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Theories of Explaining Causes of Large Scale Blackouts*

- Current Literature and a Future Research Framework -

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최근 대정전(large scale blackouts)은 지구적 관심사가 되고 있으며, 한국의 전력산업도 복잡한 송전망구조로 볼 때 한 번 일어나면 파국적인 결과를 초래하는 대정전에 점차로 노출되고 있다. 현재 대정전의 원인을 설명하기 위한 다양한 논의가 진행되고 있다. 본 논문은 이와 같은 다양한 논의를 "기술·경제적인 접근"과 "복잡성 및 네트워크 이론"으로 나누어서 소개하고자 한다. 기술·경제적인 접근은 대정전의 원인을 송전망의 연결구조와 시장설계 방식에서 찾는다면, 복잡성 및 네트워크이론은 대정전이 일어나는 송전망의 물리적 현상을 살펴보고 있다. 하지만 이들 이론은 조직 및 제도적 문제를 간과 하고 있기 때문에 대정전 분석에 있어서 의사결정 구조를 설명하지 못하고 있다. 따라서 본 논문은 "정상사고"이론과 "높은 신뢰성 조직"이론, "신제도주의"이론을 조직 및 제도론적 접근방법으로 제시하여 기존분석의 한계를 보완하고자 한다. 끝으로 본 논문은 위 세 가지 접근방법 - 기술·경제적 접근, 복잡성 및 네트워크 이론, 조직 및 제도론적 접근 - 을 결합하여 다차원적이고 통합적으로 대정전의 원인을 분석하는 틀을 제시하고자 하였다.

주제어: 대정전, 정상사고, 신뢰성 문화, 상징주의, 권력관계

Introduction

Over the past decade, large-scale blackouts have happened repeatedly and globally. In August2003, a cascading failure started in Northern Ohio and spread over the Northeast United States and Ontario, Canada, affecting 50 million people. In September 2003, an electric power blackout hit the whole Italian territory, affecting 56 million Italian people, which was the most serious power outage in Italy in 70 years. In November 2006, an incident originating from the North German transmission grid caused a cascading outage, affecting 15 million European households, particularly in France. In September 2011, the Arizona-Southern California outages

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resulting from the loss of a single 500 kilovolt transmission line left 2.7 million customers without power for up to 12 hours. In fact, large scale blackouts have happened since power systems were interconnected together. 47 years ago, a large scale blackout in the Northeast region of the United States happened, which was the first cascading outage in electricity history. The 1977 New York City blackout, resulting from lightning, was famous for looting and arson, leading to a chaos in the whole city.

Large scale blackouts are periodical incidents that have happened repeatedly in North America and Europe since the power systems were interconnected each other. In general, members of the public have perceived causes of large scale blackouts as technological issues, not social ones, and think that technical recommendations will solve the problems. The community of electricity-related professional organizations and utilities provides solutions to prevent large scale blackout, especially focusing on technological aspects. However, technological solutions do not fundamentally prevent large scale blackouts. Therefore, recently there are many attempts to understand and explain them in different academic disciplines.

Currently South Korea is not free from large scale blackouts, either. As the power systems in Korea become more tightly interconnected each other, we have witnessed harbingers of large scale blackouts. In April 2006, the Jeju Island in Korea was under the darkness for several hours in the whole area. On September 15, 2011, South Korea experienced a rolling blackout due to the power shortage and the failure of forecasting power demand. During the 2012-13 winter season, Korean citizens experienced power shortages which could have developed into a large scale blackout. From these experiences, we need a more comprehensive understanding of large scale blackouts so that we can predict and prevent them in future. However, our vocabularies in understanding the causes of large scale blackouts are very limited. At least, we need to broaden our perspectives on them through a review of the theories developed in the United States and Europe.

Therefore, the purpose of this article is (1) to explore the theories of explaining the causes of large scale blackouts from the perspectives of techno-economics, complex and network theories, and disaster and organization theories; (2) to review the literature related to large scale blackouts in an interdisciplinary manner; (3) and to present a conceptual framework, especially focusing social aspects of large scale blackouts, that outlines the multi-dimensionality of how large scale blackouts are explained in order to help guide future research and policy.

By and large, a few representative explanations about causes of large scale blackouts can be grouped into techno-economic approaches and complexity & network theory approaches. Since they are leading explanations in the engineering literature, I introduce them along with representative large scale blackouts in the United States and Europe - the 1965 Northeast, 1977 New York City, 2003 Northeast, and 2006 European blackouts. However, they are not a framework to look at the social and human factors that organize interconnected power systems and management, and to observe power relations that decide the level at which the sector institutionalizes reliability. Therefore, the paper introduces representative disaster theories which help explain large scale blackouts, so as to develop a conceptual framework of analyzing large scale blackouts.

Techno-Economic Approach

The term, techno-economic approach, comes from a predominant mode of thought that seeks to explain large scale power failure from an economic viewpoint. Techno-economic approaches consist of three arguments: centralized power system(expanding systems), decentralizing system design, and market design and revising rules. Those who talk about centralized and power system, and market design and revising rules insist on strengthening and expanding transmission systems(Friedlander, 1966; Cook, 1967; Metz, 1977; Change, 2003; Gellings and Yeager, 2004; Joskow, 2003). In contrast, those who prefer decentralizing system design argue that distributed power systems have more diverse and redundant options in preventing large scale blackouts (Lovins and Lovins, 1982; Lovins, *et. al*., 2003).

