The frequency of large blackouts in the United States electrical transmission system: an empirical study

Authors

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Abstract

This paper gives empirical evidence that despite efforts by engineers and policy makers to improve the reliability of the US bulk electricity transmission system, the frequency of large blackouts has not decreased during the period 1984 to 2003 for which data is available. In fact, data available from NERC and the Department of Energy provide some evidence of a significant frequency increase in the most recent years (1998-2004). Excluding extreme weather events, and normalizing for demand growth, the average number of blackouts 100 MW or larger between the intervals 1984-1997 and 1998-2004 is 15 and 24 respectively. We proposes several explanations for the lack of improvement in network reliability.

1 Background

Transmission system reliability has been a major concern for the electricity industry since the early days of electrical transmission. The 22-mile Niagara falls to Buffalo, NY transmission line, energized in 1895, suffered frequent failures most often initiated by lightning strikes. Such faults frequently resulted in costly equipment damage in addition to interrupting service. As the system evolved, strategies were developed to improve the reliability of the system and prevent equipment damage. Engineers designed relays and power circuit breakers in order to protect equipment from damage, and interconnected distant systems in order to provide redundant sources for each load.

On November 9, 1965 the Northeastern United States suffered a cascading failure that interrupted service to 30 million customers. A relay with a faulty setting, on a line between Niagara and Toronto, tripped. The power shifted to three parallel lines, which quickly became overloaded, triggering subsequent relay actions. Excess Niagara generation was instantaneously sent south into New York state, overloading additional lines, and eventually resulting in a cascading failure that affected customers in seven states and much of Ontario [Spectrum, 1976]. This cascading failure triggered a number of engineering and regulatory actions intended to prevent future failures. Per the recommendations of a 1967 Federal Power Commission Report [FPC, 1967], industry formed regional reliability councils, and later the North American Electric Reliability Council (NERC), to suggest standards for the interconnected networks. Engineers developed a number of improvements to the network protection systems, including the use of backup relays, and automatic load shedding.

In 1977 another sequence of overloads left 9,000,000 New Yorkers in the dark. This blackout resulted in the development of what is now the nearly universally accepted 5-stage protection strategy that establishes the concept of "N-1" security. This method classifies any state as normal, alert, emergency, *in extremis*, or restorative and recommends actions that are appropriate to take in each condition [Fink, 1978]. In the normal state a system is to be considered "secure" if no single contingency can initiate a cascading failure.

On the west coast, the three blackouts of July and August 1996, resulted in a number of modifications in protection strategies for major transmission corridors including further improvements in the remedial action schemes (RAS)–also known as special protection schemes (SPS)–designed to protect the system as a whole. These events also highlighted the importance of testing relays frequently for hidden failures, and managing vegetation along transmission corridors.

During this time period between the 1965 and 1996 blackouts, hundreds of SPS-like systems were implemented in systems worldwide. Most were designed to shed load and/or generation automatically based on a set of often complicated criteria. A 1996 survey of more than 100 such systems shows that while some system operators report that such systems have improved reliability, results have been mixed overall [Anderson, 1996]. While the RAS designed to protect the western interconnect may have limited the extent of the 1996 events somewhat, they allowed the cascading failure to disrupt service throughout the Western US and Canada. This has led many system operators to avoid the use of automated SPS.

More recently, the Eastern Interconnect blackout of August 14, 2003 resulted in a number of changes, including the passage of legislation that will allow for nation-wide mandatory reliability rules in the U.S.; though the new set of rules will be designed and administered by an industry organization with federal oversight.

Numerous engineering solutions, related to solving the blackout problem, exist in the literature. Reports exist following each of the 1965 [FPC, 65,], 1977 [FERC, 78], 1996 [DOE 96, WSCC 96], and 2003 [US-CA 04] blackouts give extensive technical recommendations. Many technical approaches to controlling cascading failures exist in the literature [Zima 2002]. More recently, Ilic et. al [Ilic, 2005] and Makarov et. al. [Makarov 2005] propose methods to enhance system level control.

While it is clear that no networked electricity system is immune to blackouts, with all the attention that engineers, utility system managers, and policy makers have given to this problem, it seems that the frequency of large blackouts should be decreasing, at least when adjusted for demand growth. The US air traffic control system provides precedent for a large, complex system undergoing a significant decrease in risk following appropriate engineering and policy actions. Between the years 1960 and 2000 the number of fatalities per 100 million miles of air travel in the US fell from 44.2 to 1.2–resulting in a system that is now significantly safer than driving [Apt, 2004]. With this in mind, our research objective is to test the hypothesis that the frequency of large blackouts in the United States has significantly decreased during the period for which data exists (1984 to 2003). Section 2 describes our data sources and reviews a few related studies of this data. Section 3 describes our statistical analysis of this data. Section 4 gives proposes some explanation for our findings, followed by some conclusions in section 5.

