

The Regional Power Grid Team

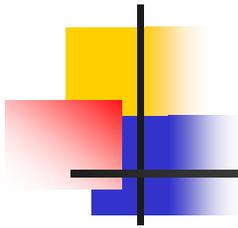
Presentation # 3: Network Results

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Katherine Steel

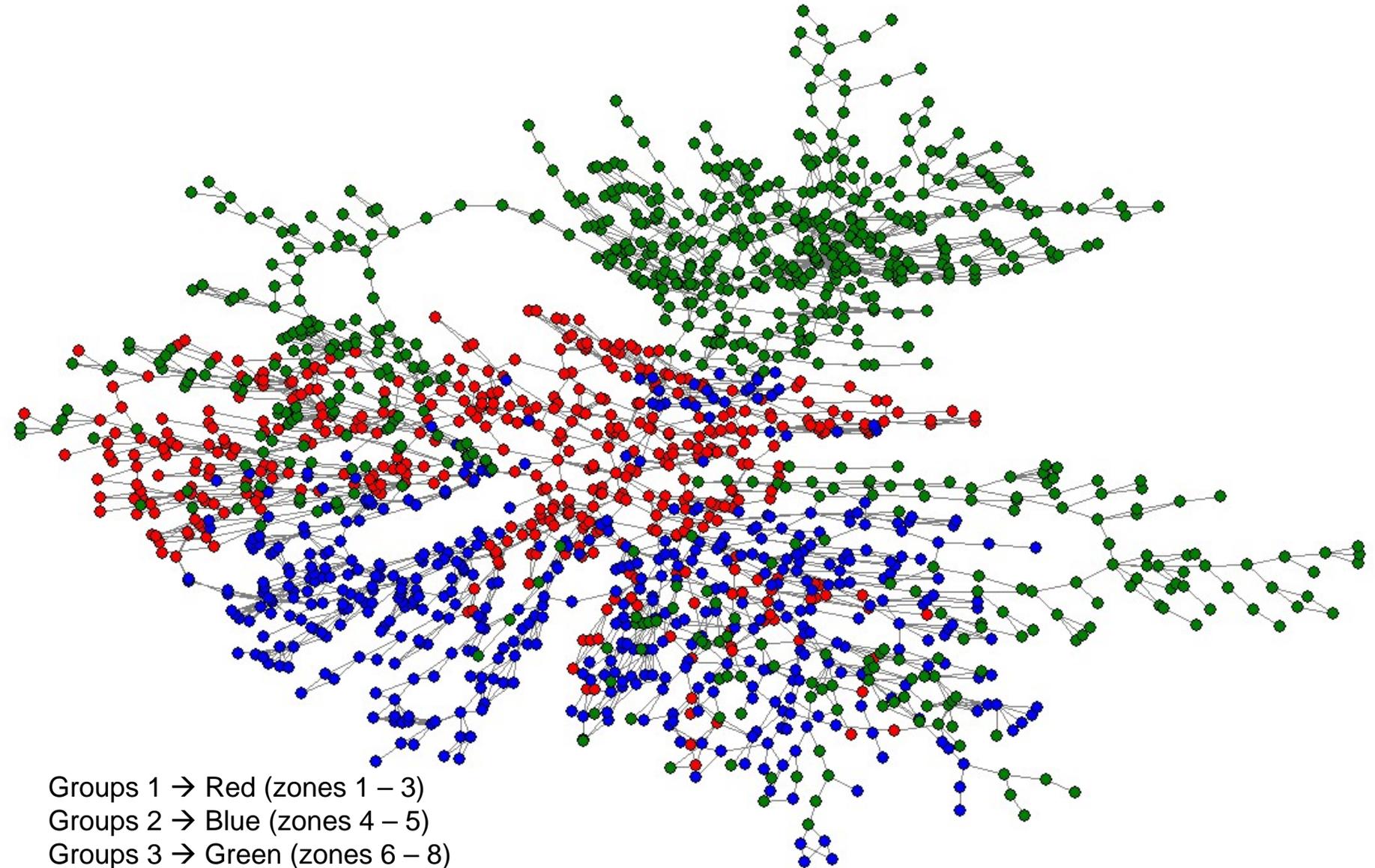
May 09, 2006



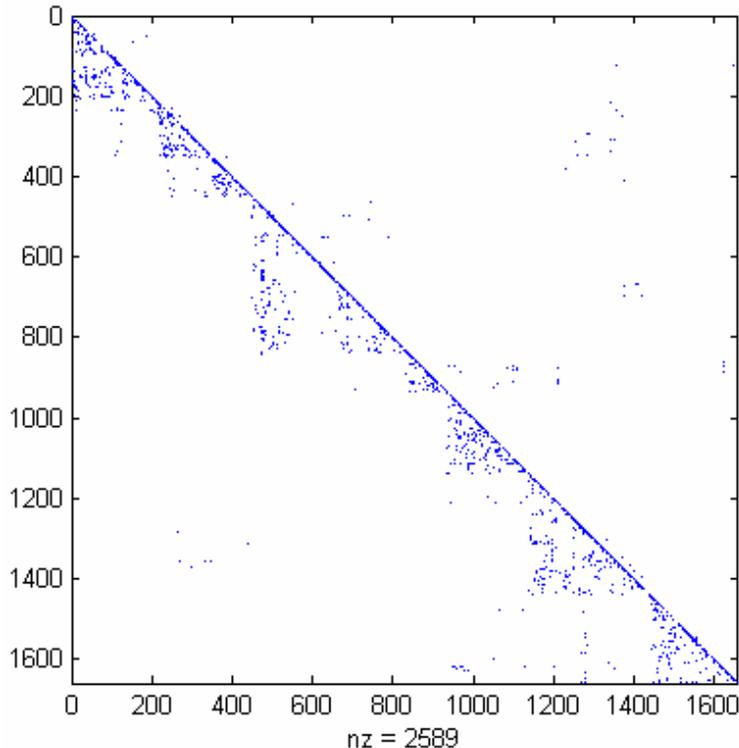
Power Grid Agenda Items

- Building Network Matrix and Images
- Network Level Results
- Zone Level Results
- Comparisons and Insights
- Comments, Questions and Answers