Centralized Power Systems: Expanding Systems

Many experts try to explain blackouts in terms of an interaction of technological events with the market structure. Most reports on large scale blackouts largely deal with technical problems1), and discussions following large scale blackouts are focused on what goes wrong technologically or how the system failure is related to the market structure. In particular, among many technological issues, experts have talked primarily about design issues related to insufficient transmission lines to absorb shocks in the system(Joskow, 2003; Seppa, 2003; Casazza, *et. al*., 2005). Therefore, one of the solutions is to strengthen the transmission network by expanding, modernizing, and

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1) Report to the President by the Federal Commission on the Power Failure in the Northeast United States and the Province of Ontario on November 9-10, 1965(Federal Power Commission, 1965); Prevention of Power Failure volume I, II, and III(Federal Power Commission 1967); The Con Edison Power Failure of July 13 and 14, 1977(U.S. Department of Energy(DOE) and Federal Energy Regulatory Commission (FERC) 1977); Western System Coordinating Council Disturbance Report For the Power System Outage that Occurred on the Western Interconnection(WECC, 1996); Interim Report: Causes of the August 14th Blackout in the United States and Canada(U&C TF, 2003); Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendation(U&C TF, 2004); Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn?(the NERC Steering Group 2004); ECAR Investigation of August 14, 2003 Blackout(ECAR Major System Disturbance Analysis Task Force 2004); Blackout 2003 - Performance of the New England and Maritimes Power Systems During the August 14, 2003 Blackout(Independent System Operator New England(ISO NE), 2004); and Interim Report on the August 14, 2003 Blackout(New York ISO, 2004).

centralizing it.[2]

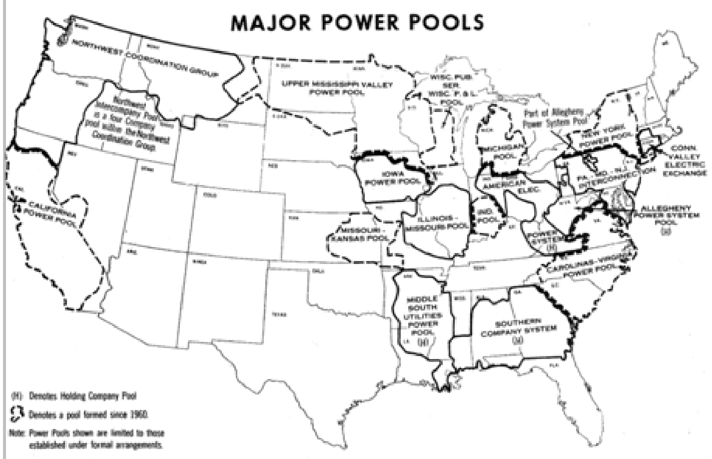

FIGURE 12

<Figure 1> Major Power Pools in the Mid 1960s

※ Source: FPC, 1967a.

After the 1965 blackout, the majority of experts were in favor of strengthening transmission lines(Friedlander, 1966). Since World War II, high-voltage transmission lines had been linked each other so as to integrate local power plants into bulk power systems. In particular, as Figure 1 shows, the Mid and Northeast power pools - Maine(Northeast interconnection), the Michigan pool, Ontario, and PJM - were interconnected by 1962(Brand, 1966; Priest, 1967). At the time, experts thought that the capacity of the transmission lines was not enough to prevent cascading outages because integration was underway and the transmission systems were not yet fully integrated (Friedlander, 1966). They argued that even small systems should be fully integrated into the bulk power system to minimize the cost of generation(Cook, 1967). Thus, they believed that to construct transmission infrastructure as planned would improve reliability.[3] As a result of the interconnection of transmission lines, some concepts were developed; the organization of the market - power pools - became a boundary within which to manage integrated transmission

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[2] Strengthening transmission systems usually refers to upgrading existing grid systems or constructing new lines. This also includes other control equipment, such as protective relays, circuit breakers, capacitors, etc.

[3] A spokesman of AEP believed that "the industry can design power supply systems to prevent widespread blackout, if the various major system components, comprising generating plants, transmission lines, and interconnections with neighboring systems, are planned as an integrated whole, with proper consideration given to their interrelated effects." Friedlander, G. D.(1968). Prevention of Power Failure - The FPC Report of 1967. IEEE Spectrum. February: 53-61.

systems; and coordination among utilities or power pools was also a basic principle for improving reliability, which led to the establishment of the North America Electric Reliability Council(NERC, Now North America Electric Reliability Corporation).

After the 1977 blackout in New York City, many engineers still believed that the existing interconnections were insufficient to maintain the systems in the city(Metz 1977). In its interim report, the Federal Power Commission(FPC, Now Federal Energy Regulatory Commission: FERC) states that the Con Edison's interconnections with the neighboring utilities, Public Service Electric & Gas Co and Long Island Lighting Co, were not strong enough to respond to the emergency(EW 1977; EW 1977). Boffey(1978) also pointed to the basic problems of physical constraints due to the weak interconnection between utilities which only had transmission lines from the north to Manhattan, and lacked connections to east and west.

