine how power flows on a network can remain elusive – how can an engineer make intuitive sense of the numerical solution of a set of a nonlinear equations?

For instance, consider the curious phenomenon of voltage collapse, where an electrical system can appear entirely healthy, yet be but one small demand increase away from a catastrophic black-out. The theory explaining such collapses was only satisfactorily developed in the 1980s, and is technically complex, remaining something of a niche area within power systems engineering. It is thus hard to succinctly explain why, for instance, the lights of Pakistan were simultaneously extinguished by blackout on the 24th of September, 2006. One pair of investigators, Younas and Qureshi, venture that, as result of several outages, the cities of Lahore and Gujranwala could only be served via a "*very long route of power*" How should one interpret this simple-seeming statement? What do power engineers mean, when, trying to explain such worrisome phenomena as these, they insist that "*reactive power doesn't travel*"?

This is not an article about voltage stability. That phenomenon is only mentioned to show that even within a purely technical realm, a proper understanding of how electrical power flows can remain elusive. What happens, then, when we erect complicated electricity markets on such foundations? Again, a simple question such as "*why is wholesale electricity cheaper in Dallas than in Chicago?*" may not be met with a simple answer.

The academic literature on power systems, both technical and economic, will often present results by using geographic single line diagrams. Is this a good choice? Physical distance is not directly relevant to any of the equations that govern power flow, and so it seems a confusing basis for diagrammatically understanding electrical systems. Consider the iconic schematic map of the London Underground network pioneered by Harry Beck. His work used the realization that, for journey planning, the interconnectivity between lines is what should be emphasized, not the precise geographic position of each tube station. The renunciation of strict geography has demystified London's transit system: can the same be done for electric power systems?

This article discusses new ways of diagramming power system data, drawing on new layout methods recently developed by the authors. In the diagrams we will present, two buses will be drawn closely together if electrical power can be transacted between them with ease. This article will also point some of the limitations of the conventional means of overlaying data on system diagrams, such as numerical annotation or with rainbow heatmaps. We want to demonstrate that, together, a more meaningful positioning of nodes, and a more direct display of bus-specific values better reveal patterns in power system data.

To frame this discussion, we will briefly reflect on the historical development of power system visualization. The technical underpinnings of the new diagrams will be briefly described. The heart of this article will compare and contrast a traditional geographic diagram of a well known electrical network (the IEEE 118 bus test system) with the proposed new displays. Various types of power system data will be presented, starting with a fundamental quantity defined at every bus: the *voltage angle*. The voltage angle describes the difference in the *phase* of the AC voltages at different buses. This difference in phase is what causes active power to flow through a transmission network, and serves as a useful at-a-glance indicator of a power system's status. More abstract data like power loss sensitivities and power transfers will also be explored and explained. The discussion will seek to demonstrate that for each type of data, a more intuitive, immediate understanding is given by the new diagrams.

2 Power System Visualizations to Date

The visualization of power systems, and their data, is a topic that has enjoyed only sporadic interest from the research community. Many authors are content with rudimentary system diagrams presented with minimal embellishment. The industry takes its cue here from Tesla himself, who once lamented: *"By an irony of fate, my first employment was as a draughtsman. I hated drawing; it was for me the very worst of annoyances."*

All the same, a flurry of visualization research commenced in the mid-1990s, spearheaded by the visionary Dr. Tom Overbye. The timing was appropriate: owing to the widespread liberalization of the energy sector, various new players were entering the industry. Many of these, such as financial traders or policy makers, did not have extensive technical backgrounds, and so better visualization were seen as a powerful way to ensure "*that the interactions between business decisions and the technical/physical constraints are understood*", as Overbye put it. To this end the traditional single line diagram soon found itself adorned with all that the software of the era could provide: animated flow arrows, coloured contour lines, heatmap overlays, branch loadings pie charts, voltage thermometers and various other baubels.

