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Novel Quality Metrics for Power System Diagrams

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Abstract—Power network diagrams are typically neither enlightening nor attractive to look at. Encouragingly, though, the visualization of generic complex networks has been an active area of research for the past two decades, and there now exist a number of widely-deployed algorithms that show a network’s structure in a revealing and aesthetic way. Additionally, recent work by the present authors has proposed techniques for diagramming power systems that explicitly use meaningful electrical distance metrics. Which is the most effective approach to diagramming? To begin to answer this question, this paper proposes new quality metrics for power system diagrams which seek to quantify how legibly a network layout reveals how power flows through it.

Index Terms—Complex networks, graph layout, aesthetic criteria

I. INTRODUCTION

A mature literature exists on drawing complex networks to best reveal their structure [1], [2]. However, to date there has only been sporadic application of automated techniques to power network diagramming [3]–[6], though the large-scale project described in [7], which used force-directed layouts [8], presented encouraging results. Recent work by the present authors [9] has shown that attractive power system diagrams can be drawn using multi-dimensional scaling [10] and inter-bus electrical distances. With these options available, how should one choose between the various algorithmic approaches to diagramming a power system?

The present paper proposes new quality metrics which gauge how legibly a diagram depicts power flows in an electrical network. Existing quality metrics for graph layouts [11], [12] assess the prevalence of undesirable and unsightly features in a graph drawing, such as edge-crossing, edge bends or departures from orthogonality. The presently-proposed metrics focus on the orderly depiction of power transfers and power flows across an electrical network.

These new metrics are trialled on various test networks for a number of layout approaches. Sample diagrams are provided to illustrate the differences between the various methods. The new metrics identify those network layout methods which best organize and regularize power flows, allowing usable intuitions to be formed for students, researchers, and operators alike.

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II. PROPOSED METRICS

There can be no definitive measure of the quality of a network layout, and there is little prior research on how power systems should be diagrammed. To address this lacuna and to stimulate research, the authors here propose three quality metrics that may be helpful, somewhat subjective as they may be:

A. Straightness of power transfer

A comparison of two alternative diagrams for a small test power system, as in Figs. 1 and 2, illustrates the motivation for this metric, where both figures depict the same physical transfer of power. In Fig. 1 the power transaction is depicted in a way that seems to meander, which makes it cumbersome to assess which transmission assets may be needed to facilitate it. By contrast, in Fig. 2, the branches facilitating the transactions are diagrammed in better alignment with the notional *direct path* between the sending and receiving bus, as shown by the dashed blue line. The quality of depiction of such a transaction between buses i and j is assessed as:

$$Q_{ij} = \sum_{l \in L} \alpha_l \phi_l \quad (1)$$

Where α_l is the angle between each branch l ’s power flow vector and the principal transaction axis, and ϕ_l is the fraction of the total transaction in each branch. Note that $0^\circ \leq Q_{ij} \leq 180^\circ$ and smaller values are preferable. The overall quality of the graph layout is calculated as the arithmetic mean of transaction qualities, Q_{ij} , for all buses pairs i and j .

B. Angular resolution of power flow

Angular resolution is a generic measure of graph layout quality, defined as the minimum angle subtended between all edges incident at a particular node [13]. Excessively small angles are believed by some to result in a cluttered and hard-to-read diagram, though this assumption hasn’t been fully vindicated in usability studies [14]. In the context of power systems, the idea of angular resolution is here adapted to gauge how easy it is to trace a flow of power from bus to bus. Does the power incoming at a certain node flow out as though following the same course, or does it veer and meander?

For power system purposes, we adapt this metric to focus on pass-through nodes: for pure sources, or pure sinks of power, it is undefined. Accordingly, this metric gauges the coherency, or

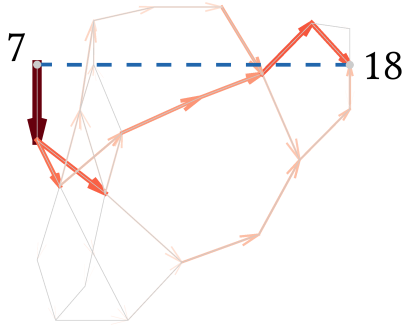


Fig. 1. A power transfer from bus 7 to 18 on the *netta_case24_ieee_rts* system, drawn using the Fruchterman & Reingold technique

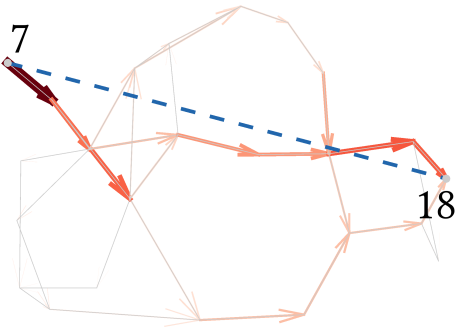


Fig. 2. The same transaction as in Fig. 1, with buses positioned to depict power transfer distances

traceability, of the power's path between generator and load. For each pass-through bus, the metric records the smallest angle, α , between any inflowing and outflowing branch, as depicted in Fig. 3. For the entire graph layout, the average over all the pass-through buses is taken.