Building Adjacency Matrix: 8 zones to 3 groups

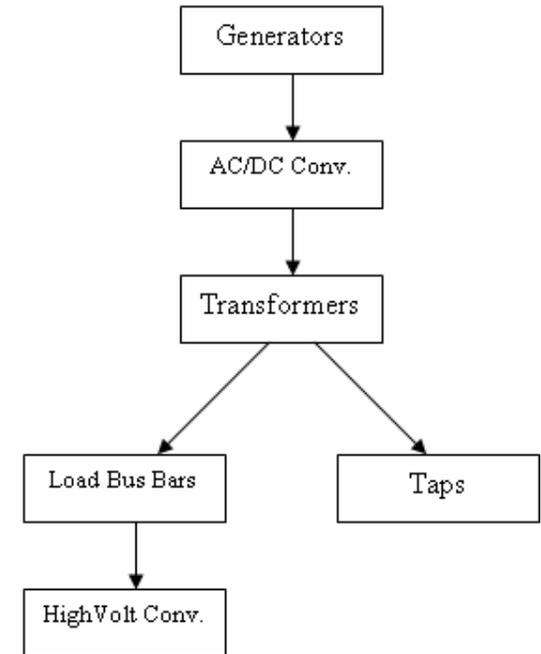


Adjacency Matrix for Grid



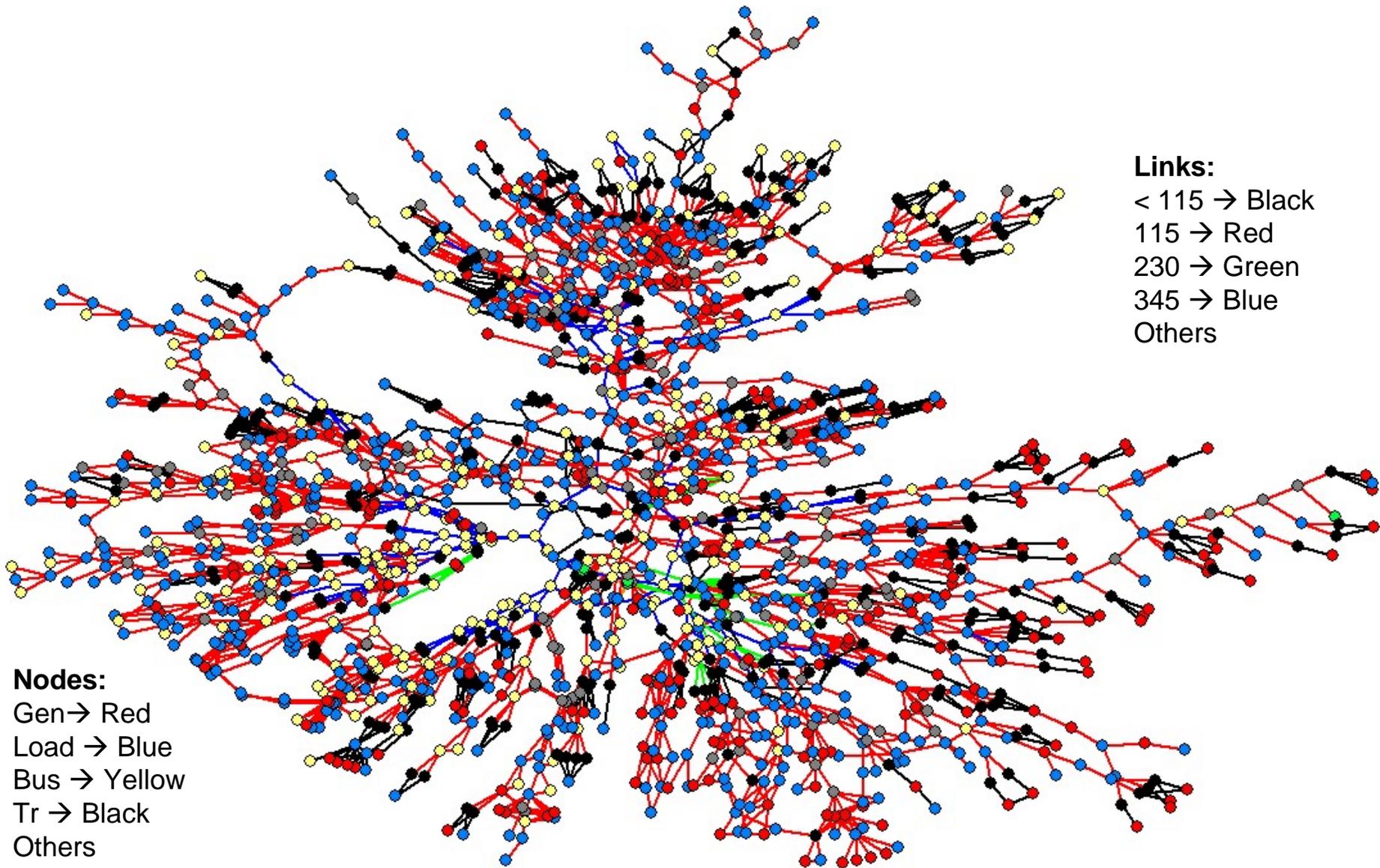
Hierarchy is evident from the structure of this adjacency matrix

Tools Used:
UCINET, Pajek,
Matlab, MSEXcel

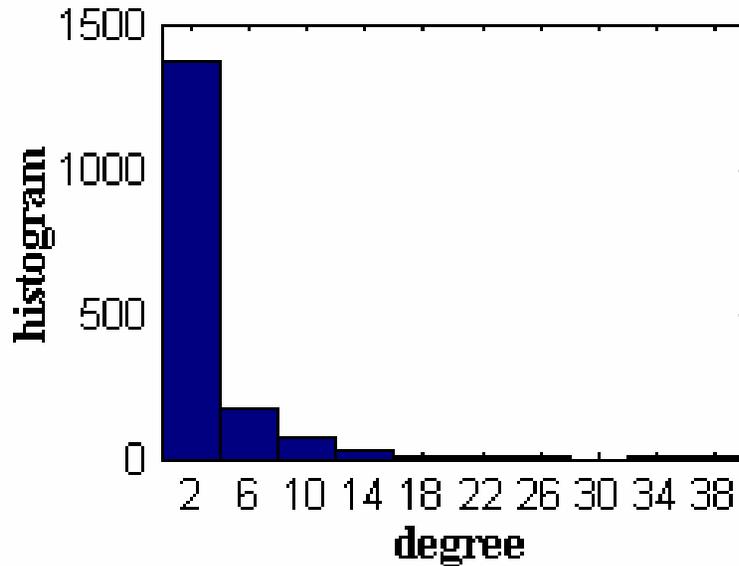


- More than 1600 nodes and more than 2500 links
- Each block (below diagonal) pertains to a zone in this power pool
- Off-diagonal entries (far off) show inter-zonal and high voltage links

Overall Power Grid



Degree Distribution Histogram

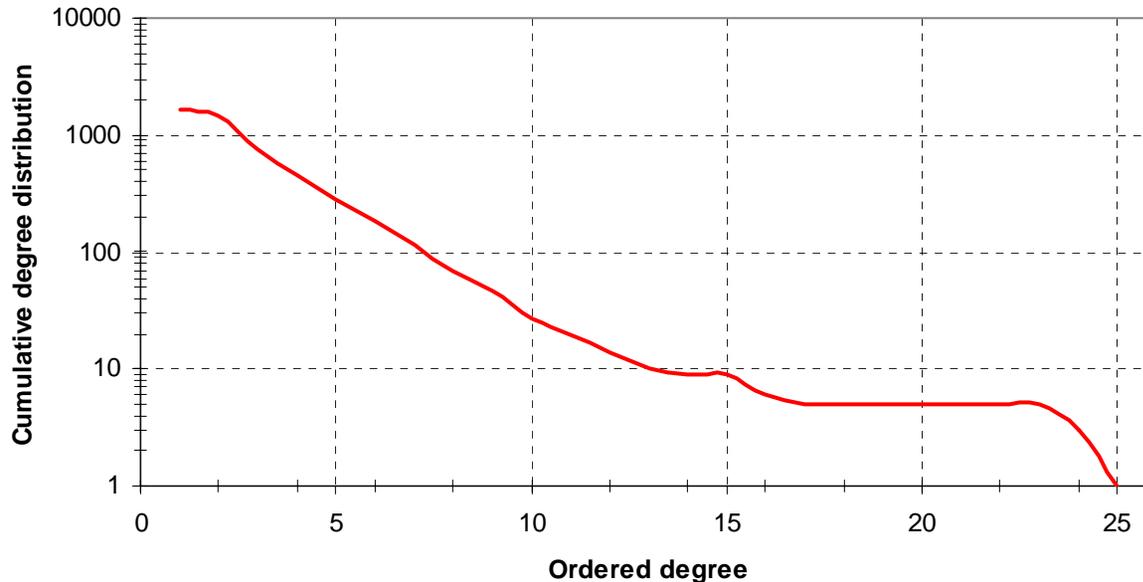


	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Overall	1658	2589	1.562	3.117	25	14.35	6.521	No	0.149	0.002	0.10

- Most nodes (more than 90%) only have two other connections
- Very few (only 27) nodes have a degree above 10
- Most nodes are localized, with few central ones (critical to network)