Now, twenty years or so later, these innovations have brought a little colour to the mainstream: Overbye himself commercialized visualization-rich power system analysis software as early as 1996, and, more recently, industry-standard packages such PSS/E have added visualization capabilities. The control room has also been enlivened: as described by the GreenGrid project, force directed lay out algorithms can be used to give a more insightful picture of the system's status in real time. Crucially, the algorithms used by GreenGrid dispense with the physical geography of the system, instead positioning nodes consistent with their mutual connectivity. This is a strong inspiration for the new diagrams discussed in this article.

In more recent visualization research, some authors have sought to escape the flatland of the conventional diagram, erecting a third dimension above this plane to portray interpolated system data. These innovations impose a meaningful scale on the vertical axis: this article seeks to order and structure power system data by imposing a well-chosen scale on the horizontal axes also.

What power system data might one visualize? The simple outputs of the load flow problem - voltages, currents and power flows - is one obvious starting point. Other quantities are also directly relevant, such as *locational marginal prices*, which identify where in the system it is cheap or expensive to accommodate an increase in power demand. This type of data can be quite intricate, and so it demands clear, lucid display if we are to wring any intuitive meaning from it.

3 A New Approach to System Diagrams

Positioning the buses

A power system, viewed one way, is a generic *complex network*: a set of nodes connected by a number of edges. A substantial literature exists on how the connective structure of such a network can best be diagrammed. In many proposed algorithms, nodes act to repel each other, but are pulled together by the spring-like forces of the edge connections. By iteratively updating this pseudo-physical system a configuration of (locally) minimal potential energy is eventually reached, which, many authors maintain, tends to look attractive, and hopefully reveals the network's innate connectivity. While these algorithms are valuable, and perhaps under-utilized in power systems research, a better algorithm for our purposes would give explicit consideration to the electrical proximities between buses in the network. How might this be achieved?

Consider a distance table, as can sometimes be found at the back of a motorist's atlas. These typically list the larger towns in a country and the crow-flies distance between them, so that journey times can be rapidly assessed (we imagine such a table would be useful for that eternal wanderer, the benighted travelling salesman!) Imagine that such a distance table is the lone artefact we have from some ancient and obscure civilization. How might we reconstruct a map of their lands, knowing only these distances? This statistical problem is best approached using *multidimensional scaling*. These iterative techniques find a configuration of points whose final inter-point distances are maximally in agreement with the desired distances known a priori.

Recent work by the authors has used multidimensional scaling to project the *electrical distances* between buses into two dimensions. Fortunately, it turns out that this can generally be achieved with minimal distortion. However, there are various ways that electrical distance could be defined for a power system, each with certain merits. The effective impedance between two buses is one obvious choice. Another option, used in this article, is to assess how much of the power system's assets are used to facilitate a power transaction between two buses. So, for a 1 MW injection at one bus, and withdrawal elsewhere, we sum up all incremental transaction flows on all branches, to gauge how much of the power system is involved when exchanging power between these buses. This electrical distance measure, whose units are *MW/MW*, has been found to produce attractive, meaningful power system diagrams, and so it will be the basis for the new diagrams we present here.

Showing the data

Those authors who overlay data on their system diagrams often choose a rainbow colormap to do so. Such a choice of colormapping is at odds with the modern best-practice in data visualization: as argued in the influential paper *"Rainbow Color Map (still) Considered Harmful"* it "*confuses viewers through its lack of perceptual ordering, obscures data through its uncontrolled luminance variation, and actively misleads interpretation through the introduction of non data dependent gradients.*" In short: sudden changes in hue confuse the eye, and make it appear that the data has defined features that do not actually exist. To avoid these problems, in this work we use perceptually-balanced single-hued colormaps, courtesy of Cynthia Brewer's marvellous ColorBrewer website.

How do we show the variation of our (tastefully-tinted) data across the extent of the power system? Some previous works have used interpolation techniques to convert data values defined at buses into a continuous heatmap overlay. We avoid this approach for two reasons:

1. The interpolation process can create artefacts, and so it may not be clear if an interesting feature in a system diagram is merely the result of the interpolation algorithm, or a genuine feature of the data

2. Data such as voltage is only meaningfully defined for each bus, so smoothly interpolating it between buses is potentially misleading

To overcome these problems, this work proposes a novel application of Voronoi tesselation. Under this tiling scheme, each bus has a catchement region associated with it, within which all points will be closer to the associated bus than to any other. By colouring these regions with the data of interest, a continuous patchwork can be created, which clearly shows the patterns in the bus data without adding artefacts or interpolation.