Note that this metric is not invariant on the graph layout, and will change as power flows and generator dispatches change.

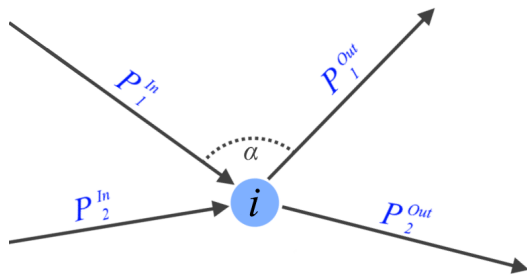


Fig. 3. The smallest angle, α , between inflowing and outflowing branches at each bus, i , is the basis for calculating the graph's directed angular resolution

C. Edge crossings

This is a classic measure of graph quality: how often do edges cross over each other? Some usability studies have found this to be among the most important determinants of diagram quality [14], [15]. This classic measure is included

to indicate if the newly-proposed criteria align with more traditional metrics of layout quality.

III. TEST CONDITIONS

A. Test systems

Twelve medium-sized test systems from the NESTA archive [16] were selected to trial these metrics. These systems range from 14 to 300 buses, and span a range of voltage levels.

B. Layout techniques

Six different approaches to laying out a power system diagram were compared:

- Fruchterman & Reingold [17]

This algorithm is a popular variant on the *force-directed* placement approach. Such approaches iteratively configure a graph drawing by imposing repulsive forces between nodes, counteracted by spring-like forces from connecting edges. The authors of [17] refine this generic framework somewhat, by also including some additional attractive forces between neighbouring nodes.

- Geodesic multidimensional scaling [9]

Multidimensional scaling positions points in N dimensional space to be in maximal agreement with the defined distances between the points. Here, the inter-node distance are taken to be *graph geodesics*, the number of edges traversed along the shortest path between all bus pairs.

- Gürsoy & Atun [18]

This algorithm uses self-organising maps [19], which are another approach to dimensionality reduction, to distribute the nodes of a network within a pre-defined topology, here taken to be a square form.

- Kamada & Kawai [20]

This approach augments the force-directed placement method with graph geodesics, to locate neighbouring nodes together in a balanced way.

- Power transfer multidimensional scaling [9]

This approach is tailored to power system applications. The inter-bus distances are calculated by summing the absolute flows in all branches when injecting 1 MW at each bus and withdrawing it at every other. This gauges how much of a power system's assets are used to facilitate a transaction between buses.

- Thévenin multidimensional scaling [9]

Here, the *effective impedances* between bus pairs are taken as the measure of electrical distance. These impedances can be calculated using the Z_{bus} matrix and the Klein resistance distance formula given in [21].

For exposition, Fig. 4 shows each technique applied to the *netta_case39_epri* system. Note the visual similarity of panes (b) and (e): in [9] the underlying distance measures were shown to be closely correlated. Furthermore, the Kamada & Kawai layout in pane (d) is quite similar, albeit rotated, because it uses the same graph geodesics, but positions nodes differently.

