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POWER GRID STABILITY IN SMALL WORLD PERSPECTIVE

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Introduction

The power grid which is designed to function as a network is vulnerable to physical and cyber disruption. The sources of vulnerability include natural disasters, equipment failures, human errors, or deliberate sabotage and attacks. As the power grids become heavily loaded with long distance transmission, the complex system become even more vulnerable as we have observed in several massive outages in the last decade. In a vulnerable system, a simple incident such as an equipment failure or a line touching a tree can lead to a cascaded sequence of events, leading to widespread blackouts.

The power grid, unconcerned to most public most of the time when it is operating in normal condition, gets attention only when such outages occur. As shown in Table I, there were several major power outages in the US power grid in the last three decades [1, 2]. Additionally, in August 2003, even a greater outage occurred in the North-eastern United States. However, since our research on the small world perspective started in 2002, the 1996 outage, the most vivid and greatest disaster in power system reliability at that time, was the main focus of the paper.

Actually, the 1996 outage occurred twice, apart by about a month. On July 2, 1996 a short circuit on a 345-kV line in Wyoming started a chain of events leading to a break-up of the western North America power grid which resulted in five islands with a blackout in southern Idaho with loss of 11,750MW of load. The August 10, 1996 failure resulted in break-up of the Western Systems Coordinating Council (WSCC) grid into four islands with loss of 30,390 MW of load affecting 7.49 million customers in western North America [3].

In general, generators in power systems are always subject to periodic disturbances, e.g., periodic load variations in steady state, swings of the other generators in transient state, and so on. The response of a power system to these impacts is oscillatory. If the oscillations are damped, so that after sufficient time has elapsed the deviation or the change in the state of the system due to the small impact is small (or less than some prescribed finite amount), the system is stable. If, on the other hand, the oscillations grow in magnitude or are sustained indefinitely, the system is unstable. When the stability of the system is investigated, it is often convenient to assume that the disturbances causing the changes disappear. Stability is then assured if the system returns to its original state.

***TABLE I**.* MAJOR ELECTRICITY RELIABILITY EVENTS IN NORTH AMERICA.

Major Events	Dates
Northeast Blackout	November 9-10, 1965
New York City Blackout	July 13-14, 1977
Los Angeles Earthquake	January 17, 1994
Western States Cascading Outage	December 14, 1994
Western States Cascading Outage	July 2, 1996
Western States Cascading Outage	August 10, 1996
Minnesota-Wisconsin "Near Miss"	June 11-12, 1997
Northeast Ice Storm	January 5-10, 1998
Upper Midwest Cascading Outage	June 25, 1998
San Francisco Blackout	December 8, 1998

The overall system dynamics can be represented by a set of dynamic equations (one for each dynamic device) together with a set of static network equations which define the interaction between the dynamic devices [4].

If the mathematical description of the system is in state-space form, i.e., if the system is described by a set of first-order differential equations,

$$\frac{dx}{dt} = Ax + Bu ,$$

and the free response of the system can be determined from the eigenvalues of the *A* matrix. If all eigenvalues have a negative real part, all modes decay with time and the system is said to be stable. If any one eigenvalue has a positive real part, the corresponding mode grows exponentially with time and eventually dominates the system behavior. Such a system is said to be unstable.

However, the cascading outages experienced in summer 1996 disclosed the inherent need for an enhancement in the current power grid operation and dynamic system analysis. One of the prominent mechanisms of failure was a transient oscillation, under conditions of high power transfer on long paths that had been progressively weakened through a series of seemingly routine transmission line outages. Later analysis of monitor records provided many indications of potential oscillation problems. Less direct indications of a weakened system were observed by system operators for some hours, but there had been no means of interpreting them. Operating records suggested that better tools might have provided system operators with about six minutes warning prior to the event that triggered the actual breakup [5].

A better detection and recognition of instability "signatures" in system dynamic activity was suggested as an interim solution. However, the broader message left by the outages was that a new paradigm is needed for an enhanced overall control of large power systems.

However, more serious and vexing problem is that, as reported in the 2003 Northeast Blackout report from NERC, there are causes but there is not the cause of wide spread blackout. In other words, some events contributed to the blackout but they are not necessary the cause of the blackout. Also, dynamic simulations and contingency plans are available but not used accurately nor on-time. Moreover, one cannot simulate all the situations in advance. Therefore, the causes of the blackouts are similar and the recommendations after the havocs are similar, but the problems have not been solved.