One problem with a direct Voronoi tesselations is that some buses will have large, or infinitely, sized regions associated with them. To mitigate this in a novel way, in this work the *"data presentation region"* assigned to each bus is calculated as the union of each bus' Voronoi cell and a circle of defined radius.

4 Voltage angles and loss sensitivities

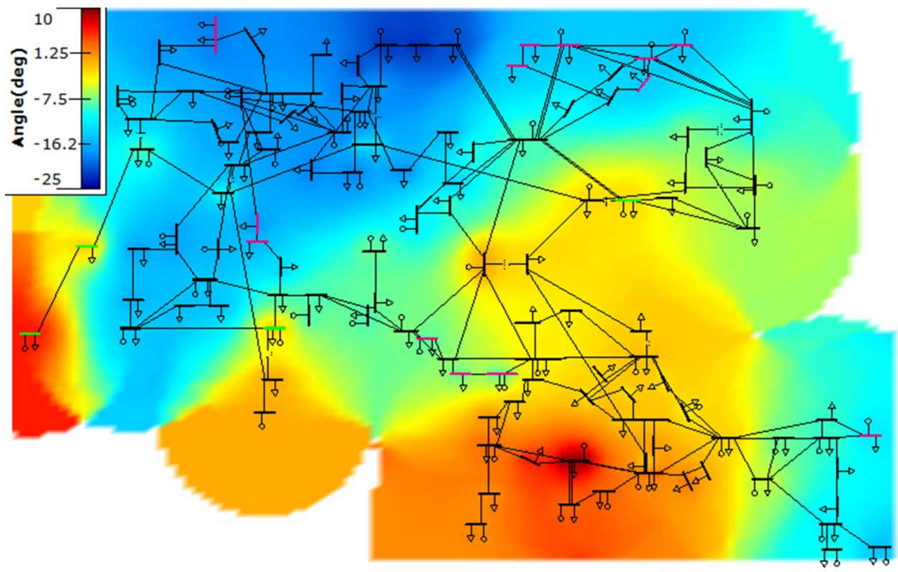

Figure 1: PSS/E en fête: a conventional single line diagram of the 118 bus system, here sporting the gaudy raiment of a spectral colourmap

Transmission networks exist to move electrical power from point to point, and it is the difference in voltage angle between buses that drives this transmission. The diagram of figure 1 shows how a voltage angle profile may be visualized in PSS/E, using the conventional diagram for the 118 bus system. We feel this diagram can be improved. First of all, it's very hard to discern the different nominal voltage levels in the system. There is a lot of visual clutter, with many load symbols vying for attention. The spectral mapping makes it appear as though definite step changes in voltage angle exist between system areas, whereas careful inspection shows these gradients to be fairly linear. The same node positions and data are visualized in figure 2: the improved colour map and lack of interpolation make the voltage angle profile easier to discern. Generator nodes are marked in blue, and the thicker edges denote the higher voltage branches in the system, which operate at 345 kV.

Figure 3 shows the disposition of voltage angle across the system using the new bus positions. One key difference between figure 3 and figure 2 is that in the new layout, the 345 kV buses naturally form a central spine in the system, whereas in the geographic layout they are widely dispersed. In figure 3, the 138 kV buses are neatly arranged in a peripheral relationship to the 345 kV system, whereas in figure 2 these distinct voltage levels appear somewhat entangled. Considering the disposition of voltage angles, the new layout clearly shows that there is a centre of power generation at lower right, with power flowing out from here via the 345 kV system and on out to the more peripheral 138 kV buses. The same disposition of power flows is also shown relatively clearly in the geographical layout of figure 2, though the 345 kV systems's electrical cohesiveness with this generator center is not made as clear.