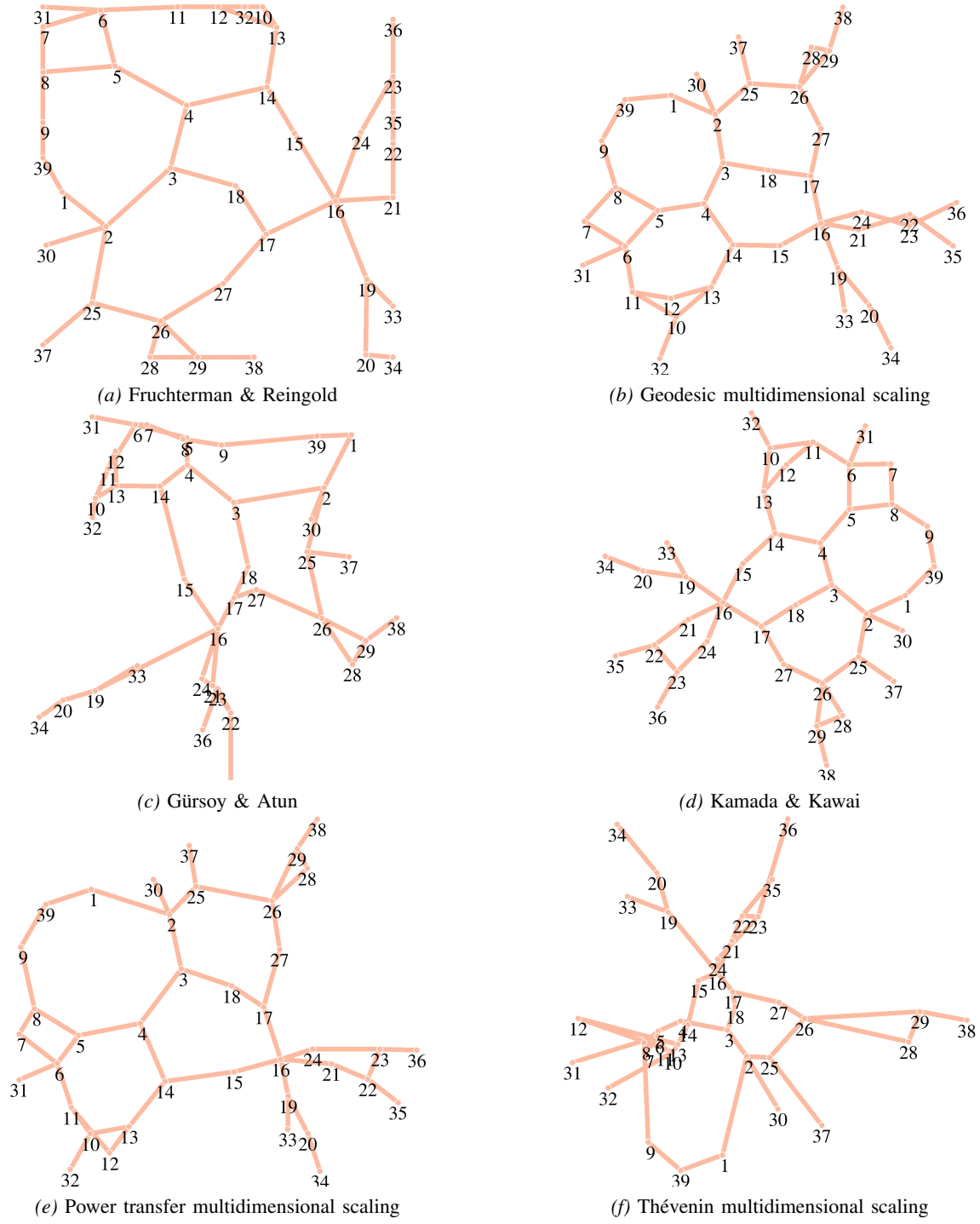


Fig. 4. An example of the six distinct diagramming approaches on the *nest_a_case39_epri* system

TABLE I
POWER TRANSFER DEPICTION QUALITY

System Name	Power transf. MDS	Geodesic MDS	Kamada & Kawai	Thév. MDS	Frucht. & Reingold	Gürsoy & Atun
<i>nesta_case14_ieee</i>	47.60	47.31	48.05	49.47	48.92	52.39
<i>nesta_case24_ieee_rts</i>	50.85	50.61	50.23	56.69	51.38	55.53
<i>nesta_case29_edin</i>	48.89	46.75	46.89	53.22	53.29	56.42
<i>nesta_case30_ieee</i>	53.80	53.13	52.87	58.82	54.83	62.28
<i>nesta_case39_epri</i>	45.60	46.77	46.44	51.02	49.09	53.33
<i>nesta_case57_ieee</i>	55.36	56.66	56.33	59.99	59.26	59.31
<i>nesta_case73_ieee_rts</i>	53.48	53.55	56.53	54.58	64.80	61.09
<i>nesta_case89_pegase</i>	55.76	59.98	60.47	59.23	63.45	63.02
<i>nesta_case118_ieee</i>	54.36	57.01	58.63	61.07	62.40	64.34
<i>nesta_case162_ieee_dtc</i>	59.85	62.83	63.84	64.46	67.60	67.65
<i>nesta_case189_edin</i>	47.09	46.84	51.95	54.76	65.32	66.31
<i>nesta_case300_ieee</i>	52.54	54.27	65.97	68.06	67.65	64.84