This paper suggests an alternative look on the power grid and blackouts, not using the conventional system dynamics but from a new graphical point of view. This paper does not attempt to find causes or sequences of blackout, instead, it wants to explain in terms of network topology what the difference is before a blackout and after, and thus tries to argue that a topological index could be used, or at least further investigated, for blackout analysis. Further, it is hoped that the index is utilized in the normal situation to monitor the strength of the power grid and the vulnerability of it.

System Dynamics and Network Topology

Analysis by eigenvalue techniques has shown that low frequency oscillations are inherent to inter-connected power systems. The frequency and damping of inter-area modes depends on the weakness of the tie line and on the load carried by the tie line. Also, higher frequency modes are caused by relatively weak transmission link between interconnected areas.

It is well known that the WSCC system for instance is prone to lightly damped low frequency inter-area oscillations in the frequency range of 0.2 – 0.3 Hz; they have been observed on the system many times. These oscillations are a characteristic of groups of machines oscillating against other groups of machines through weak ties. This is a phenomenon associated with small-signal stability, and is a function primarily of network/generator topology and excitation controls.

However, the nature of the oscillations is not yet fully understood. This inter-area oscillation is the "weakest link" in the current dynamic analysis based on the eigenvalue technique. Full understanding can only be obtained following the detailed study of a number of different real systems, followed by systematic validation by measurements and practical experience [6].

The blackouts reported, thus, expressed the need for an enhanced and a more robust technique to be adopted for modeling and analysis of system dynamics. In general, one may argue that unreliable models in planning process provided a common point of failure for the entire decision making whereby the power system was planned and operated. Further, the control engineer often found that major control systems produced wide area effects that were not well instrumented at that time, and that they sometimes operated under conditions that planning studies could not anticipate [7].

It has been vaguely but steadily recognized that the inter-connections tend to be weaker than the tightly meshed local networks, and that a linearly stretched network could be related to the instability phenomenon [6]. However, network topology has never entered in to the dynamic analysis.

Network anatomy is important to characterize because structure always affects function. It is recognized in power system dynamics that the qualitative nature of a system's connectivity is important in determining both its structural and dynamic properties. In many networks there is a dynamical aspect of error tolerance: the removal of a node could affect the functionality of other nodes as well. Thus in many systems errors lead to cascading failures, affecting a large fraction of the network. Therefore, topology may offer insightful explanations to the questions on cascading failures: How is it that small initial shocks can cascade to affect or disrupt large systems that have proven stable with respect to similar disturbances in the past? Why did a single power line trigger a massive cascading failure, when similar failures in similar circumstances did not do so in the past? As the topology of social networks affects the spread of information and disease, the topology of the power grid may affect the robustness and stability of power transmission.

Recently, power grid obtained another attention, this time not from public but from scientists and engineers whose interests are in the area of complex systems and non-linear behaviors, by an article in sociology, which stated that power grid is one of "small world" networks [8]. In graph theory, "small world" comes between random and complete graphs. In a complete graph where nodes are connected as lattice, average distance between arbitrary nodes is much bigger than that of random graph in which nodes are connected in a random fashion. Small world is a semi-random graph which produces a sharp reduction of the average distance between arbitrary nodes while the system is still relatively localized.

The wide appeal of this concept of small world is that the small world property seems to be a quantifiable characteristic of many real-world structures and networks. Many papers in many different scientific and societal fields report similar small world behavior in the real-world networks. The real world structures reported as having small world phenomena are: World Wide Web (WWW) sites, Internet domains, professional article co-authorship, E. coli. graph, food webs, synonymous words, and C. Elegans worm neural networks.

Some publications of small world presentation suggest that power grid may be an example of a small world. More interesting question is that, if all power grids are indeed small worlds, what implication of the small world property of power grid would have in power grid operation, planning, stability, and vulnerability. Specifically, related to the cascading outages experienced in the last decade, what information of the small world property of the power grid can be of use to prevent similar events and to give early warnings to the grid operators to avoid such disasters, or at least, to explain those events in a different perspective other than systems dynamics.