2 Blackout data

We collected data from NERC Disturbance Analysis Working Group (DAWG) reports and supplemental data from the Department of Energy, Energy Information Agency (EIA) form 417 reports. The DAWG database website includes data for the years 1984 to 2002 [NERC, _____]. Additional data for 2003 is included in minutes from a

2004 DAWG meeting [NERC, 2004]. Data is available from the EIA for the mid 1990s through Sept. 2005 [USDOE / EIA, _____]. This data is included in the relevant figures, but because it differs slightly from the NERC data it is excluded from our statistical analysis. Figures 2.1 and 2.2 give the frequency of large blackouts, from this data set, without any major modifications.

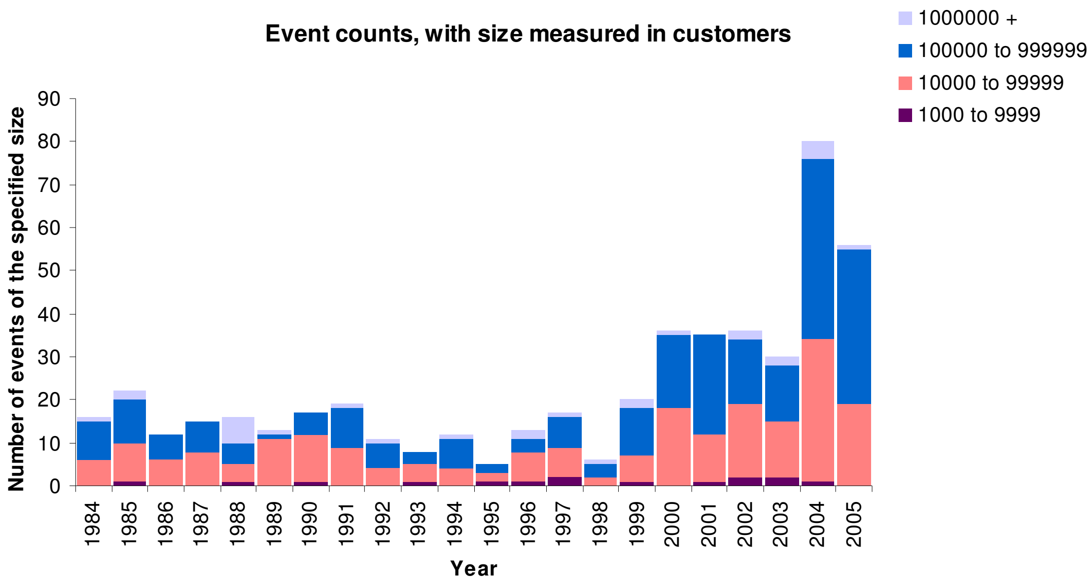

Figure 2.1 — Blackout frequencies for the years 1984 to 2005. Size here is measured in the number of customers affected. 2004 and 2005 data come from the EIA (2005 data is for Jan-Sept only), all other data is from the NERC DAWG records.

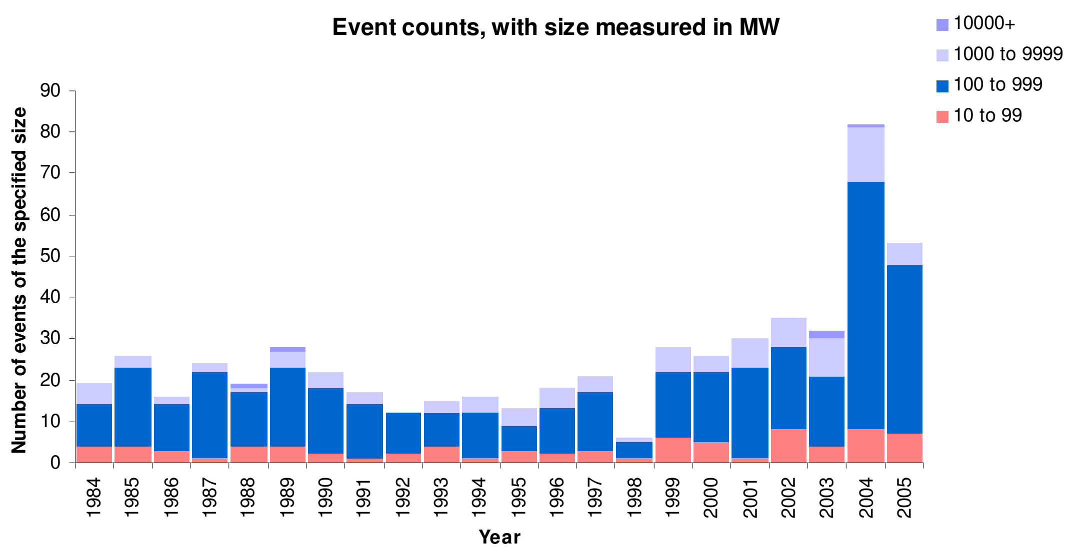

Figure 2.2 — Blackout frequencies for the years 1984 to 2005. Size here is measured in the number of MW interrupted. 2004 and 2005 data come from the EIA (2005 data is for Jan-Sept only), all other data is from the NERC DAWG records.