Before and after the 2003 blackout, experts warned that transmission lines should be modernized because existing transmission lines, many of which were constructed more than 50 years ago, are too old to sustain high reliability(Chang 2003; Firestone and Revkin, 2003; Gellings and Yeager, 2004). They point out the fact that the investment in transmission lines has declined since the introduction of deregulation, because it does not guarantee profits for transmission system owners (Firestone and Revkin, 2003). Joskow(2003), who advocates deregulation, draws attention to the mismatch among organization, management, regulation, and physical infrastructure because of the poorly designed market. He argues that the federal(central) government should be given primary regulatory jurisdiction over transmission lines to promote investment in them. Therefore, they support the expansion of transmission lines whose capacity is currently short due to low investment.

After the 1965 and 1977 blackouts, as discussed above, experts said that interconnections were too scarce to support each power pool in times of emergency. After the 2003 blackout, experts argued that transmission lines are antiquated and weak in the era of deregulation. Their arguments are relevant in each time. Considering several large scale blackouts that happened between 1965 and 2003, however, we have witnessed that extending and integrating transmission systems are not fundamental solutions to those blackouts. The following view point contrasts with the belief that transmission lines should be added and strengthened.

Decentralizing System Design

The expansion of transmission lines is viewed skeptically by those who raise questions about the current centralized architecture of the power system(NYT 1965; Lovins and Lovins, 1982; Lovins, Datta et al. 2003). Amory Lovins advocates for decentralized power systems rather than centralized ones in the electricity industry. He points out some attributes of the structure of current energy systems: centralization of supplies, long haul distances, limited substitutability, continuity and synchronism in grids, specialized labor and control requirements, and potential for misuse of energy distribution systems(Lovins and Lovins, 1982). “As the interconnected electric energy systems become more tightly interconnected over larger regions, systems problems are emerging which neither are presaged, predicted, or addressed by classical electrical engineering and which are no longer amenable to ad hoc solution”(Lovins and Lovins, 1982: 138). Therefore, he argues that we cannot predict a large scale power failure due to the complexity of the transmission network and unpredictable interactions within the system. Lovins indicates that the 1965 Northeast blackout and the 1977 New York blackout are representative consequences of the current energy structure. To avoid the brittleness of centralized systems, he seeks alternative ways; more dispersed, diverse, local, and redundant modules. He suggests a decentralized electricity supply with newly developed technologies and small-scale renewable sources, which, he argues, not only prevent large scale blackouts, but also improve energy efficiency.

They perceive cascading outages as a result of the highly interconnected transmission lines that connect current centralized power systems from Canada to Florida. Lovins's argument, however, does not discuss advantages of the current transmission systems which are based on such principles as economies of scale, universal systems, load diversity, and load factor. The electricity industry has grown with the fact that the integration of the transmission network is a way to improve reliability as well as efficiency. If one generator in an area is out of service due to its maintenance schedule, other generators in another area can supply power through transmission lines thereby keeping current. These advantages of centralized power supply systems are real and important. But Amory Lovins argues that district heating and industrial cogeneration have more economic advantages than a centralized power system, considering construction time, thermal efficiency, reserve margin, and the costs of construction, delivery and operation(Lovins and Lovins, 1982). He also argues that a system that includes many small scale power plants is more reliable because they might not fail simultaneously compared to just a system with a few large nuclear power plants.

Admittedly, both arguments, centralized and decentralized power systems, have their own valid explanation about technological problems of a cascading outage although they have some deficiencies in suggesting more relevant solutions. Strengthening transmission systems in centralized systems remains a question of how many transmission lines are enough. Amory Lovins's argument for decentralizing power systems is a radical approach to the solution of cascades, leaving open the question of how to deal with current centralized power systems. While physical designs have been a recurrent factor in large scale blackouts since the 1965 blackout, revising current reliability standards and setting new ones are recent issues with the introduction of deregulation in the competitive electricity market.

Market Design and Revising Rules

Joskow(2003) and Hogan(2004), who actually designed competitive electricity markets, diagnose inconsistency of market design with transmission networks as a key cause of the 2003 Northeast blackout. As mentioned earlier, Joskow argues for strong transmission systems. He tries to find an answer from a well-designed market with ‘performance based regulatory mechanisms’ to encourage utilities’ investment in transmission systems(Joskow, 2003). Joskow agrees with expanding transmission lines to a certain degree to meet the market demand, and insists on giving more power to the federal(central) government. Although he mentions a variety of problems of mismatch among organization, management, regulation and physical infrastructure including monitoring, communication, and control capabilities, his discussion focuses on the market design(Joskow, 2005). As a result, his argument is, to some extent, simplified in explaining reasons for large scale blackouts.

Hogan perceives the problem to be that the centralized, vertically integrated power systems are designed for the market of natural monopoly, not for the competitive market. He points out an issue with highly interconnected and interdependent transmission lines with too many control areas in the United States, which might result in more blackouts(Hogan, 2003). If the transmission lines are more interconnected, they can easily absorb lots of little shocks, but ultimately they will provide a better chance of a large power failure spreading over the network(Nadis, 2004). Thus the only way, he says, is to mitigate the consequences of large scale power failure by implementing policies for nationwide power management. Hence he draws attention to the role of Federal Energy Regulatory Commission(FERC) in providing good reliability standards and market design simultaneously(Hogan 2004). He insists on the additional role of the federal(central) government to design efficient and consistent rules to the extent that the government intervention does not overrun the market(Hogan, 2006). Because Joskow and Hogan focus on the market design, they overlook how institutions for reliability should be rearranged, how utilities, more specifically control centers of individual utilities, could reorganize their behavior in order to make electricity reliability work under deregulation, and how the federal(central) government’s regulatory power can be linked to the industry’s reliability institutions.