TABLE II
POWER DIRECTED ANGULAR RESOLUTION

System Name	Power transf. MDS	Geodesic MDS	Kamada & Kawai	Frucht. & Reingold	Gürsoy & Atun	Thév. MDS
<i>nesta_case14_ieee</i>	84.38	80.50	64.56	79.05	64.23	74.64
<i>nesta_case24_ieee_rts</i>	96.60	101.46	99.90	98.55	93.21	91.75
<i>nesta_case29_edin</i>	68.10	72.05	74.47	94.66	66.00	68.83
<i>nesta_case30_ieee</i>	93.32	78.46	84.28	75.18	81.34	75.87
<i>nesta_case39_epri</i>	102.54	94.88	102.09	84.29	107.56	93.30
<i>nesta_case57_ieee</i>	102.76	110.55	107.59	103.33	106.17	98.90
<i>nesta_case73_ieee_rts</i>	99.96	94.99	89.35	95.47	91.30	94.92
<i>nesta_case89_pegase</i>	68.19	71.97	67.57	63.23	70.15	66.71
<i>nesta_case118_ieee</i>	98.37	86.74	77.83	92.49	78.80	70.71
<i>nesta_case162_ieee_dtc</i>	80.57	71.87	72.29	72.98	70.92	68.00
<i>nesta_case189_edin</i>	112.11	116.10	91.65	107.76	95.83	90.68
<i>nesta_case300_ieee</i>	89.25	84.35	48.78	85.33	78.33	69.89

TABLE III
TOTAL EDGE CROSSINGS

System Name	Geodesic MDS	Kamada & Kawai	Power transf. MDS	Frucht. & Reingold	Gürsoy & Atun	Thév. MDS
<i>nesta_case14_ieee</i>	1	1	2	2	1	1
<i>nesta_case24_ieee_rts</i>	6	6	8	4	7	14
<i>nesta_case29_edin</i>	1	2	3	2	21	11
<i>nesta_case30_ieee</i>	5	4	4	3	21	11
<i>nesta_case39_epri</i>	2	0	1	0	5	12
<i>nesta_case57_ieee</i>	22	19	25	19	42	26
<i>nesta_case73_ieee_rts</i>	26	40	24	53	30	37
<i>nesta_case89_pegase</i>	392	377	642	547	442	793
<i>nesta_case118_ieee</i>	65	120	39	85	112	132
<i>nesta_case162_ieee_dtc</i>	216	304	288	328	322	346
<i>nesta_case189_edin</i>	24	75	17	172	50	113
<i>nesta_case300_ieee</i>	102	594	124	347	195	1028

IV. RESULTS

A. Comparison of techniques

The quality metrics for each system and each layout technique are given in Tables I to III. Each of these tables are sorted ordinally to give the best-performing techniques on the left. Cells are also coloured in an ordinal sense: the best performing technique for each network is denoted with the richest green, the worst with dark red.

Table I shows how each layout technique performs at depicting power transfers. Notably, this table is consistent, with the power transfer and geodesic multidimensional techniques prevailing on nearly all test systems. The related Kamada & Kawai approach is in third place here, with the remaining techniques consistently under-performing.

These rankings are broadly maintained for power directed angular resolution, as shown in Table II. Again, the related power transfer and geodesic approaches fare best, following by Kamada & Kawai and the remaining techniques. Notably Table II is not as consistent as Table I; for instance, the generally poor Gürsoy & Atun technique is the best-performing for the *nesta_case39_epri* system, and the best-ranked power transfer approach fares poorly on the *nesta_case29_edin* and *nesta_case57_ieee* systems.

The edge crossings counts in Table III align with the foregoing results, in that the separation into a best three and a worst three techniques is maintained. The numerical results here are striking: on the *nesta_case300_ieee* system, the worst technique, Thévenin multidimensional scaling, results in just over ten times as many edge crossings as the best technique.

B. Traditional diagrams

Traditional power system diagrams are drawn in a pseudo-geographic way. How might this compare with the automated techniques discussed above? To briefly assess this, two systems are selected from the test set for which a canonical diagram is available: *nesta_case24_ieee_rts* and *nesta_case118_ieee*. The diagram for the former is taken from the geographic positions given in [22], the latter from the diagram broadly circulated online [23]. The diagram for the *nesta_case24_ieee_rts* system does not impress, ranking 7th best in power transfer depiction quality, 5th best in power directed angular resolution, and joint 5th in edge crossings. The diagram for the *nesta_case118_ieee* system fares better, ranking 4th, 2nd and 2nd, respectively, in the above criteria.

V. CONCLUSIONS

The results show clearly that multidimensional scaling, using power transfer distances or graph geodesics, is a good basis for producing legible power system diagrams. However, using Thévenin effective impedances as an electrical distance measure gives consistently poor diagrams. This is unfortunate, as these impedances have a direct relationship with a power's system admittance matrix, and are a fundamental, meaningful descriptor of network structure. Of the force-directed layout approaches, Kamada & Kawai consistently outperformed Fruchterman & Reingold. Finally, with the settings trialled

here, the Gürsoy & Atun technique does not recommend itself for the automatic production of power system diagrams.

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