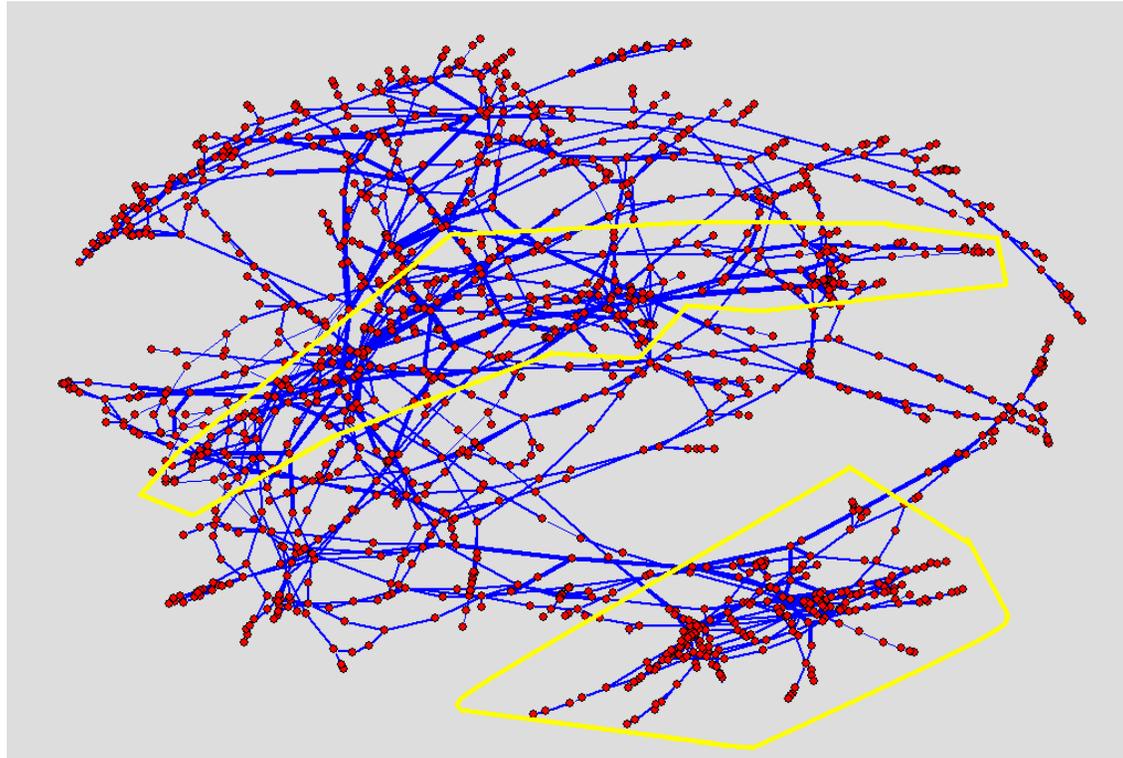
Degree Distribution on log-lin

Cumulative degree distribution - Overall Grid



- Exponential degree distribution (looking at whole curve)
- Distribution depends on the scale chosen for degrees
- Small world effect - high clustering coefficient and similar path length as compared to a random network

Homogenized Network Image

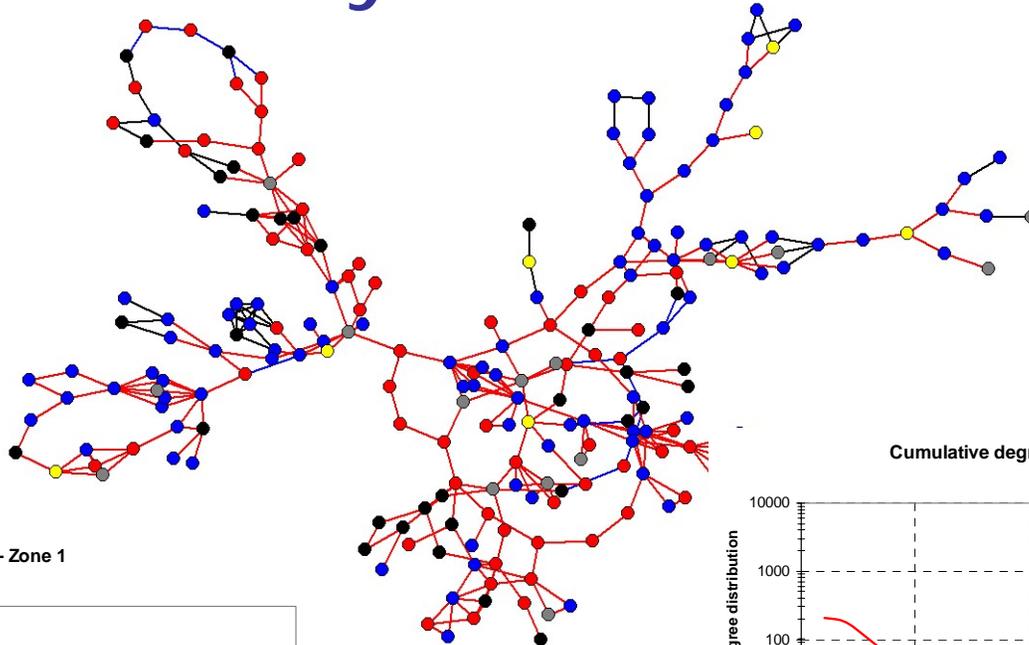


- Two congested zones in the grid (in yellow) namely zone 4 and zone 8
- 345 kV lines are “backbone” for grid level, 115 kV lines for zonal level
- Less congested zones have smaller lines and sparsely distributed nodes

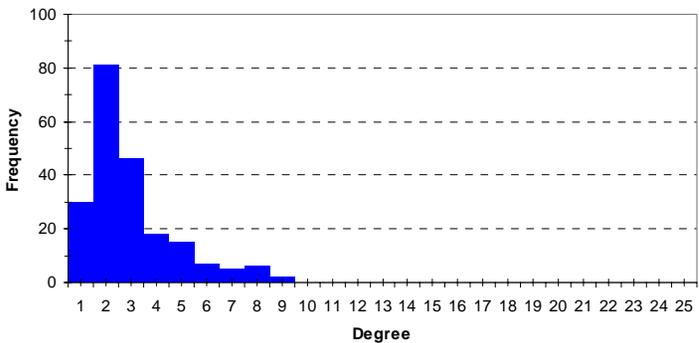
Zonal Analysis – Zone 1

Nodes:
 Gen → Red
 Load → Blue
 Bus → Yellow
 Tr → Black
 Others

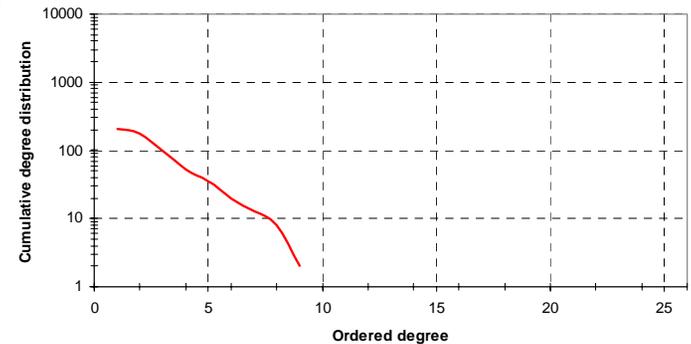
Links:
 < 115 → Black
 115 → Red
 230 → Green
 345 → Blue
 Others