Expanding transmission lines is criticized by Kirschen and Strbac(2003) who raise a question of improving the reliability in the existing rules, particularly the N-1 criterion.[4] Following the 2003 blackout, Kirschen and Strbac argue that upgrading the transmission network will improve the security of the system in the short run, but consequently confront another capacity problem due to the increased power transfers from regions with cheap energy resources to others under the competitive electricity market(Kirschen and Strbac, 2003). The increased power transaction and stress on the transmission network may augment the probability of blackouts, especially under deregulation, and thus deterministic security rules, such as the N-1criterion, may not be adequate

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[4] According to N-1 Criterion, an electrical system should work properly and maintain its stability although it loses any one component of its N components.

any more(Kirschen and Strbac, 2003). To reduce probability of blackouts, they suggest introducing new rules, such as probabilistic criteria, that reflect quantify risk of large scale blackouts. Although Kirschen and Strbac discuss the problem of highly connected transmission lines, they do not explicitly mention how to reshape the physical structure of centralized and interconnected power systems. They try to find solutions in the market design and alternative policies, particularly reviewing the level of security rules - the N-1 criterion.

In sum, the above viewpoints try to explain causes of recent large scale blackouts from the perspective of an incomplete market design in the process of deregulation. They are interested in setting the game rules - market design - including new policies for reliability. In addition to the rules, Joskow and Hogan emphasize the role of the federal(central) government as an umpire to make electric utilities comply with rules for reliability without hurting market efficiency. Because their focus is on the economic behavior of utilities, as discussed above, they do not critically deal with other reliability-related issues, such as monitoring systems, communication, decision making processes for coordination among control centers, system operators' training, and the effects of institutional settings on system operators with respect to the role of the federal(central) government and other reliability institutions. Overall, their arguments do not take into account the physical and institutional environment of rule-making processes and the behavior of key players - usually system operators and electrical engineers - who interact with reliability standards.

Complexity and Network Approach

The second popular explanation for blackouts is to observe the cascading outage itself as a physical phenomenon independent of the social organization of technological events. An initial small variation, like 'the butterfly effect,' becomes a large event due to the integration of local electrical systems into bulk power systems through high-voltage transmission lines. This explanation is derived from two dominant theories - self-organized criticality and highly optimized tolerance in explaining complexity - in physics(Bak, Tang et al. 1988; Carlson and Doyle, 1999; Sachtjen, Carreras et al. 2000; Carlson and Doyle, 2002; Carreras, Lynch et al. 2002; Dobson, Newman et al. 2002; Carreras, Newman et al. 2004; Dobson, Carreras et al. 2004; Nedic, Dobson et al. 2005; Newman, Carreras et al. 2011), and from small world phenomena in Milgram's network theory(Watts and Strogatz 1998; Watts 1999; Newman, Strogatz et al. 2001; Strogatz 2001; Watts 2002).

Complexity and Cascades

Bak et al. criticize those who try to predict the performance of large interactive systems by analyzing elements separately. Then they introduce a concept of self-organized criticality(SOC) which explains the behavior of spatially extended dynamic systems(Bak, Tang et al. 1988; Bak and Chen, 1991). They pay attention to the generic properties of naturally occurring dynamical systems. Drawing on phenomena in natural ecosystems, they state that all systems with interdependent subsystems having degrees of freedom evolve to the self-organized critical point at which they sustain their stability. They depict it as follows;

> …Ecological systems are organized such that the different species “support” each other in a way which cannot be understood by studying the individual constituents in isolation. The same interdependence of species also makes the ecosystem very susceptible to small changes or “noise.” However, the system cannot be too sensitive since then it could not have evolved into its present state in the first place. Owing to this balance we may say that such a system is “critical.”(Bak, Tang et al. 1988: 364)

If there is a microscopic variation, a large interactive system has a higher than expected probability to collapse due to its self-organized criticality which is a function of its vulnerability to small changes. Then the impact spreads over the system in the form of chain reaction until it finds its equilibrium at another critical point at a lower level. These phenomena can be found in avalanches, forest fires, breakdown of stock exchange price indices, etc. They argue that “this self-organized criticality is the common underlying mechanism behind the [catastrophic] phenomena”(Bak, Tang et al. 1988: 365).

Carreras, Lynch, and Dobson apply the above argument to a designed system - transmission networks. The Carreras-Lynch-Dobson group thinks that there are the same principles working as those in natural catastrophes behind the phenomena of chain reaction trips in power transmission systems due to the complex interconnection among substations and power plants. They display a graph of the probability distribution function of power grid failure which shows that the size of blackouts is randomly distributed and that the graph has a power law scaling(Dobson, Newman et al. 2002). Figure 2 is a display of the cumulative probability distribution by size - loss of load. The probability of blackouts decreases as the size of blackouts increases, but does not disappear. Because of the power law tail,[5] large scale blackouts have more probability to happen than they might be expected(Dobson, Newman et al. 2002; Fairely 2004 cited again). They find that interconnected power systems are operating almost at a critical point where power failures are inevitable.