This paper studied power transmission grid of several typical networks to examine if they are small world and attempted to explain if there is any inherent correlation between the small world graphical properties of a power grid with cascade outages it experienced.

Graph Theory and Small World Networks

A power grid's inherent risk of failure depends on factors such as the magnitudes of population and loads in relation to generation resources. It is suggested that highly meshed transmission networks with evenly distributed load and generation are more reliable than networks arranged longitudinally, in loops, or radial (as on peninsulas, for instance) [9]. Also, a linearly stretched network is weaker than tightly meshed local networks [6]. This chapter first reviews graph theory and the "small world" network, following the excellent sections presented in the reference [10], and then explores implications of the small world network in the power grid.

a) Basic Graph Theory

A graph is nothing more than a set of points connected in some fashion by a set of lines. More theoretically, a graph G consists of nonempty set of elements, called vertices (or nodes), and a list of unordered pairs of these elements, called edges (or lines). Graphs can be used to represent all kinds of networks, where the vertices represent network elements such as substations, transformers, and generators in power grid system and the edges, some predefined relationship between connected elements such as high voltage transmission lines.

The set of vertices of the graph G is called the vertex set of G denoted by $V(G)$, and the list of edges is called the edge list of G, denoted by $E(G)$. If v and w are vertices of G, then an edge of the form vw is said to join or connect v and w. The number of vertices in $V(G)$ is termed the order of the graph, n, and the number of edges in $E(G)$, its size, M. The maximum size of $E(G)$, $M_{\max} = \binom{n}{2} = \frac{n(n-1)}{2}$ corresponds to a "fully connected" or complete graph. On the other hand, sparseness implies $M << M_{\max}$.

On the other hand, the number of edges incident with a given vertex v, i.e., the number of v's adjacent neighboring vertices, is called the degrees of v, denoted by k_v. One static frequently used in network classification is the average degree, k, which quantifies the relationship between n and M:

$$k = \frac{2M}{n}. \tag{1}$$

However, one of the two most important statistics of graph is the characteristic path length, $L(G)$, that is, the average distance between every vertex and every other vertex. The "distance," $d(i, j)$, here refers not to any separately defined metric space but to the minimum number of edges that must be traversed in order to reach vertex j from vertex i. In other words, L is the shortest path length between i and j. For a random graph, a reasonable asymptotic approximation is

$$L_{random} \approx \frac{\ln(n)}{\ln(k)}. \tag{2}$$

The other important statistic is the clustering coefficient of a graph. The neighborhood of a vertex v, $\Gamma(v)$, is defined as the sub-graph that consists of the vertices adjacent to v (not including v itself). Then, the clustering coefficient of $\Gamma(v)$, γ_v, characterizes the extent to which vertices adjacent to any vertex v are adjacent to each other. In other words, the clustering coefficient of a vertex v is defined by the ratio of the number of edges in the neighborhood of v and the total number of possible edges in the neighborhood:

$$\gamma_v = \frac{|E\{\Gamma(v)\}|}{(k_v \cdot (k_v - 1))/2} \tag{3}$$

where E is the expected value of the neighborhood of a vertex. A measure of clustering over the entire graph G, γ, is defined as the average of γ_v over all $v \in V(G)$. Therefore, $\gamma = 1$ would imply a complete graph, and $\gamma = 0$ would imply that no neighbor of any vertex is adjacent with any other neighborhood. In power grid, γ implies the degree to which substations (or generators or load centers) are connected via transmission lines to each other. For a random graph, a reasonable approximation for the clustering coefficient is $\gamma_{random} \approx \frac{k}{n}$.

b) Small World Networks

A recent paper, *Collective dynamics of "small-world" networks*, which appeared in *Nature*, has attracted considerable attention [8]. The paper investigated what happens between the two extreme graphs: complete and random graph. Their computer experiments indicated that introducing a relatively small number of random connections dramatically changed the character of the graph. That is, the graphs retained their properties of being highly clustered, but the average path lengths dropped dramatically. These new graphs are called "small world" networks.