In order to isolate the transmission system disturbances, we removed the disturbances that were primarily caused by extreme natural events–specifically earthquakes, tornadoes, hurricanes, and ice storms. For other weather-related events, we removed only those disturbances that clearly only affected the distribution system, since some storms can initiate cascading failures without being clearly classified as this type of problem. Finally, we normalized the data in several ways. Where either the number of customers or MW were recorded as N/A, unknown, or left blank, we interpolated the value based on the average number of customers affected per MW over the entire data set (768 customers per MW). Secondly, in order to adjust for demand growth, we scaled the event MW sizes by the total energy consumption during the year in question. Similarly we scaled the customer counts by total US population for the given year. Thus event sizes are recorded in our data set as year-2000 MW or year-2000 customers, reducing the size of post-2000 events and increasing the size of pre-2000 events slightly. Eqs. 2.1 and 2.2 describe these measures formally:

$$\text{year-2000 MW} = \left(\text{actual MW for event in year X}\right)\frac{\text{demand in year 2000}}{\text{demand in year X}} \tag{2.1}$$

$$\text{year-2000 customers} = \left(\text{size of event in year X}\right)\frac{\text{population in year 2000}}{\text{population in year X}} \tag{2.2}$$

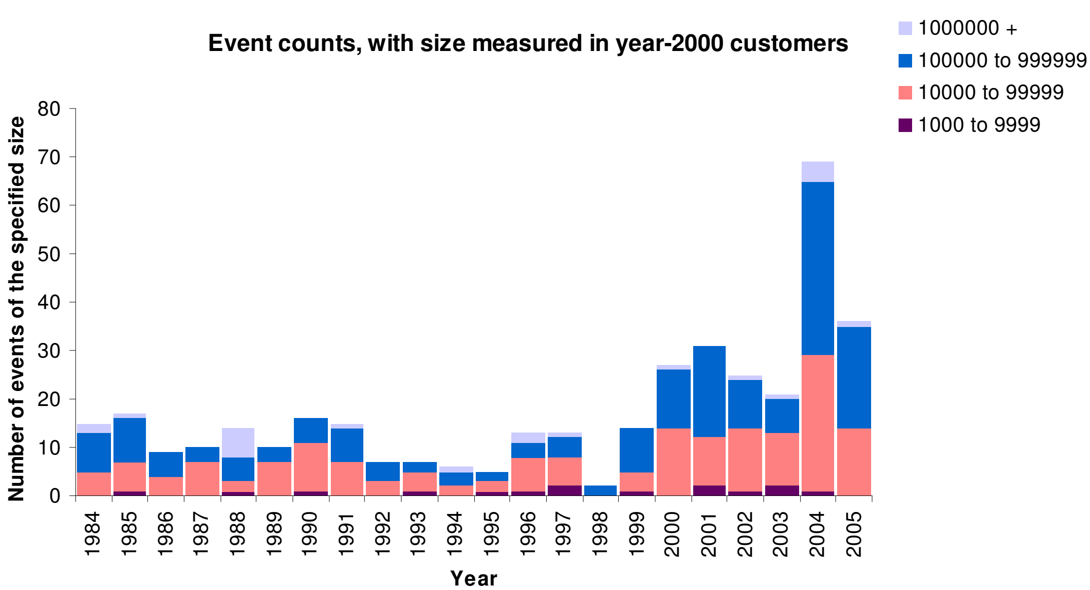

Figure 2.3 – Blackout frequencies for the years 1984 to 2005 after normalizing data. Size is measured in year-2000 customers (normalized by US population). 2004 and 2005 data come from the EIA (2005 data is for Jan-Sept only), all other data is from the NERC DAWG records.