Degree distribution - Zone 1



Cumulative degree distribution - Zone 1

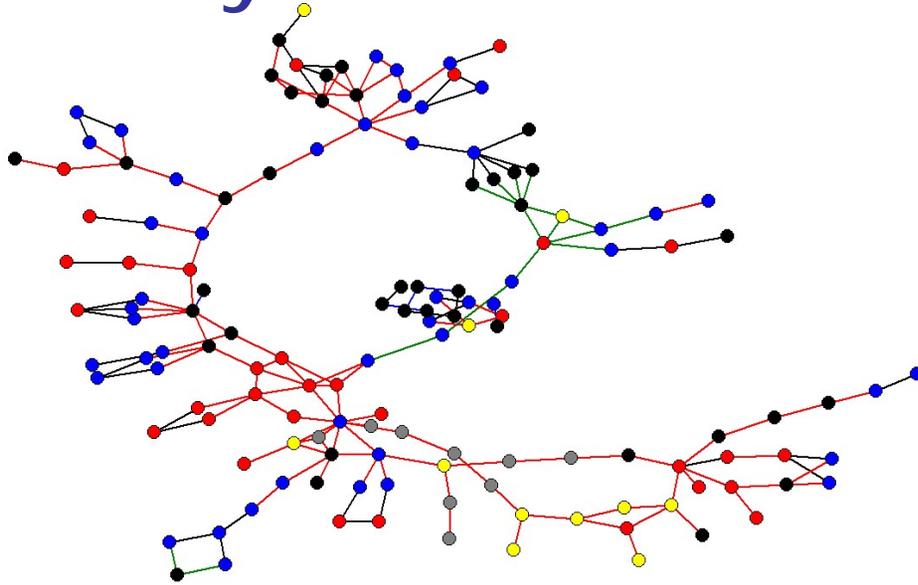


	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 1	210	314	1.495	2.952	9	9.514	4.939	No	0.155	0.014	-.094

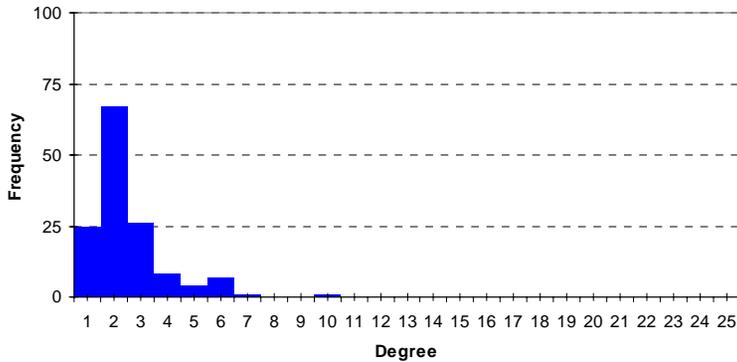
Zonal Analysis – Zone 2

Nodes:
 Gen → Red
 Load → Blue
 Bus → Yellow
 Tr → Black
 Others

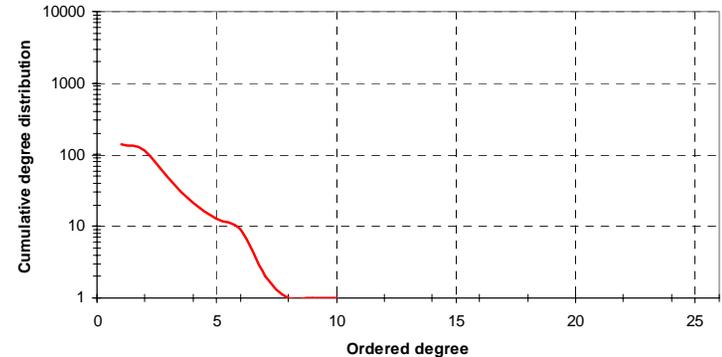
Links:
 < 115 → Black
 115 → Red
 230 → Green
 345 → Blue
 Others



Degree distribution - Zone 2



Cumulative degree distribution - Zone 2

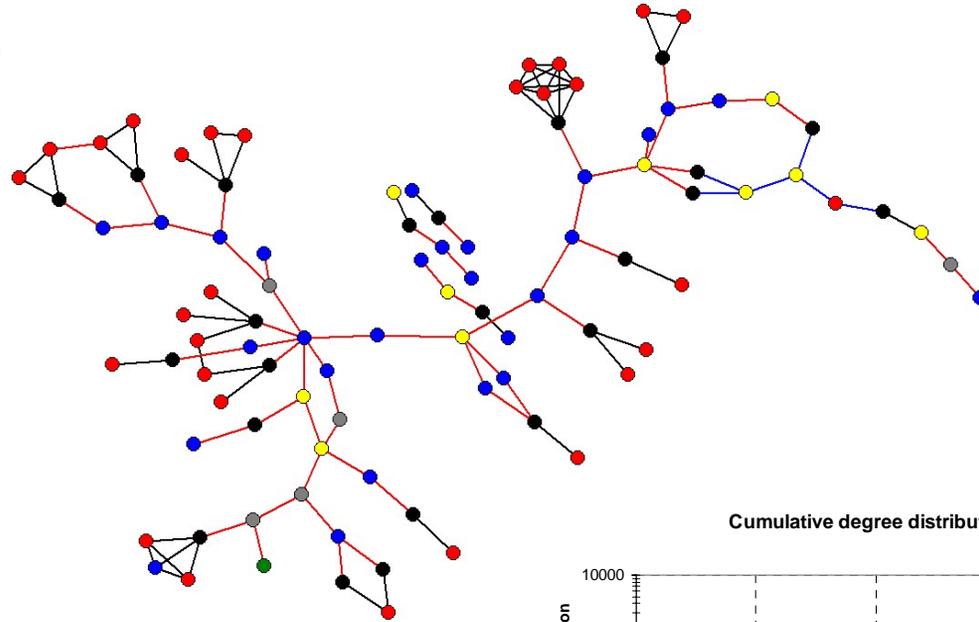


	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 2	139	175	1.259	2.504	10	9.174	5.376	No	0.073	0.018	.001

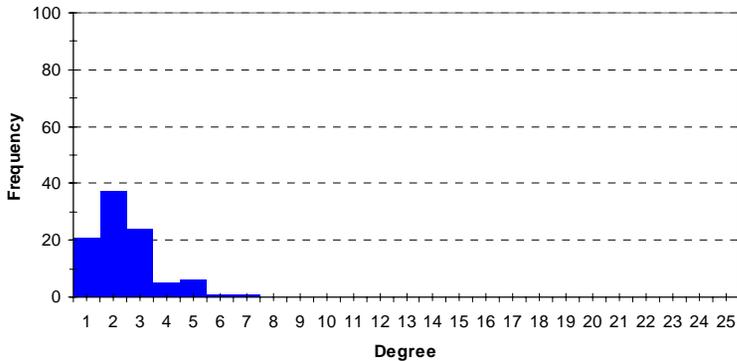
Zonal Analysis – Zone 3

Nodes:
 Gen → Red
 Load → Blue
 Bus → Yellow
 Tr → Black
 Others

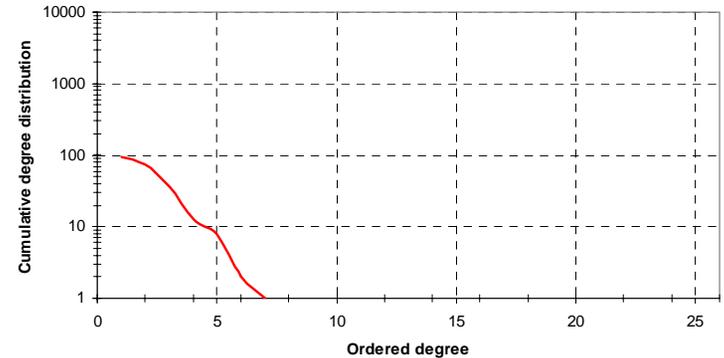
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 230 → Green
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 Others



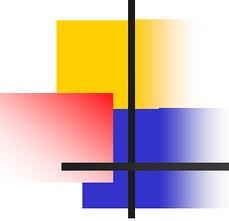
Degree distribution - Zone 3



Cumulative degree distribution - Zone 3



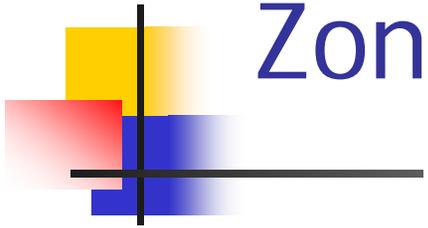
	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 3	92	115	1.250	2.421	7	7.809	5.114	No	0.179	0.026	.208