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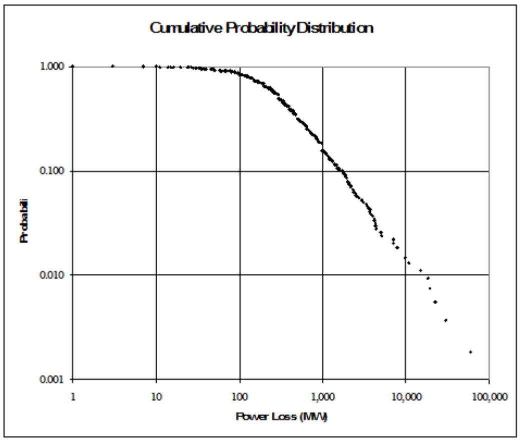
[5] The power tail law refers to the probability on the right side tail in the probability distribution function which is thicker than expected. The power law tail is represented in terms of $p(x) = 1/x^{\alpha}$, where α is a positive number. According to this distribution, “the probability of a blackout is related to its magnitude by some constant exponent” Fairely, P.(2004). The Unruly Power Grid. IEEE Spectrum. August: 22-27.



<Figure 2> Cumulative Probability Distribution of North America Power Disturbance[6)]

※ Sources: NERC(1984-2002); DOE(2003-2005.11).

Doyle and Carlson have also studied the vulnerability of transmission systems(Carlson and Doyle, 1999; Carlson and Doyle, 2002). They introduce a concept of highly optimized tolerance(HOT) that contrasts with SOC in its depictions of the characteristics of complexity. HOT draws more attention to highly structured, heterogeneous, internal configurations of the systems, while SOC emphasizes internally generic, homogeneous configurations among the systems. They also describe features - "robust, yet fragile" - of high complex systems which are different from SOC. When confronting some emergencies, modern technological systems such as the central processing unit(CPU) and the Boeing 777, which are designed to respond to various predictable variations, usually work properly without losing their functions, and thus are robust to uncertainty in their environment; yet they are fragile because "this complexity can amplify small perturbations"(Carlson and Doyle 2002: 2539). Therefore, they also argue that there is a power law distribution in complex systems, which means that there are rare but unanticipated cascading failures even in highly structured systems(Figure 2). Doyle argues that engineers may prevent small disturbances with given resource allocations according to a highly optimized tolerance model, but cannot avoid large scale blackouts due to the complexity of grid design. Hence, Doyle says, "I don't think there are simple policy fixes"(Fairely 2004: 22). Further, Doyle's curve predicts that a large power failure happens periodically - one event every 35 years, which, conveniently, almost

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6) The probability distribution function by the size of power loss depends on the number of observations that researchers use: the probability distribution function in the Carreras-Lynch-Dobson group's graph is a little different from that of the Carnegie Mellon University group, but both of them show $p(x) = 1/x^{\alpha}$ and its cumulative probability distribution is $P(x) = \Phi[\Sigma(1/x^{\alpha})]$. The coefficient of α varies from researcher to researcher due to the different conditions of their experiments; the range by the Carreras-Lynch-Dobson group is from 0.6 to 1.9; and the Carnegie Mellon University group give the range of the coefficient between 1 and 2. What is important is that the distribution has a heavy tail.

equals to the interval of 38 years between the 1965 and 2003 blackouts in the Northeast in the United States(Fairely, 2004).

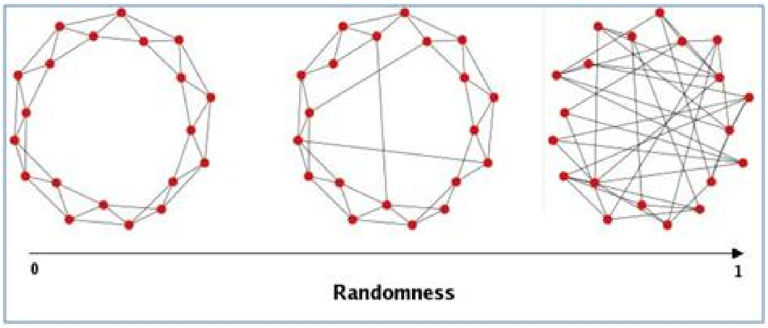
Considering Carreras-Lynch-Dobson group's theory, the Carnegie Mellon group turns their focus toward survival after cascading outages rather than prevention of them(Talukdar, Apt et al. 2003). Because of more than 100,000 devices in a grid system which "can be either 'off' or 'on'", their possible configuration is $2^{100,000}$ which is too large to be dealt with regarding the possibility of all contingencies(Talukdar, Apt et al. 2003: 27). Thus, the focus of their solutions is on how to minimize the social costs of large scale blackouts; identifying socioeconomic missions fulfilled by electric power, determining the critical missions that should be protected even after blackouts, prioritizing the missions, checking weak links in city systems and infrastructures such as domestic but important airports - La Guardia near JFK - requesting new hardware for protection, seeking cost-effective technologies, and making a system for the allocation of resources to achieve these missions(Talukdar, Apt et al. 2003).

In sum, on the basis of complexity theory, the above groups agree that large scale blackouts are inevitable although they have low possibility to occur, and that strengthening transmission lines are not an appropriate solution to them. They want to see the current grid systems in an entirely different way: a holistic approach to the nature of the system rather than viewing each component of the system separately, and think that engineers need to change fundamentally their way of operating grid systems(Fairely, 2004).