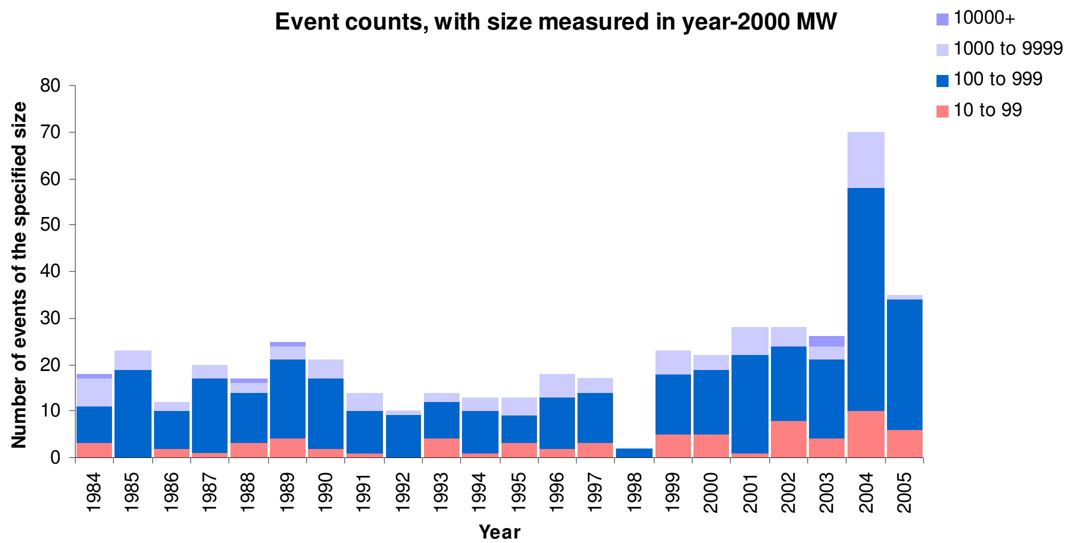

Figure 2.4 – Blackout frequencies for the years 1984 to 2005 after normalizing data. Size is measured in year-2000 MW (normalized by yearly net generation). 2004 and 2005 data come from the EIA (2005 data is for Jan-Sept only), all other data is from the NERC DAWG records.

2.1 Related reviews of similar data

Several analyses of this or similar data exist in the literature. Carreras et al [2005] and Talukdar et al [2003], among others, show that the size distribution for large blackouts falls with a power law tail. Carreras et al [2005] argues that this and other properties of the transmission system indicate the existence of self organized criticality in the nature of power networks. Weron and Simonsen [2005/6] question the appropriateness of applying self-orgainized criticality models to the US data set, but confirm the existence of a fatter-than exponential tail in the distribution. Figures 2.5 and 2.6 show the size distributions for the complete 1984-2005 data set. As in Talukdar et al [2003] we fit all blackouts of size 500 MW and larger to the standard power law inverse cumulative distribution function ($cumulative\ density = multiplier \cdot size^{slope}$). We find a fairly good power-law fit with a slope of -1.13. This essentially confirms the results of the above studies.

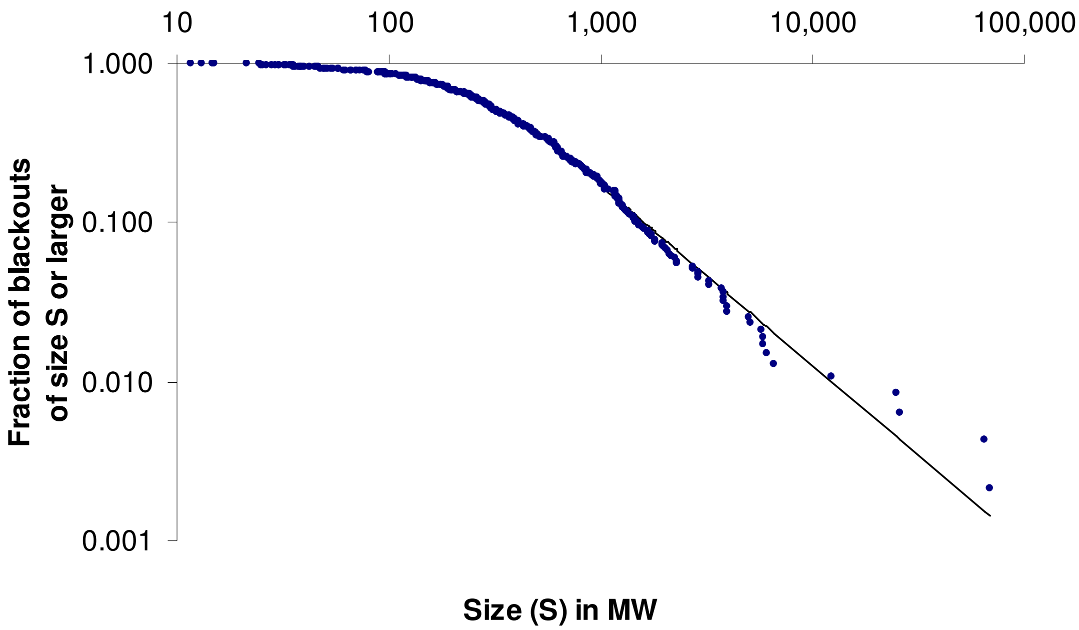

Figure 2.5 – Inverse cumulative density function (1-CDF) for blackout sizes in our data set. Size here is measured in year-2000 MW. The solid line indicates the power-law fit for blackouts 500 MW or larger.