Notes on Zones 1 - 3

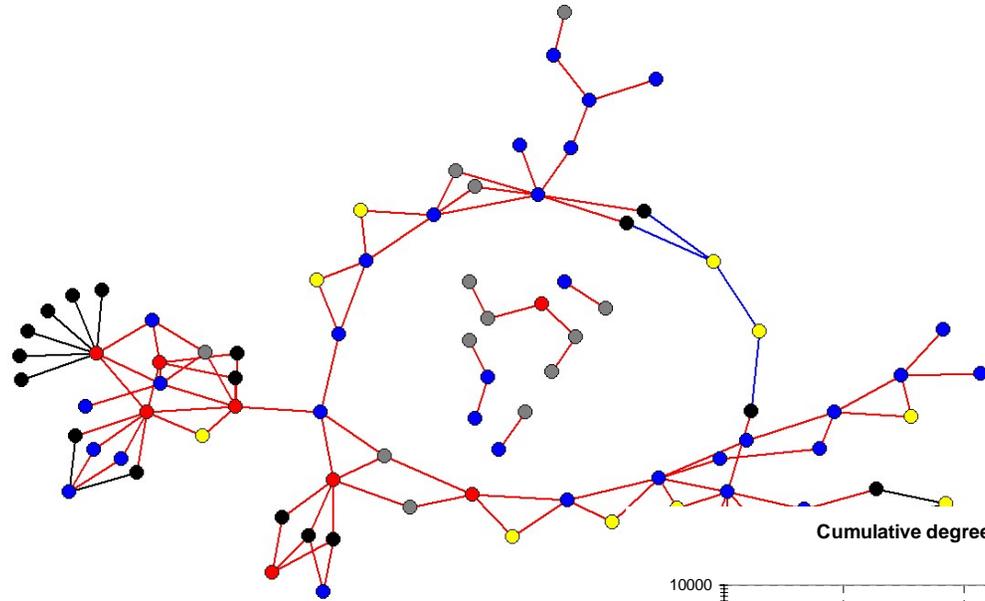
- These three zones are the most sparse in terms of nodes and links, and relatively small
- Lots of localized generation – zone 3 has some large units (export power to rest of grid)
- Degree correlations of zone 1, zone 2 are ~ 0 , zone 3 is ~ 0.2 (highly connected generators)
- Average path length is smaller than overall
- Edge to node ratio is low

Zonal Analysis – Zone 5



Nodes:

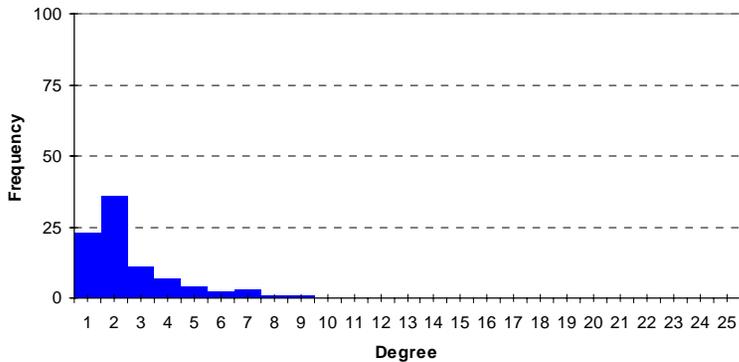
Gen → Red
 Load → Blue
 Bus → Yellow
 Tr → Black
 Others



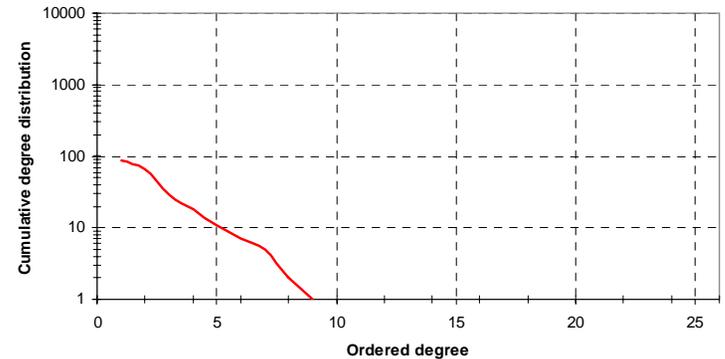
Links:

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 Others

Degree distribution

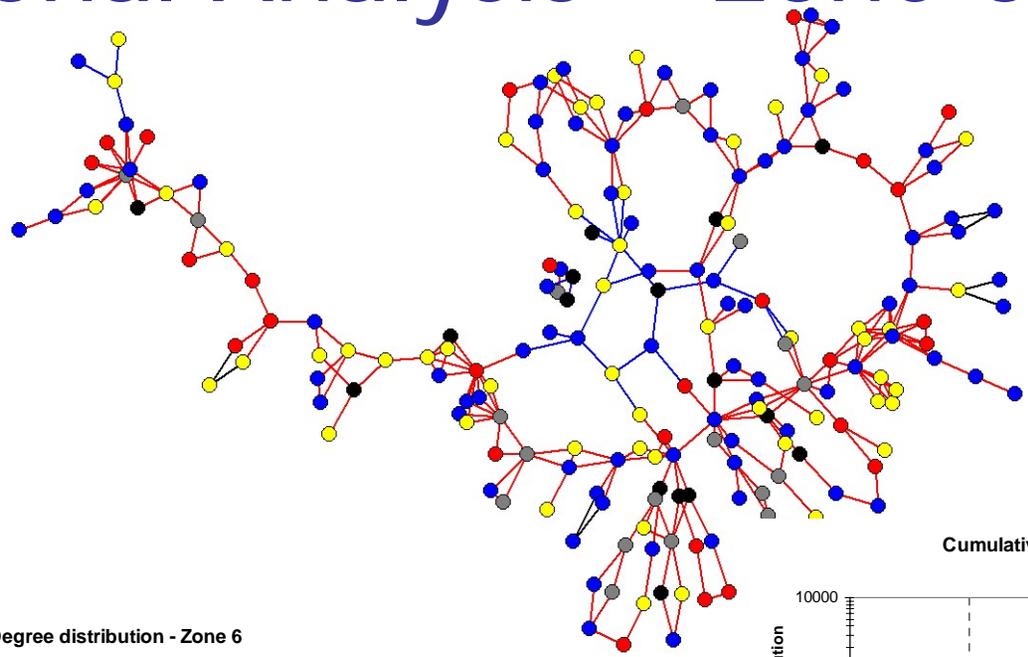
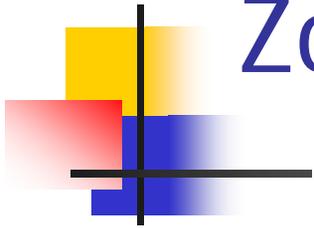


Cumulative degree distribution - Zone 5



	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 5	88	113	1.284	2.568	9	6.287	4.747	No	0.160	0.029	-0.16

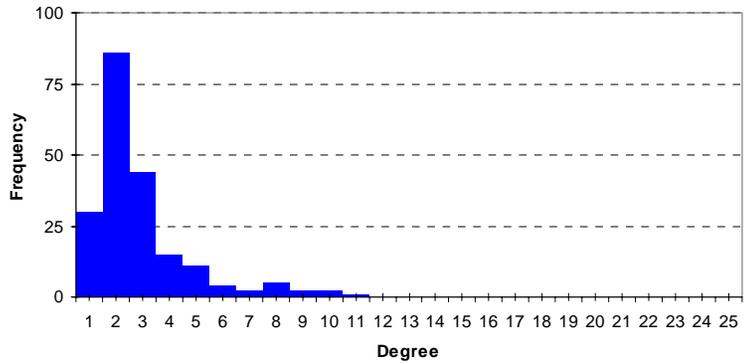
Zonal Analysis – Zone 6



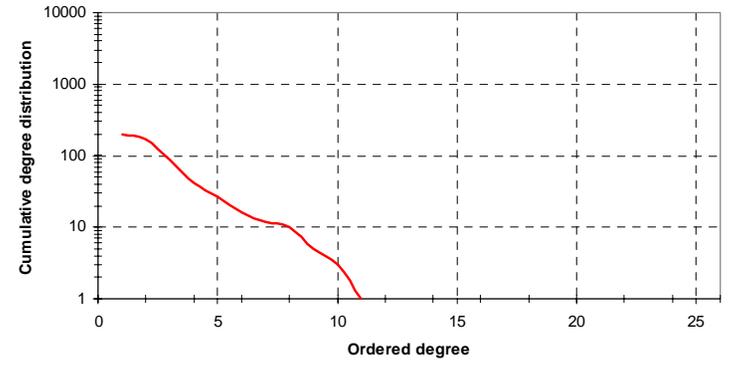
Links:
 < 115 → Black
 115 → Red
 230 → Green
 345 → Blue
 Others