For such reasons, the geographic layout makes it harder to note the consistently high voltage angles within the 345 kV system. In the geographic layout, the high voltage angles in the 345 kV buses appear as isolated pockets, particularly to the left of the diagram, with many 138 kV buses here interrupting the diagram's continuity. The new layout does not completely avoid these problems, but it does improve the contiguous display of the voltage angle profile in the 345 kV sub-system.

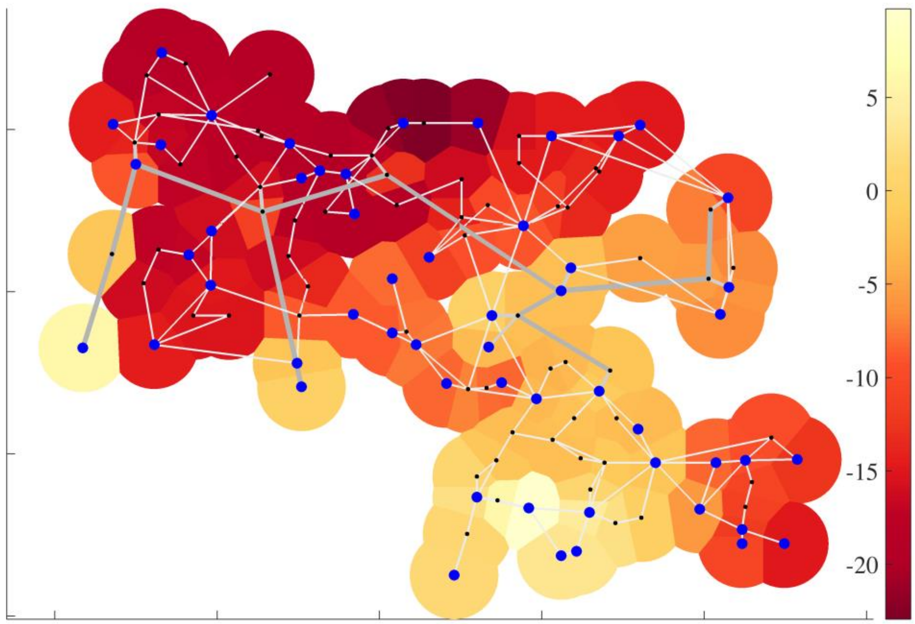

Figure 2: Voltages angles in the 118 bus system, shown here using the geographic node positions

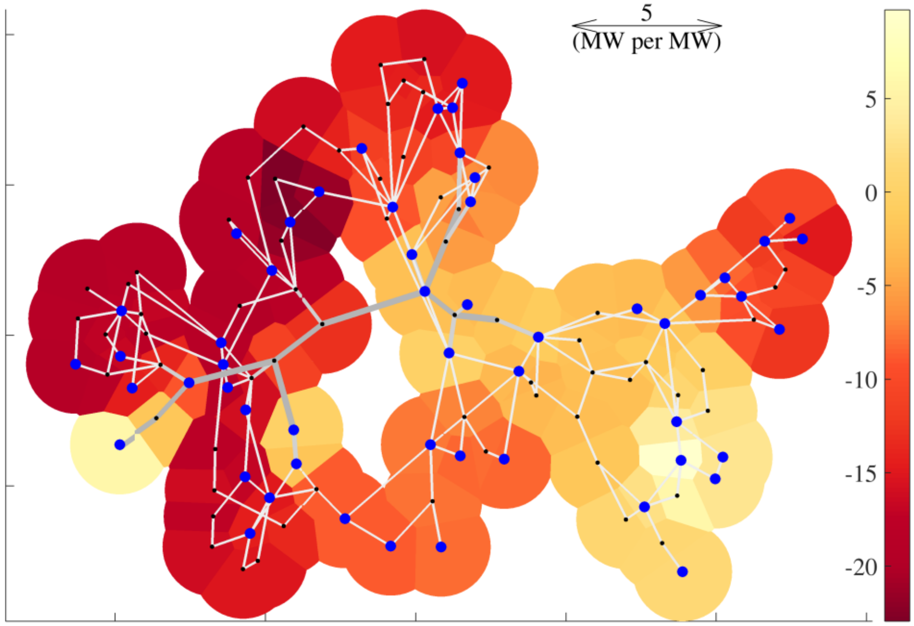

Figure 3: Voltages angles in the 118 bus system, shown here using the new node positions