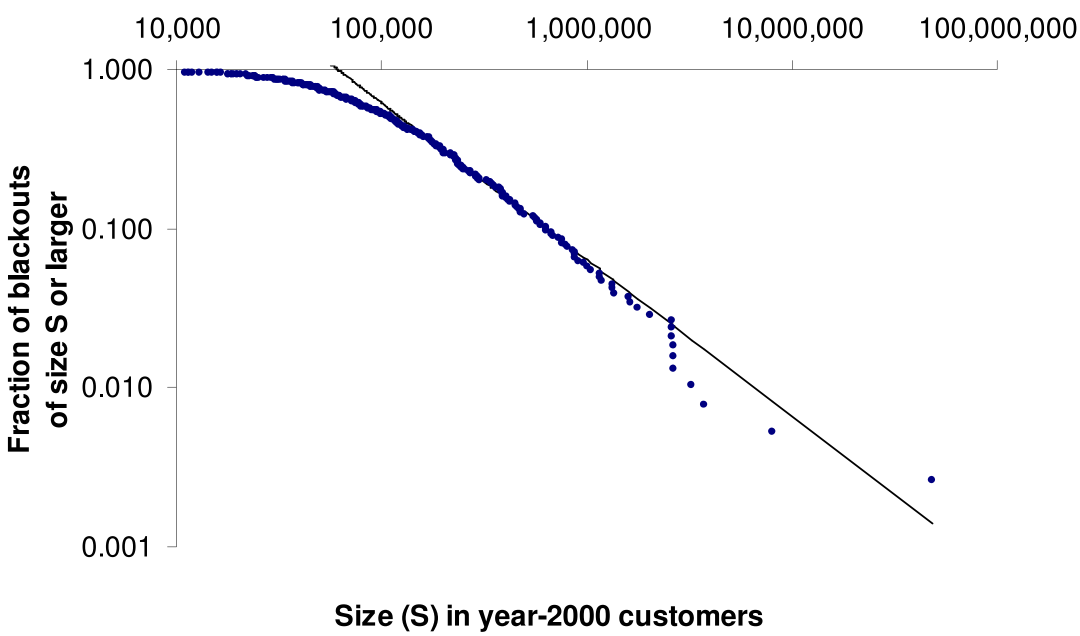

Figure 2.6 – Inverse cumulative density function (1-CDF) for blackout sizes in our data set. Size is measured in year-2000 customers. The solid line indicates the power-law fit for blackouts 384,000 customers (500 MW * 768 customers/MW) or larger.

3 Data analysis

As mentioned previously, we seek to confirm or reject the hypothesis that the frequency of large blackouts in the United States is decreasing with time. We use two measures to test this hypothesis. A correlation test gives the sign and significance of the relationship between years and frequency. A Kruskall-Wallis (KW) non-parametric t-test allows one to find the direction and significance of difference between the distributions in subsets of data. We use the KW t-test because it avoids the Gaussian distribution assumptions underlying standard t-tests. For the KW test we divide the data as pre and post 1998. 1998 was chosen because of significant changes occurring at this time in the US electricity system. The New York ISO opened in 1997, and the California ISO opened in 1998, representing important, nation-wide changes in electricity trading mechanisms. 1996 marked the 3 large blackouts in the western US providing some motivation for electric system operators to revisit their operating policies.

Each of the above tests was run for several different event size categories. Tables 3.1 and 3.2 give the complete data and statistics.

Table 3.1 – Event frequencies and statistics with sizes measured in year-2000 customers. Statistics exclude data from years 1998, 2004, and 2005.

Number of events of size S or larger. Size measured in year-2000 customers

year	1	10	100	1,000	10,000	100,000	1,000,000
1984	16	16	15	15	15	10	2
1985	18	18	17	17	16	10	1
1986	10	10	10	9	9	5	0
1987	12	12	11	10	10	3	0
1988	14	14	14	14	13	11	6
1989	12	11	10	10	10	3	0
1990	20	18	17	16	15	5	0
1991	17	16	16	15	15	8	1
1992	7	7	7	7	7	4	0
1993	8	8	7	7	6	2	0
1994	6	6	6	6	6	4	1
1995	7	6	5	5	4	2	0
1996	13	13	13	13	12	5	2
1997	13	13	13	13	11	5	1
1998	2	2	2	2	2	2	0
1999	17	15	14	14	13	9	0
2000	30	27	27	27	27	13	1
2001	31	31	31	31	29	19	0
2002	27	26	26	25	24	11	1
2003	23	21	21	21	19	8	1
2004	70	70	70	69	68	40	4
2005	36	36	36	36	36	22	1
total	**303**	**290**	**282**	**277**	**263**	**139**	**17**
statistics							
Mean 84-97	12.36	12.00	11.50	11.21	10.64	5.50	1.00
Mean 98-03	21.67	20.33	20.17	20.00	19.00	10.33	0.50
P - K-W t-test	0.0026	0.004	0.0047	0.0047	0.0046	0.009	0.9198
Corr coef	0.511	0.4797	0.5005	0.5161	0.4765	0.3322	-0.1678
P - corr. coef.	0.0254	0.0377	0.0291	0.0237	0.0392	0.1646	0.4922

Table 2.2 – Event frequencies and statistics with sizes measured in year-2000 MW. Statistics exclude data from years 1998, 2004, and 2005.