The small world graph, which is highly clustered yet have characteristic path length equivalent to random graphs, exhibits the following characteristics:

$$L \approx L_{random}(n,k) \text{ and } \lambda >> \lambda_{random}(n,k) \qquad (4)$$

The small-world networks seem to be good models for a wide variety of physical situations. According to the model, the power grid for the western U.S., the neural network of a nematode worm, and the Internet Movie all have the characteristics of "high clustering coefficient but low characteristic path length" of small-world networks.

For the Western States Power Graph (WSPG), they analyzed the power transmission grid for the states west of the Rocky Mountains and calculated the topological characteristics. The resultant WSPG was large and sparse, with n = 4941 and k = 2.67. The critical path length and the clustering coefficient were L_{WSPG}= 18.9 and γ_{WSPG} = 0.08, respectively. This clustering coefficient γ_{WSPG} is 160 times larger than the expected value for an equivalent random graph, but L_{WSPG} is only about 1.5 times greater. So it was decided that the WSPG was small world after all. However, the reference [10] is the only material of reporting a power grid as a small world network. Others, without actual analysis, merely quoted the reference and declared the power grid as a small network.

In addition to the degree sequences, shortest connecting paths, and clustering coefficient as presented in the section, a graph associated with adjacency matrices can be characterized by spectral method, which also provides global measures of the network property [11, 12].

In the spectrum analysis, the eigenvalues of a graph are defined as the eigenvalues of its adjacency matrix.

The adjacency matrix $A(G)$ is the $n \times n$ matrix which $A_{i,j}$ is the number of edges joining the vertices i and j.

If the weight of the edges is the same, then all entries of the matrix would be either 0 or 1. The set of eigenvalues of a graph is called a graph spectrum, and this characterizes the principal properties and structure of a graph. For example, if the biggest eigenvalue $\lambda_1 = 0$, we know G is not connected, and “wide” graphs tend to have higher λ_1 than “narrow ones” [13]. In the paper, the graph spectrum is not considered in the analysis of power grid.

c) An Example with 14-Bus Network

An example using a simple power network would be appropriate to illustrate the two graphical statistics and their calculation. Shown in Figure 1 is the 14-Bus network [14], which has 14 nodes and 20 edges (or lines).

The degree (or number of neighbor nodes), the critical path length, and the clustering coefficient of each node are calculated and tabulated in the Table II.

From the table, we can draw the following: with average number of neighbors 2.857, average critical path length (L) is 2.374 and the clustering coefficient (γ) is 0.367. On the other hand, a random graph with the same number of node, with the same degree of 2.857, would have L_{random}=2.51 and γ_{random}=0.204.

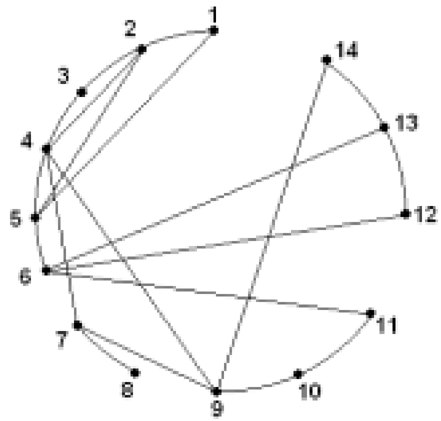

Figure 1. 14-Bus Network

The critical path length of the 14-Bus network is close to that of the random graph, but the clustering coefficient is only twice of that of the random graph. The 14-Bus network then is more like a random graph. As can be seen in the following chapter, the number of nodes in the power network seems to determine the characteristics of the network: bigger networks are more of "small world" networks while smaller ones are usually close to random networks.

TABLE II.GRAPHICAL PROPERTIES OF THE 14-BUS NETWORK

Node Number	Degree, k	Critical Path Length	Clustering Coefficient
1	2	2.692	1.0
2	4	2.154	0.5
3	2	2.615	1.0
4	5	1.836	0.3
5	4	1.923	0.333
6	4	2.077	0.167
7	3	2.231	0.333
8	1	3.154	0.0
9	4	1.923	0.167
10	2	2.462	0.0
11	2	2.538	0.0
12	2	2.769	1.0
13	3	2.462	0.333
14	2	2.385	0.0

d) “Small World" Implication to Power Grid

As we discussed before, the key topological characteristic of small world phenomenon is the presence of a small fraction of a very long-range, global edges, which contract otherwise distant parts of the graph, while most edges remain local, thus contributing to the high clustering coefficient.