Nodes:
 Gen → Red
 Load → Blue
 Bus → Yellow
 Tr → Black
 Others

Degree distribution - Zone 6



Cumulative degree distribution - Zone 6



	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 6	137	288	2.102	2.851	11	9.500	4.696	No	0.231	0.021	-0.09

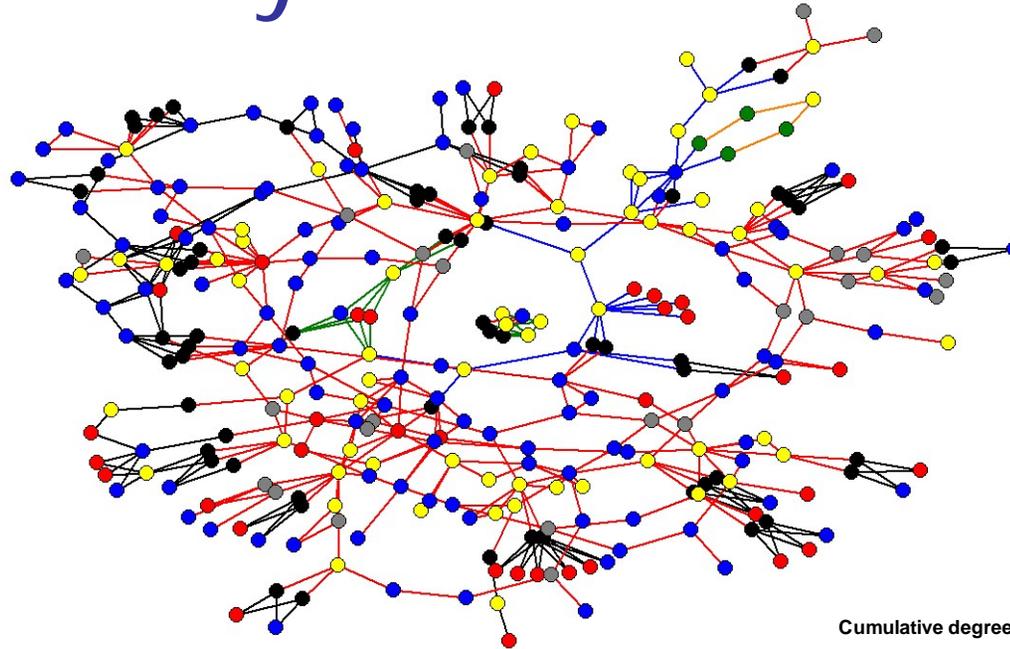
Zonal Analysis – Zone 7

Nodes:

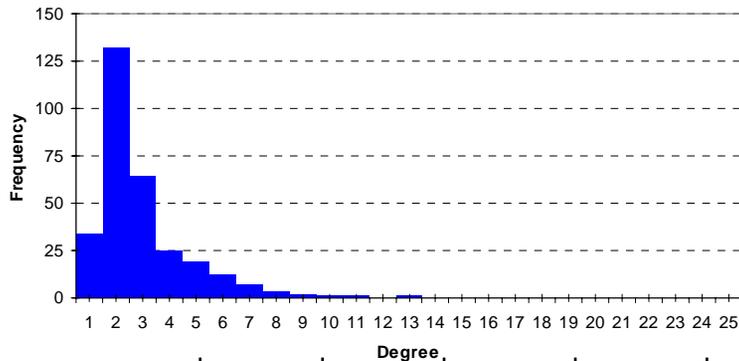
Gen → Red
 Load → Blue
 Bus → Yellow
 Tr → Black
 Others

Links:

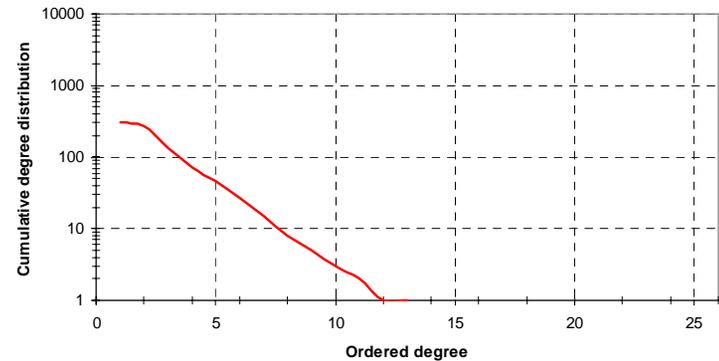
< 115 → Black
 115 → Red
 230 → Green
 345 → Blue
 Others



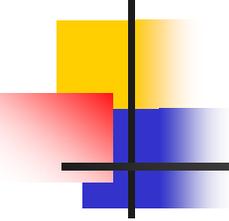
Degree distribution - Zone 7



Cumulative degree distribution - Zone 7



	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 7	301	441	1.465	2.93	13	7.902	5.309	No	0.121	0.010	-.086
											15



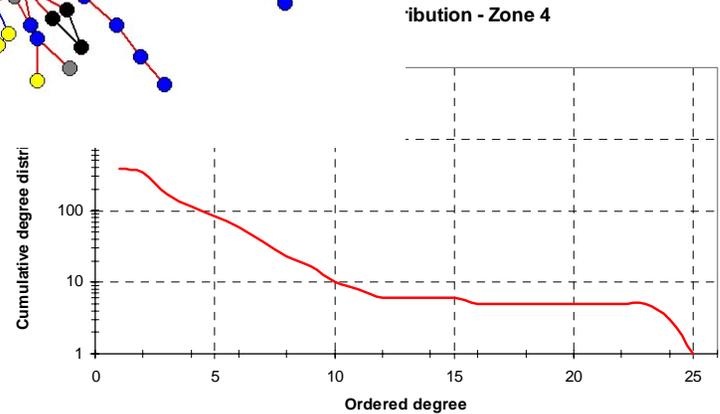
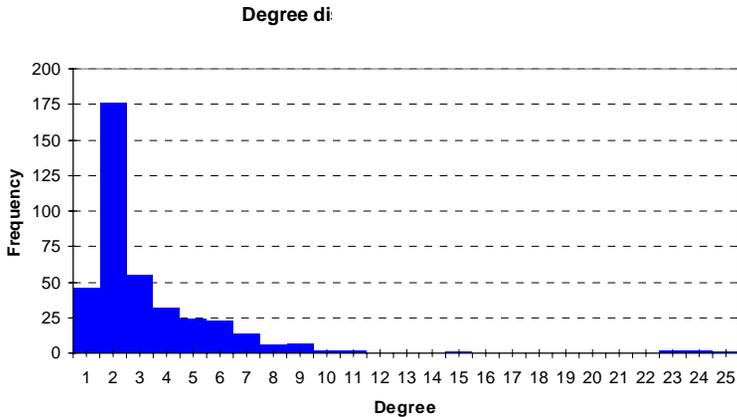
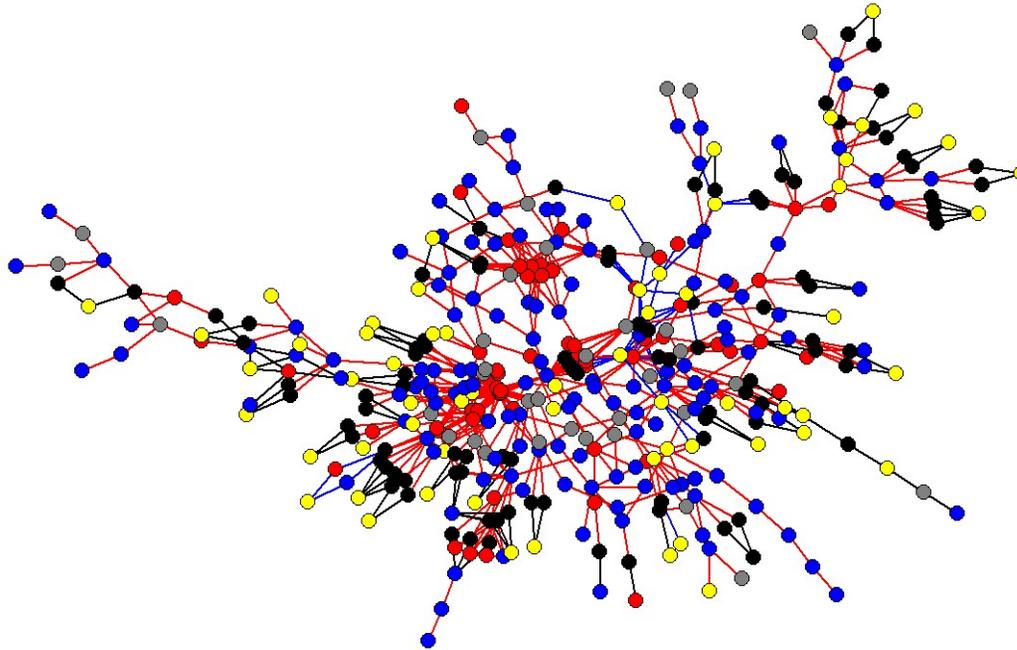
Notes on Zones 5 - 7