Number of events of size S or larger. Size measured in year-2000 MW

Year	1	10	100	1000	10000 <– S
1984	18	18	15	7	1
1985	23	23	23	4	0
1986	12	12	10	2	0
1987	20	20	19	3	0
1988	17	17	14	3	1
1989	25	25	21	4	1
1990	21	21	19	4	0
1991	15	14	13	4	0
1992	10	10	10	1	0
1993	14	14	10	2	0
1994	13	13	12	3	0
1995	14	13	10	4	0
1996	18	18	16	5	0
1997	19	17	14	3	0
1998	2	2	2	0	0
1999	23	23	18	5	0
2000	22	22	17	3	0
2001	28	28	27	6	0
2002	28	28	20	4	0
2003	26	26	22	5	2
2004	71	70	60	12	0
2005	35	35	29	1	0
statistics					
Mean 84-97	17.07	16.79	14.71	3.50	0.21
Mean 98-04	28.57	28.43	23.71	5.00	0.29
P - K-W t-test	0.043	0.0428	0.159	0.3755	0.9528
Corr coef	0.2544	0.2435	0.1271	0.0435	-0.0081
P - corr. coef.	0.2792	0.301	0.5932	0.8554	0.973

From the customer event frequency data and statistics we see a significant positive correlation between years and event frequency for all but the largest event categories. For events 1000 MW or larger the correlation coefficient is +0.52, with P=0.02. Thus we can conclude with more than 98% certainty that the frequency of large events (measured in number of customers affected) is not decreasing. The KW test similarly indicates that the blackout frequency is significantly greater in the second period (1998-2003) compared to the first (1984-1997). Thus we can again conclude with certainty that the blackout frequency has not decreased after 1998.

The MW event frequency data tells a similar, though slightly less convincing, story. The correlation test gives a weak positive correlation for most size categories. We cannot therefore conclude that there is a significant increase in the frequency with this measure, but must also reject the hypothesis that there a measurable decrease exists. The KW test similarly shows no significant decreases, and a significant increase in the frequency of events greater than or equal to 10MW.

Therefore we can safely conclude that the frequency of large blackouts is not decreasing, and that there is at least some evidence that the frequency has significantly increased in recent years.

4 The causes and prevention of large blackouts

There are 529 events in the NERC DAWG database from 1984-2000 for which a cause was identified. Figure 4.1 shows the breakdown of causes for these largely transmission-related events. These causes indicate the initiating event, but in many cases the blackout size increased through a sequence of dependent failures–a cascading failure.

It is difficult to isolate the cascading failures without detailed information about each event.

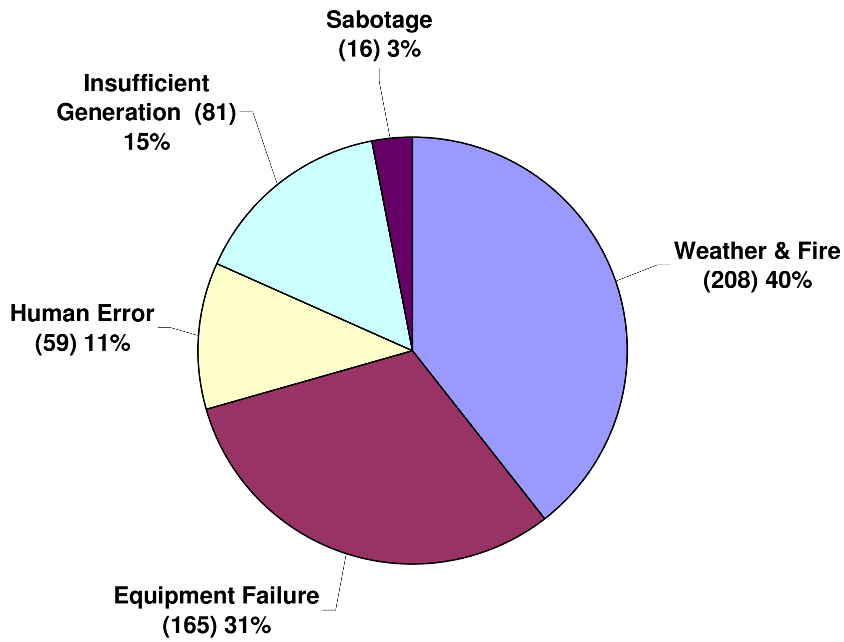

Figure 4.1 – The causes of the 529 disturbances recorded in the NERC DAWG database between the years 1984 and 2000.

While it is clear that the frequency of large blackouts is not decreasing, it is difficult to identify a clear explanation for this result. Thus, this section discusses several potential explanations.

One commonly espoused explanation is a lack of transmission system investment in recent years. The national transmission grid study [Abraham, 2002] notes that the frequency of transmission loading relief (TLR) events–a measure of system stress–has increased simultaneously as the level of transmission system investment has decreased [Abe, 2002]. Hirst [2004] demonstrates that the quantity of available transmission has over the period (1999 – 2002) has steadily decreased when normalized by summer peak demand. On the other hand, perhaps due to the attention that this issue has received, actual transmission investment has increased fairly steadily since 1999 [Hirst, 2004].