Networks, Small-world, and Cascades

Another explanation of the cascades in complex systems comes from network theory focusing on small world phenomena. Strogatz discusses the problem of large scale blackouts(Strogatz, 2003); the question is not how it started, but why it spread so fast and far. At first, Watts and Strogatz explain the 1996 Northwest blackout and the social network of film actors in terms of 'small-world' networks: analogy with Milgram's small-world problem(Watts and Strogatz 1998: 440). Milgram finds that to link two randomly selected individuals, surprisingly there are only five intermediate acquaintances on average between the two(Milgram, 1967); that is called a small world phenomenon. This notion became popular through the Broadway play and later movie Six Degrees of Separation(Guare, 1994; Watts, 1999). Strogatz and Watts, inspired by the idea of Milgram's small-world problem, tried to find general principles in the typology of network systems, such as the diffusion of innovation, electric power grids, the World-Wide Web, citation networks of science, etc(Strogatz, 2001; Watts, 2003).

They describe a specific model of complex systems - the systems are networked and located between completely regular and random in their network typology(Figure 3) - which is different from that of SOC and find that the structure of networks is highly clustered to some nodes locally, yet has small characteristic path lengths through which information or diseases spread more easily(Watts and Strogatz, 1998; Watts, 1999). Additionally Watts introduces a threshold concept on each node to explain the degree of its changing state by its neighbors(Watts, 2002). Each node has a different threshold fraction, keeps its state(either 0 or 1), and is connected to other nodes by edges. The lower a threshold fraction is and the more degrees of connectivity to neighbors there are, the more vulnerable it is to a shock. The threshold fraction and the number of connections are heterogeneous. According to the local dependencies threshold rule, the nodes' state can be affected by their neighbors and then becomes 1, if enough of the node's neighbors change their state from 0 to 1. Watts assumes that the features - local dependencies, fractional thresholds, and heterogeneity - are necessary for the dynamics of cascades and that there is a finite fraction of vulnerable clusters in an infinite network(Watts, 2002). Even with the finite fraction of vulnerable clusters, an initially small seed strikes neighbor nodes and forces them to change their stable state into susceptible state, extending the size of vulnerable clusters. The result is that a global cascade occurs when an initial shock affects the neighboring nodes which have the low thresholds and highly connected nodes, extending vulnerable clusters, which then spread over all networks through small characteristic path lengths. This model can be applied to power grids which are also network systems with nodes(generators, substations) and edges (transmission lines). According to this model, vast and complex grid systems itself have the possibility of cascading outages because of the topology of complex networks.

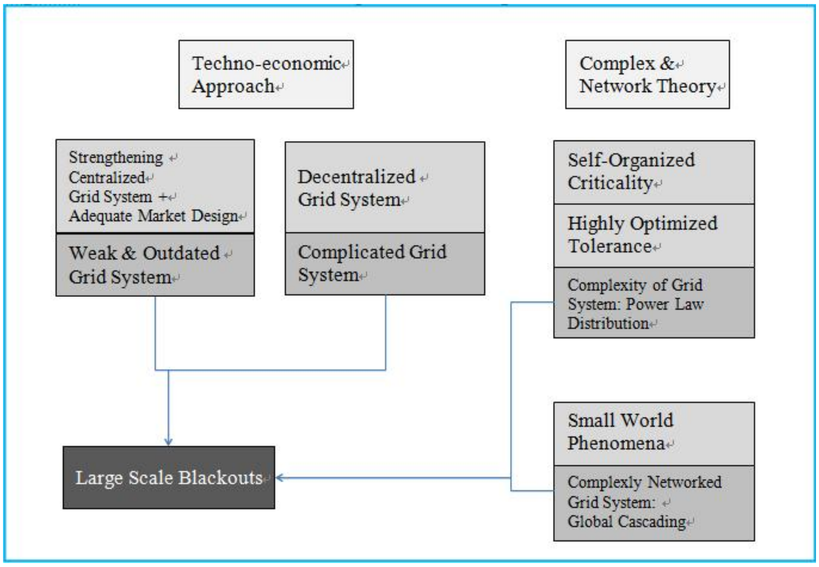


<Figure 3> Progressive transition between regular and random graphs

※ Source: Watts and Strogatz(1998).

In sum, the above three ways of explanations - self-organized criticality, highly optimized tolerance, and small-world phenomena - accept the fact that cascading outages cannot be avoided because of the complexity in transmission systems. In addition, the Carreras-Lynch-Dobson group assumes that economic principles of maximization of return by reducing investment in transmission equipment force engineers to perform their tasks at the higher power levels(Fairely, 2004), thereby making some bad situations worse. In this sense, "Big blackouts are a natural product of the power grid"(Fairely, 2004: 25). The only solution to cascading outages is to fundamentally change systems. However, the groups do not detail what is the fundamental change of the operation which is an organizational issue.

So far, theories of explaining large scale blackouts can be represented in Figure 4. Their focus is usually on the physical structure of electricity in explaining causes of large scale blackouts. Their arguments do not deal with the social construction of technological failure and how to apply their findings to the operations of power grid systems in the historically developed reliability institutions in the United States and Europe. We need to consider interaction between technological systems and social structure. As Thomas Hughes argues, development of electricity cannot be separated from the social contexts in which it is located(Hughes, 1983). A technological failure is a collapse of a socio-technical system, neither exclusively attributable to purely technical nor purely human factors(Reason, 1990). On the basis of these perceptions, it will be helpful to construct a framework that is a combination of the different theories in different disciplines when we analyze internal and external conditions of technological failure.