Since the qualitative nature of a system’s connectivity is important in determining both its structural and dynamic properties, the removal of a node (i.e., the outage of a generator or substation transformer, or a sudden pull-out of a large load) or an edge (a transmission line) could affect the functionality of other nodes as well.

In some case, notably in disease spreading, the relevant dynamical properties seem to be dominated by the characteristic length of the graph. In other cases, the dominant one of the dynamic relevance is the clustering coefficient, or both. Of course, there are cases neither one seems to have any relevance with dynamic property [15].

In terms of network vulnerability, it is shown that "scale-free" graphs are much less vulnerable to random perturbation than are traditional random graphs with same average degree [16]. Scale free networks are those whose degree distribution follows a power law for large *k*, and those, even whose degree distribution has an exponential trail; degree distribution significantly deviates for a Poisson distribution, which is typical of random graph.

Is power grid actually a small world network? Are its dynamic properties relevant to its graphical statistic such as the critical path length or the clustering coefficient? At least we know that the shape of network is, at least qualitatively, connected to the stability of power grid [5]. Also, from the graph theory, we know that topology affects the dynamic aspect of node/edge removal. To answer the two questions, therefore, we need a topological analysis of power network and of relationships of topology and system dynamics. In the analysis, two topological measures (L and γ) are explored as possible indices or indicatives of cascading failures.

In this paper, we trace the topological measures with the sequence of the cascading events to relate the topology and the inherent instability of a power grid.

Topological Analysis of Power Grid and Outages

We first analyzed power grids for a small world network investigation. Second, we reconstructed the 1996 outages using the power grid data and the outage report. Then, we performed a sensitivity analysis to compare the graphical statistics of the line removals following the actual sequence of cascading outages and those of the removal of randomly selected lines.

a) Topological Analysis of Power Grids

We analyzed several power networks of various sizes to inspect if power network in general is small world network. The networks we analyzed are:

- IEEE Standard 118-Bus network [14] which has 118 nodes and 179 edges,
- MAPP (Mid-Continental Area Power Pool) network of 230kV and above only, which has 575 nodes and 754 edges,
- Nordel network, the interconnected power systems of Finland, Norway, Sweden, and parts of Denmark, of 100 kV and above only, which has 410 nodes and 564 edges,
- KEPCO (Korea Electric Power Corporation) network of 66kV or above only, which has 553 nodes and 783 edges, and
- ERCOT (Electric Reliability Council of Texas) network of 345kV only, which has 148 nodes and 209 edges.

Actually, a program to read data of connectivity and to calculate the necessary outputs needs a well-designed algorithm. For the algorithm of calculating the critical path and the clustering coefficient, we applied a cellular automata approach as a search tool for neighboring nodes. This approach saved a lot of code space and running time.

Table III below summarizes the graphical properties of the networks. One thing common to all the networks, regardless of the number of nodes or edges, is that the average degrees (k) are almost the same ranging from 2.62 to 3.03. This means that a power node has about 3 neighboring nodes in average. The L and γ do not show a consistent result: one network's critical path length is close to that of random graph while its clustering coefficient is not big enough compared with that of random graph, or one with a big clustering coefficient has twice big critical path length of that of random graph. Also, bigger networks show higher clustering coefficients and, at the same time, slightly longer critical path lengths, and could join the group of small world networks.

TABLE III. GRAPHICAL PROPERTIES OF SELECTED POWER NETWORKS

	node, n	edge, M	degree, k	L / L_{random}	γ / γ_{random}
118Bus	*118*	*179*	*3.03*	1.47	6.8
MAPP[1]	*575*	*754*	*2.62*	2.39	18.4
Nordel[2]	*410*	*564*	*2.75*	2.37	21.4
KEPCO[3]	*553*	*783*	*2.83*	1.24	23.5
ERCOT[4]	*148*	*209*	*2.82*	1.47	7.3

[1] 230kV and above only; [2] 100kV and above only; [3] 66kV and above only; [4] 345kV only

b) WSCC Network

According to a FERC 715 report [17], WSCC network of year 1996 consists of different levels of high voltage transmission lines. The network with 100kV and higher voltage contains 4610 nodes and 6244 edges. It has 1646 nodes and 2348 edges if only voltages of 200kV and higher are considered. If only transmission voltage of above 300kV is included, it has 352 nodes and 449 edges. Topological analysis of WSCC grid shows that it could be classified as a small world (see Table IV), similarly claimed in [10], even though there are no clear cut-off lines in the ratios of L / L_{random} and γ / γ_{random} for being a small world network.