Another frequently cited explanation is the lack of mandatory, enforceable reliability rules for transmission system owners and operators. The Energy Policy Act of 2005, with its requirement that the Federal Energy Regulatory Commission (FERC) establish an Electricity Reliability Organization (ERO) with the authority to establish and enforce such rules, may help in this regard. The effectiveness of this policy will likely depend on the extent to which the ERO is isolated from industry pressure, and can verify and enforce compliance, without negative repercussions.

A few common themes have emerged in investigations of the 2003 and earlier blackouts:

- Monitoring of the power grid is sparse, and even these limited data are not shared among power companies.
- Operators are not trained routinely with realistic simulations that would enable them to practice dealing with the precursors to cascading failures and the management of large-scale emergencies.
- Power companies have widely varying levels of equipment, data, and training. Some companies can interrupt power to customers quickly during an emergency, whereas others are nearly helpless.
- Decades-old recommendations to display data in a form that makes it easy to see the extent of a problem have been ignored. This was a contributing cause of the 1982 West Coast blackout, where "…the volume and format in which data were displayed to operators made it difficult to assess the extent of the disturbance and what corrective action should be taken."
- Monitoring of the power system is everywhere inadequate, both within regions and between them.

Very few of theses themes have been thoroughly addressed in the literature. It has been argued [Apt 2004] that grid operations can be significantly improved by:

1. National power flow telemetry and data system standards;
2. Realistic simulation training;
3. National standards for control center control capability;
4. Periodic checks of sensors and load shedding devices;
5. National standards for transmission system maintenance; and
6. A permanent professional accident investigation board, independent of the grid operators or regulators.

Finally, it is possible, though unlikely, that reporting has increased in recent years thereby masking an actual decrease in blackout frequency.

4.1 Cascading failures and the existing protection strategy

Cascading failures are a side effect of the existing protection strategy. This strategy is to de-energize (switch off) each and every device that develops overstresses, such as exceedingly high or low currents or voltages. A disturbance, such as a short circuit, often produces overstresses in the devices close to the disturbance. De-energizing these devices eliminates these overstresses. But sometimes, the de-energizations produce overstresses in other parts of the network. When this happens, a cascading failure is underway. Cascading failures, and the associated blackouts, are fine if one doesn't care about their costs. But if one does care, then one should seek ways to eliminate overstresses without producing more overstresses. How can this be done?

Let

t	be time
D	be a disturbance that occurs at t = 0
X(t)	be a real vector of node voltages and branch currents at time $t \geq 0$
U(t)	be a binary vector of switch positions at time $t \geq 0$.(A "1" in this vector denotes a closed switch, a "0" denotes an open switch.)
c(X(t), U(t))	be the societal cost of X and U

$S(X(t))$	be a vector of the overloads, overstresses and out-of-range values produced by X
$\Omega(t)$	be the protection goal. As long as $S(X(t)) \leq \Omega(t)$, no harm will come to the devices in the network
$\vartheta(.)$	be the response of the system, that is: $X(t) = \vartheta(X(0), D, U(t))$

P, the Protection Problem

Find U(t) such that:

$$S(X(t)) \leq \Omega(t) \qquad (1)$$

$$X(t) = \vartheta(X(0), D, U(t)) \qquad (2)$$

Existing protection systems solve this problem by measuring X(t), calculating S(X(t)), and quickly de-energizing every device where (1) is violated. This is a perfectly good solution, if, as mentioned earlier, one doesn't care about de-energizations that precipitate cascading failures. But if one does care, then the problem should be formulated as follows.

P&C, the Protection and Cascading-failure-control problem

$$\underset{U(t)}{\text{Minimize}}\ c(X(t), U(t))$$

$$\text{St:} \quad S(X(t)) \leq \Omega(t)$$

$$X(t) = \vartheta(X(0), D, U(t))$$

Many solutions to cascading failures have been proposed, without any regard for the specifics of the problem. These solutions, when implemented, have probably been ineffective. Some solutions, such as RASs and SPSs have probably been more effective, but they certainly haven't been shown to be optimal.

If we want optimal or near-optimal solutions, we will have to address problem P&C directly.

5 Conclusions

The frequency of large blackouts, and apparently cascading failures, in the United States is not decreasing. Engineers and policy makers have implemented numerous proposed solutions to this problem, but the effect of such changes in not evident in the data. In fact, there is some evidence that the frequency of large blackouts is increasing. The electricity industry is not winning the fight against large blackouts, and there is some evidence that it may be losing.

We suggest several explanations for this observation. First, investment in transmission infrastructure has significantly decreased in recent years. In many cases, adding transmission is most difficult in areas of the country where solutions are most needed [Vaijhala, 2003], therefore a large increase in transmission construction in the near future seems unlikely. Second, reliability rules in the United States during the period in question, were neither uniform, nor enforceable. Third, systemic operational issues have not been systematically addressed.