<Figure 4> Location of Theories in the Explanation of Large Scale Blackouts

Social Theories of Technological Disaster

Studies on Unintended Disasters in Social Science

A starting point for explaining the causes of cascading outages is that they are social phenomena constructed by society. Bijker, *et. al.*(1987) state that the construction of scientific knowledge is a social rather than epistemological task(Pinch and Bijker, 1984: 401). Scientific findings and technological artifacts are not free from the social conditions of those who research natural phenomena and invent artifacts. Generally, private organizations and the government decide whether to adopt particular technologies(Perrow, 2002). In the electricity industry, Hughes(1983: 2) argues that "electric power systems embody the physical, intellectual, and symbolic resources of the society that constructs them." Although it is true that the engineers control interconnected power systems according to the law of physics, it is also true that decisions on particular technologies and management of grid systems are affected by the interaction of private organizations and governmental institutions.[7] In this view, technological failure is products of how society manages technological artifacts.

Some examples of how social conditions influence scientific uncertainties and technological failures are found in the works of Clarke(1989) and Vaughan(1996). They discuss the social construction of uncertainty, which results in technological failure, between and within organizations, and how the uncertainty is accepted in society. Clarke explains how risk assessment is constructed in organizational contexts, as he explores the organizational response to an accident at the Binghamton State Office Building, the inside of which was contaminated by toxic chemicals – dibenzofurans and naphthalenes – as a result of high heat and fire(Clarke, 1989). He concludes that relative power between organizations decides the acceptable risk rather than scientific judgment. In contrast to the relative power, Vaughan(1996) pays more attention to cultural factors in socially accepting uncertainties, using other scholars' analytical tools – core-set[8](Collins 1981), trading zones[9](Galison, 1997; Vaughan, 1999), the experimenters' regress[10](Collins, 1985), epistemic culture[11](Cetina, 1999), and flexible interpretation(Pinch and Bijker, 1984) – to explain the

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[7] The configuration of power systems as a result of various social conditions, however, does not overlook the effect of electric power systems on social change. David Nye explores how electrification has shaped American society and landscapes(Nye, 1990).

[8] Core-set refers to a few scientists who are actively involved in experimentation or observation, or contribute to the theory of the phenomenon. Here 'set' means a group of people who share similar interests. And these scientists, whether proponents or opponents, when involved in the controversy over a scientific finding, tend to resolve the controversy not by way of 'the outcome of experiments', but through 'outcomes of the argument over definition of success', on the basis of social contingency, in other words, their "world view"(Collins, 1981: 6-19).

[9] Structural differentiation of organizational forms leads to the development of local knowledge, creating conflicts among sub-cultures. Then these subcultures engage in exchanges in "trading zones," an intermediate domain to coordinate action and belief(Vaughan, 1999:913-943).

[10] Experimenter's regress happens in the situation in which "it is hard for a test to have an unambiguous outcome because one can never be sure whether the test has been properly conducted until one knows what the correct outcome ought to be" and so on(Collins, and Pinch: 1998).

[11] Epistemic culture refers to the cultures – aggregate patterns – of knowledge settings or machineries of knowing processes; particularly, these settings for obtaining knowledge are possible by separating "objects from their natural environment and their installation in a new phenomenal field defined by social agents" (27), which means that knowledge is inseparable from its social contexts – external regulators, publishers, funders, suppliers or customers(Cetina, 1999). Epistemic Cultures: How the Sciences Make

production of techno-scientific knowledge at the organizational level. As she investigates the space shuttle Challenger explosion, she identifies that the uncertain and unruly complex technologies brought about by an unprecedented design are transformed into acceptable artifacts with certainty in intra- and inter-organizational processes(Vaughan, 1999). Although organizations multiply and institutionalize uncertainties due to the conflicting meanings of their distinctive local knowledge (Geertz, 2000), they convert them into official certainty through organizational procedures in which people produce and use administrative texts[12] and change the conditions for techno-scientific knowledge production so as to reach a consensus on acceptable risks(Vaughan, 1999).

Latent uncertainties, which are masked by irrelevant rules or power relations between and within organizations, can lead to technological failure. The electricity industry developed, interacting with its societal environment. At the same time, it also retained latent structural problems, especially balkanized operation of interconnected transmission lines, because electrical utilities as a dominant power decided to manage grid systems in this way. Thus the individualized operations could not provide system operators with the full picture of the interconnected power systems that was necessary for integrated control.

Studies of large-scale technological failure in social science are only beginning to deal with these latent uncertainties or problems in social structure. Excepting some studies of natural disasters which started after World War II(Quarantelli, *et. al.*, 2006), not much research on technological failure was systemically conducted before the mid-1970s. Technological failure was a topic that was usually analyzed by scientists and engineers. In the early 1970s, Roberto Vacca(1973: 4) mentioned that “our great technological systems of human organization and association are continuously outgrowing ordered control: they are now reaching critical dimensions of instability.” He pointed out that, however, we did not have the basic theory or terminology for dealing with technological failure in social science(Vacca, 1973).