TABLE IV GRAPHICAL PROPERTIES OF THE WSCC NETWORK

WSPP	node, n	edge, M	degree, k	L	γ	L/L_{random}	γ/γ_{random}
>100 kV	4610	6244	2.71	25.25	0.046	2.87	78.23
>300 kV	352	449	2.51	17.28	0.048	2.56	7.10

d) Topology of 1996 WSCC Power Outage

Based on the FERC 715 network of WSCC and the outage reports [3, 5], the cascading faults of summer 1996 are reconstructed. Only the lines and substations of above 300kV are considered in the study. The node names are the ones used in the FERC 715 report, but the line numbers (numbers next to lines) are generated by the authors for the analysis. The area of the 1996 failures is illustrated in Figure 2. The nodes encircled with dotted lines indicate generating sites.

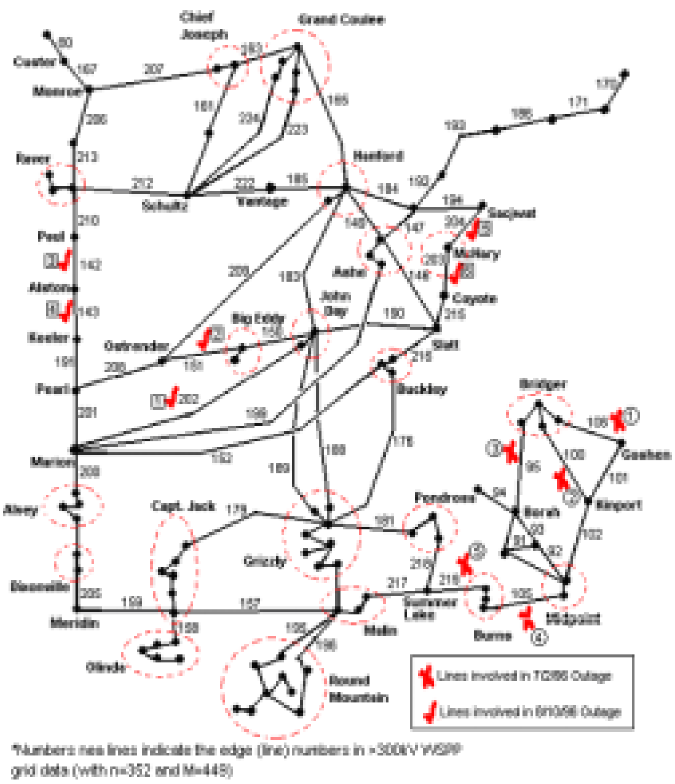

Figure 2. Reconstruction of the WSCC outages in 1996.

The July 2 failure was triggered by an event of flashover to a tree on the Jim Bridger-Goshen line (line #106). Then, the Jim Bridger-Kinport line (#100) was tripped. These two line losses tripped Jim Bridger units and, consequently, the line #95 was removed from the service. Later, lines #105 and #219 were also removed from the service [9].

The triggering event for the August 10 failure occurred when the Allston-Keeler line (line #143) sagged close to a tree and flashed over. However, prior to the failure, there were two forced outages of John Day-Marion (line #202) and Big Eddy-Ostrander (line # 151) lines. On the failure date, after the loss of line #143, the Keeler-Pearl line (line #191) opened by the Keeler breaker operation. At the same time thirteen McNary units sequentially tripped and, consequently, lines #204 and #203 were lost. This started system power and voltage oscillations [3].

d) L and γ Comparison - random 4 lines removal vs. the failed 4 lines in the cascading faults

To inspect any topological changes when the root cause of the power lines was removed from the WSPP grid, and to compare the results with those cases when randomly selected lines were removed from the grid, we calculated the critical path lengths and the clustering coefficients on the following simulated scenarios.