- These zones are intermediate in terms of nodal (and also population) density, load vs. generation balances out
- High voltage lines in these zones are also grid's backbone
- The degree correlation is negative for all three, which is different from other zones
- Removing these interconnecting lines to other zones leaves one zone (5) highly disconnected

Zonal Analysis – Zone 4

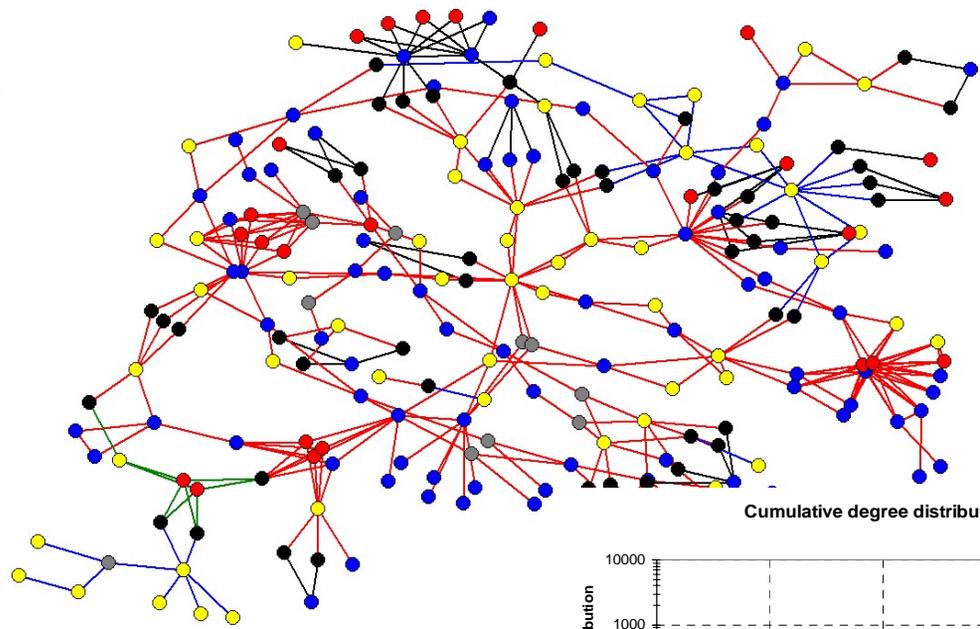
Nodes:
 Gen → Red
 Load → Blue
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 Tr → Black
 Others

Links:
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 115 → Red
 230 → Green
 345 → Blue
 Others



	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 4	393	667	1.697	3.394	25	7.853	4.889	No	0.111	0.009	0.34

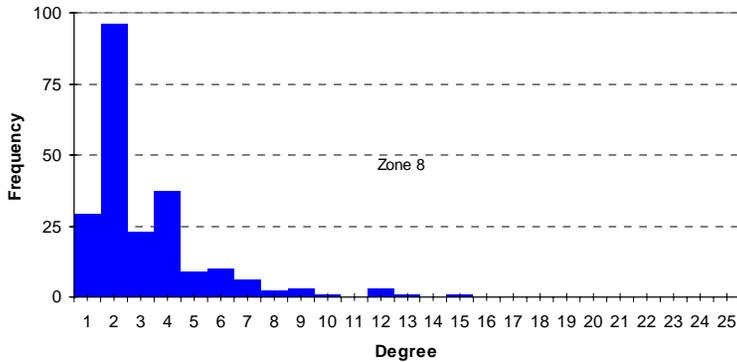
Zonal Analysis – Zone 8



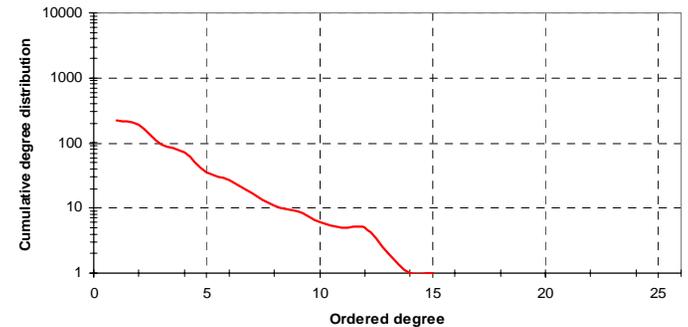
Links:
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 115 → Red
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 345 → Blue
 Others

Nodes:
 Gen → Red
 Load → Blue
 Bus → Yellow
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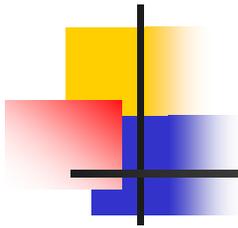
Degree distribution - Zone 8



Cumulative degree distribution - Zone 8

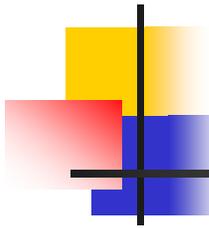


	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
Zone 8	221	351	1.588	3.176	15	6.282	4.671	No	0.193	0.014	0.08



Notes on Zone 4 and Zone 8

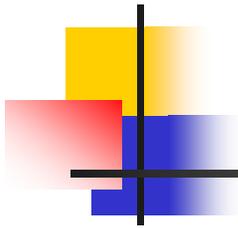
- This sub-group, especially zone 4, is very densely populated and generation-starved. Congestion component of locational marginal price is high
- Smaller lines form the backbone of these zones, that is lots of load nodes coming off the grid
- Two critical nodes lies in zone 8, which also has fair amount of office buildings and industry → demand
- Avg. path length is relatively short, m/n is higher
- Clustering coefficient is relatively higher, degree correlation is positive (as high as 0.34 in zone 4)