Finally, the protection system design frequently causes cascading failures, rather than controlling them. Essentially, this is the result of poor problem formulation. We therefore suggest that the problem be solved by looking at the system-wide costs, rather than only the local costs, as what should be protected. It may turn out, for example, that burning out a transmission line gives enough time to shed load and prevent a cascade which would otherwise have been triggered when a relay opened to protect the line.

References

Anderson, P. M. and K. K. LeReverend. "Industry Experience with Special Protection Schemes." *IEEE Transactions on Power Systems*, v. 11, no. 3. 1996.

Apt, J., L. B. Lave, S. Talukdar, M. G. Morgan, and M. Ilic. "Electrical Blackouts: A Systemic Problem." *Issues in Science and Technology*. Summer 2004.

Benjamin A. Carreras, David E. Newman, Ian Dobson, IEEE, and A. Bruce Poole. "Evidence for Self-Organized Criticality in a Time Series of Electric Power System Blackouts." *IEEE Transactions on Circuits and Systems–I: Regular Papers,* v. 51, no. 9. Sept. 2004.

Fink, L. H. and K. Carlsen. "Operating under Stress and Strain." *IEEE Spectrum*: Mar. 1978.

Friedlander, Gordon. "What went wrong VIII: The Great Blackout of '65." *IEEE Spectrum*. Feb. 1966. pp.83-86.

Hirst, Erik. "U.S. Transmission Capacity: Present Status and Future Prospects." Edison Electric Institute report. August 2004.

Ilic, Marija, Erik H. Allen, Jeffery W. Chapman, Charles A. King, Jeffery H. Lang, and Eugene Litvinov. "Preventing Future Blackouts by Means of Enhanced Electric Power Systems Control: From Complexity to Order." *Proceedings of the IEEE*, v. 93, no. 11. Nov. 2005.

Makoarov, Yuri, Viktor Reshetov, Vladimir Stroev, and Nikolai Voropai. "Blakcout Prevention in the United States, Europe, and Russia." *Proceedings of the IEEE*, v. 93, no. 11. Nov. 2005.

NERC Disturbance Analysis Working Group. "DAWG Meeting Agenda - October 26, 2004 (Chicago, IL)." Oct. 14, 2004. Online: http://www.nerc.com/~filez/dawg.html.

NERC Disturbance Analysis Working Group. "DAWG Database." Online: http://www.nerc.com/~dawg/.

O'Leary, Henry. "The Electric Power Outages in the Western United States, July 2-3, 1996." U.S. Dept. of Energy. Aug. 2, 1996.

Talukdar, S. N., J. Apt, M. Ilic, L. B. Lave, and M. G. Morgan. "Cascading failures: Survival versus Prevention." *The Electricity Journal.* Nov. 2003.

U.S. Department of Energy. Federal Energy Regulatory Commission. June 1978. "The Con Edison Power Failure of July 13 and 14, 1977." Washington, DC: U.S. Government Printing Office.

U.S. Dept. of Energy, Energy Information Agency. "Electric Power Monthly [various months]–Appendix: Major Disturbances and Unusual Occurrences." Online: http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html.

U.S. Federal Power Commission. "Prevention of Power Failures, v. I-III." Washington, DC: US Government Printing Office, June-July, 1967.

U.S. Federal Power Commission. 6 December 1965. "Northeast Power Failure: November 9 and 10, 1965." Washington, DC: U.S. Government Printing Office.

U.S.-Canada Power System Outage Task Force. "Final Report on the August 14, 2003 Blackout in the United States and Canada." April 2004.

Vaijhala, Shalini. "Transmission Line Siting: A Quantitative Analysis of Transmission Demand and Siting Difficulty." Carnegie Mellon University Electricity Industry Center working paper (CEIC 03-06). 2003. Online: www.cmu.edu/ceic.

Weron, Rafal and and Ingve Simonsen. "Blackouts, risk, and fat-tailed distributions." Proceedings of the 3rd Nikkei Econophysics Symposium, Springer-Tokyo, 2005/6.

WSCC Operations Committee. "Western Systems Coordinating Council Disturbance Report." WSCC, Sept. 1996.

Zima, Merek. "Special Protection Schemes in Electric Power Systems: Literature Survey." Zurich: ETH Power Systems Laboratory. July 6, 2002.

Appendix – Detailed description of statistical tests

Centered Correlation (covariance) Coefficient.

Given two random variables, x and y the centered correlation coefficient gives the extent to which y can be predicted from x (or visa-versa). If E[.] is the expected value operator and |.| is the 2 norm, the formal definition of the centered correlation coefficient is:

$$\rho = \frac{E\left[(x-\bar{x})*(y-\bar{y})\right]}{|x||y|}$$

Kruskall – Wallis (KW) t-test

The KW t-test is a two tailed t-test used to compare sets of data that cannot be described using Gaussian probability density functions. It tests the hypothesis that two sets of data come from a distribution with the same median. The p-value gives one the probability that the observed difference in the medians is due to chance rather than a change in the underlying process.