scenario 1: No line is removed from the grid
scenario 2: August 10 outage simulation (lines removed are: #142, #203, #143, and #204)
scenario 3: August 10 outage simulation (lines removed are:#151, #202, #142, and #203)
scenario 4: July 2 outage simulation #1 (lines removed are: #106, #100, #95, and #219)
scenario 5: July 2 outage simulation #2 (lines removed are: #106, #100, #95, and #105)
scenario 6: Arbitrary 4 lines are removed: #100, #200, #300, and #400
scenario 7: Arbitrary 4 lines are removed: #101, #202, #303, and #404
scenario 8: Arbitrary 4 lines are removed: #103, #203, #304, and #405
scenario 9: Arbitrary 4 lines are removed: #10, #20, #30, and #40

A question may arise on this assumption that random removal of lines would not cause major disturbance: how could we assume that the removal of the randomly selected 4 lines would keep the system undisturbed? An answer would be found from the fact that a sequence of events cascaded into the major outages. This means that a sequence of events is a necessary and sufficient condition for a cascading outage not a random event.

From the calculation results of the above 9 scenarios, which are illustrated in Figure 3, we can see that the critical path lengths for the July outage (scenarios 4 and 5) show much higher than those of other scenarios including the no-outage scenarios.

We can also see a little increase in the path of the two August outage scenarios (2 and 3). However, it is significant that the path lengths of the August scenarios are still higher than the average of those of no-outage scenario. The clustering coefficients do not show any noticeable difference in the outage and the no-outage scenarios.

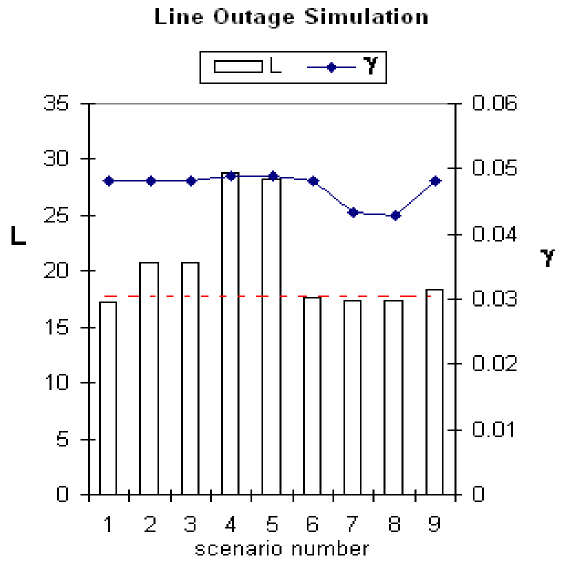

Figure 3. Illustration of the graphical property changes in 9 different scenarios.

We admit that the study is literally preliminary and there is an on going research effort on this subject matter. The comparison of the scenarios could include more cases. The sequential event (or line removal) and its effect to the critical path length and the clustering coefficient could be performed. Moreover, the study was performed on reduced size grid of the WSCC grid. However, the results shed some insight in that they could relate the cascading outages to static topological measures, along with the dynamic indices that have been traditionally used in the power system operation.

Conclusions

Recent major outages revealed the need to improve on the current stability analysis methods of modeling and simulation of system dynamics and oscillations. This paper presented an approach to see the current grid problem in another angle: grid outages and vulnerability assessment by using topological estimators, i.e., critical path length and clustering coefficient.

The small world perspective would be able to determine the priority or importance of each transmission line in a power grid in terms of its possible role as a triggering point, if faulted, for a cascading failure and outage. Those highly prioritized lines, then, should be first considered in maintenance, repair, and upgrade.

Also, the preliminary result of the paper would supplement existing, dynamic analysis of eigenvalue and frequency, and spur research activities for fundamental solution for the current energy and power grid crisis.

Another area of the small world application is that it could be a valuable tool as a route and connection guideline when new transmission lines are added or removed. The added or removed lines, even though they may perfectly fit to power, voltage, and other stability and dynamic consideration, would greatly affect the grid topology.

The future work is to further investigate the possible correlation of the topological measures to cascading outages using the 2003 Northeast outage data. Eventually, we seek to perform a graphical analysis of all North American power grids that experienced major outages, and to explain power grid and outages in terms of topological statistics.

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