The idea of a bus' electrical centrality, as made concrete in the new diagrams, may be helpful to explain why some loads in a system cause more losses than others. To explore this, we add a 1 MW load to each bus in turn, and record the resulting increment in active power losses. These *loss sensitivities* are depicted in figure 4. It can be seen that the loads which cause the most incremental losses, depicted in light blue, are those that are remotest from the 345 kV system and the generational center at bottom right. An incremental load at these remote buses must be served via a long route of power, and this explains why they cause higher incremental losses. Similar effects, coupled with branch congestion considerations, may help explain why locational marginal prices differ throughout a power system.

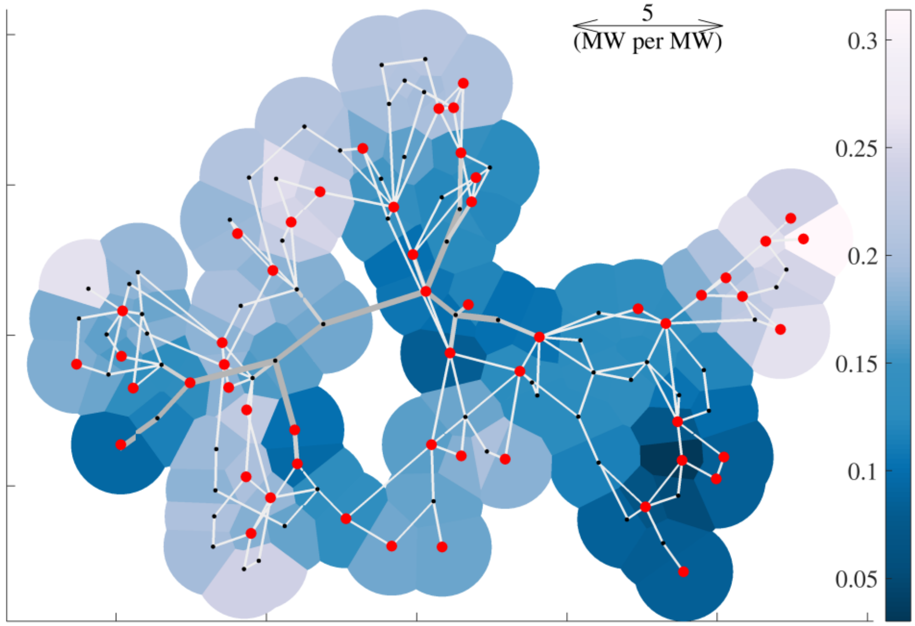

Figure 4: Power loss sensitivities across the power system, shown here using the new node positions

5 Making straight the path: visualizing power transfer distribution factors

How does active power propogate through a network, from generator to demand customer? Power transfer distribution factors offer one way of exploring this fundamental question, as they show the incremental flows that arise for a power injection at one bus and corresponding withdrawal at another. This way of describing *wheeling* flows is used in some systems to determine if a proposed trading of power is permitted, or if it will cause undue *congestion* of transmission assets.

For instance, the approximate incremental flows that would attend a power transfer from bus 53 to bus 87 in the 118 bus system are shown in figures 5 and 6, using the new and geographic node locations, respectively. Branches which participate in the transaction are depicted in maroon, with edge thickness denoting the portion of the power carried.