Zonal Comparative Analysis - Summary Metrics

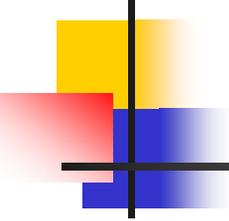
Entity	N	M	m/n	<k>	Max k	L	logn/log<k>	Alpha	C	<k>/n	R
WestGrid	4941	6594	1.335	2.67	34	18.990	8.661	No	0.080	0.001	0.004
NewGrid	1658	2589	1.562	3.117	25	14.354	6.521	No	0.149	0.002	0.100
Zone 1	210	314	1.495	2.952	9	9.514	4.939	No	0.155	0.014	-0.094
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Zone 5	88	113	1.284	2.568	9	6.287	4.747	No	0.160	0.029	-0.160
Zone 6	137	288	2.102	2.851	11	9.500	4.696	No	0.231	0.021	-0.090
Zone 7	301	441	1.465	2.93	13	7.902	5.309	No	0.121	0.010	-0.086
Zone 8	221	351	1.588	3.176	15	6.282	4.671	No	0.193	0.014	0.080

- There are less than two links per node, signifying lots of them are terminal
- Clustering coefficient is 0.15 and average path length ~14
- Pearson coefficient positive which is different from technological networks



Comments on Comparisons

- A random network generated using the same structure as the grid has:
 - Average path length = 15
 - A clustering coefficient on the order of 10^{-3}
- Hubs have effect, power grid is small-world
- Most other metrics are like Western Power Grid, except clustering coefficient and Pearson degree correlation are much higher

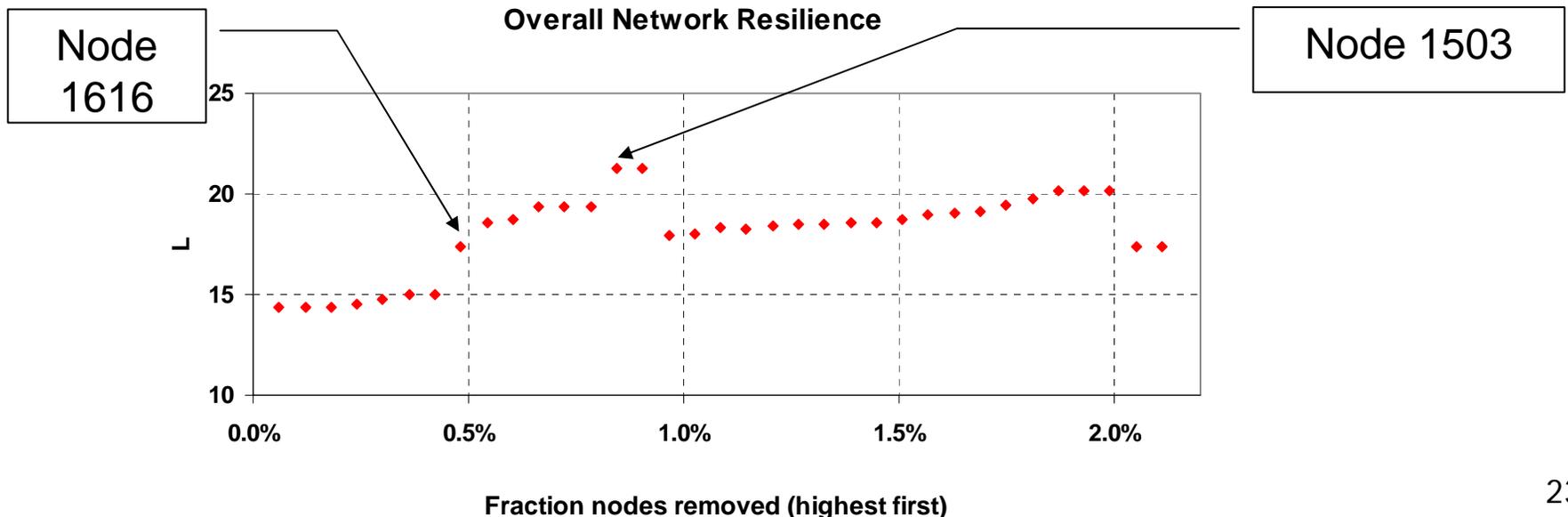


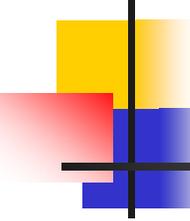
Existence of Hubs & Robustness

- Removing critical (e.g. very highly connected nodes) has an effect on avg. path length
- For example, node #687 has effect (major generator in the most congested zone)
- Removing this node increases avg. path length
- Network accessibility affected by targeted node removal of the ones with the highest degree

Overall Grid Resilience

- Diameter = 37 (vs. 40 for the random network)
 - From node 19 (gen. in zone 1) to node 860 (load in zone 4)
- Resilience analysis
 - Diameter: from 37 to 67
 - Mean geodesic: 14.35 to 21.30 (critical nodes in zone 8)
 - Node 1503 (generation unit), Node 1616 (backbone bus)

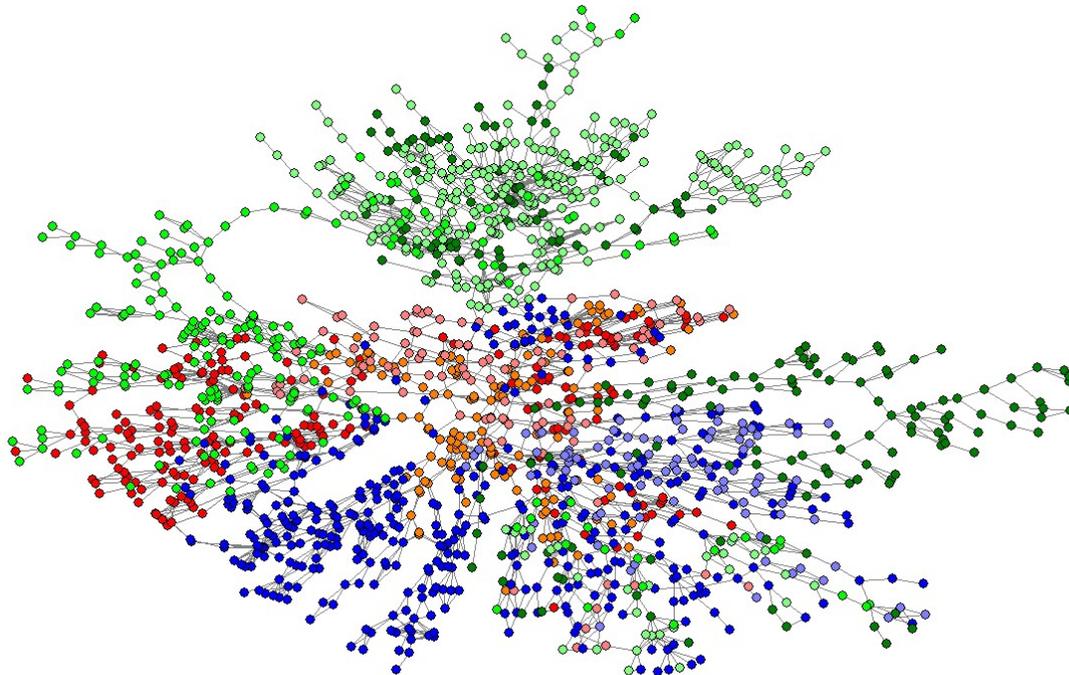


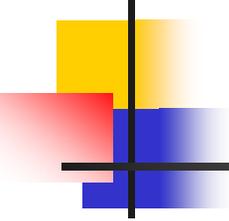


Comments, Questions and Answers

- Please share any new ideas for interesting and useful analyses

Thanks! (Karen, JZ, Steel)





More on Network Metrics

- Constraints on clustering and connectivity
 - cost and demographics dictate the constraints
 - only geographic proximity can define a cluster
- Network Betweenness Centralization = 0.33
- Network Closeness Centralization = 0.08
- Highly connected nodes: 1616 (345kV bus), 1503 (gen), 475-478 (gen), 1197 (gen), 1555 (load), 502 (gen), 687 (load)
- 1616 and 1503 are important nodes