Figure 5: The incremental flows attending a power transfer from bus 87 to 53, shown on the new power system layout

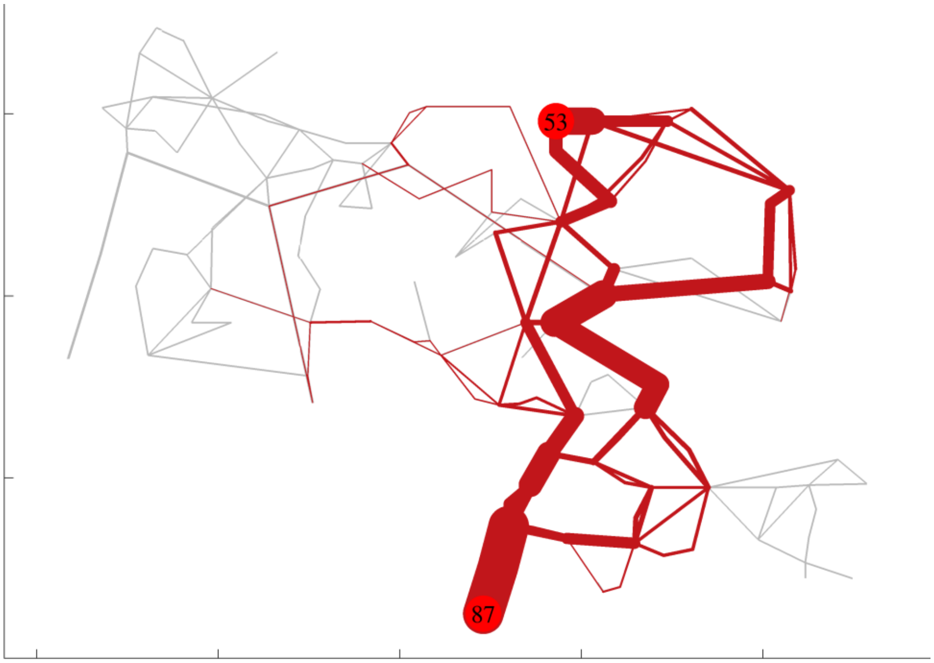

Figure 6: The same incremental flows attending a power transfer from bus 87 to 53, here shown using the conventional system layout

As figure 5 is arranged in an electrically meaningful way, the power transaction is depicted in an orderly, simple fashion. Only branches that are on the straight path between bus 53 and 87 are involved in the transaction, with the branches in the shortest path carrying the bulk of the power. All of this accords with intuition. If, for instance, one of these branches were congested, it is easy to see why transacting power between buses on either side of it may legitimately be prohibited.

Compare this orderly depiction with the haphazard figure 6. Here, the same transaction seems to follow a winding path through the system. Observe bus 53: the bulk of power leaving this node is oriented in a completely different direction to its destination, bus 87. From this odd beginning the power is depicted as meandering through the system in a counterinutive way. Essentially, the bus positionings in figure 6 place many branches between buses 53 and 87 which are not actually between those buses in an electrical sense. Many of the lines which important in facilitating this transaction are positioned to appear tangential to it. The geographic bus positions make it needlessly difficult to spot which branch congestions might preclude a certain transaction.

6 Closing Thoughts

We are lucky that transmission networks have an electrical structure than projects well into two dimensions. This gives us many new ways of understanding electrical grids and all their attendant data. It also offers new ways of explaining power systems to a lay audience: whether to discuss energy prices, blackout risks, congestion bottlenecks, or to justify building a new line. Power engineering needn't be a dark art, and better diagrams are a good place to start the demystifying process!

7 Further Reading

Paul Cuffe and Andrew Keane. Visualizing the Electrical Structure of Power Systems. *IEEE Systems Journal*, pages 1–12, 2015.

Pak Chung Wong, K. Schneider, P. Mackey, H. Foote, G. Chin, R. Guttromson, and J. Thomas. A Novel Visualization Technique for Electric Power Grid Analytics. *IEEE Transactions on Visualization and Computer Graphics*, 15(3):410–423, may 2009.

David Borland and Russell Taylor Ii. Rainbow Color Map (Still) Considered Harmful. *IEEE Computer Graphics and Applications*, 27(2):14–17, mar 2007.

Federico Milano. Three-dimensional visualization and animation for power systems analysis. *Electric Power Systems Research*, 79(12):1638–1647, dec 2009.

T.J. Overbye and J.D. Weber. Visualizing the Electric Grid. *IEEE Spectr.*, 38(2):52–58, 2001.

Edward R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, CT, USA, 1986.

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