In the mid-1970s, social scientists began to pay attention to the development of a systematic understanding of the disasters originated by human forces - “man-made”(Perry, 2006). These man-made disasters or technological failures began to be understood as unintended disasters, which are different from natural or deliberate disasters(Perrow, 2006). Some representative cases of technological failures to which social scientists have paid attention as the social events are such accidents as asbestos-related illnesses since the 1970s, DC-10 crashes in 1972, 1974, 1979

Knowledge. Cambridge, MA, Harvard University Press.

[12] According to Smith, textually mediated forms of ruling organize contemporary industrialized societies; that is, documents, which objectify knowledge, organization, and decision-processes, reproduce social relations. And the documentary reality is created by the social organization of production of account. Particularly, “our relation to others in our society and beyond it is mediated by the social organization of its ruling. Our knowledge is thus ideological in the sense that this social organization preserves conception and means of description which represent the world as it is for those who rule it, rather than as it is for those who are ruled”(Dorothy, 1974: 257-269; Smith, 1984).

and 1989, the Tenerife runway collision in 1977, the Ford Pinto rear-end collisions in 1978, the nuclear power radiation leak in Three Mile Island in 1979, Hyatt-Regency walkway collapse in 1981, Tylenol poisoning in 1982 and 1986, Bhopal poison gas release in 1984, space shuttle Challenger catastrophe in 1986, and the Chernobyl nuclear catastrophe in 1986(Weick, 1990; Shrivastava, 1992; Vaughan, 1996; Perrow, 1999; Manion and Evan, 2002). Starting with Turner's research on man-made disasters in 1976(Turner, 1976; Turner and Pidgeon, 1997), the study of technological disaster has become an organized field of social science research. After analyzing 84 large scale accident and disaster reports published by the British Government during the period from 1965 to 1975, Turner identified common patterns of those disasters and constructed a theory of 'the incubation model'; that is, man-made disasters have preconditions whose warning signs are ignored or misinterpreted because they are indistinguishable in the incubation period, and therefore Turner's focus is on the failures of foresight(Turner and Pidgeon, 1997).

After the nuclear power accident at Three Mile Island in 1979, social scientists, particularly in sociology, recognized problems of social systems with respect to large scale technological failure, and showed interest in theorizing about technological accidents and disasters. Among those who analyze social aspects of technological failure, Perrow takes the central position in theorizing them and opens a new field of studies on technological failure in social science. Before Perrow's analysis of the Three Mile Island accident, there were discussions about the structural problems behind human errors related to large scale technological failures. Since Perrow, this new academic field has been extended and deepened by Rasmussen, *et. al.*, 1987), Weick(1987: 1990), La Porte(1991), LaPorte and Consolini(1991) Clarke(1989: 1999), Westrum(1991), Shrivastava(1992), Reason(1990: 1997), Vaughan(1990; 1996; 1999; 1999; 2004), Sagan(1993; 1994), Rudolph and Repenning(2002), Manion and Evan(2002), and others. And this field has become a major part of organization theory(Scott, 1998). Although there are many controversial issues - arguments over difference between natural and technological hazards, contribution of social constructionism to theories of risk, fairness and trust related to risk perception, human errors or organizational, institutional & cultural factors, and organizational response to accidents(Clarke and Short, 1993) - the main thrust of the argument is on the two representative theories - Normal Accidents Theory proposed by Charles Perrow and High Reliability Organizations Theory by Todd La Porte and his colleagues - which are repeatedly tested by others as main frameworks for observing failures in large scale technical systems, such as interconnected power systems.

Normal Accident Theory

After the Three Mile Island accident, Charles Perrow(1999) asked whether better organizations would help, or more money and resources for better people and equipment? He agrees with Simon's position on individual decision makers who have bounded rationality; 'administrative men' pursue their self-interests, but have limited knowledge about their condition and alternatives (Perrow, 1986; Perrow, 1999). Hence, Perrow starts with an assumption that there is no perfect solution to technological failure. In addition, he is not sanguine about governments' and industries' efforts. He enumerates major factors that cause technological failures in terms of DEPOSE - *d*esign, *e*quipment, *p*rocedures, *o*perators, *s*upplies and materials, and *e*nvironment. Then he pays more attention to the ramifications of how these factors produce system disasters: interactions of small failures, small beginnings resulting in a large accident(transformation), and the role of organizations and management - organizational contradictions caused by decentralization and centralization at the same time.

From the above premises, Perrow argues that we can neither avoid accidents nor eliminate risk from high-risk systems in modern society, and that "no matter how effective conventional safety devices are, there is a form of accident that is inevitable"(Perrow, 1999: 3). "Complexly(or linearly) interactive"13) and "tightly(or loosely) coupled,"14) which are properties of high-risk systems, are his key words for explaining and categorizing technological accidents. Because of these properties of high-risk technological systems, an unexpected interaction between parts, between units, and between subsystems is normal. From this perception, he coins the odd term "normal accident"15) in the sense that, considering the characteristics of high-risk systems which are complexly interactive and tightly coupled, we inevitably confront multiple and unexpected interactions of small failures resulting in catastrophic system accidents although they are rare(Perrow, 1999). Perrow applies the concepts of interactive complex and tight coupling to both human organizations and technological systems, which leads to different starting points in supporting or criticizing his theory.16)

Regarding organizational performance, Perrow discusses a dilemma of operating high-risk

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13) To explain complex interactions, he introduces the three essential indications of interactiveness: 'common-mode'(components in a machine serve multiple functions), 'proximity'(close proximity causes an unanticipated interaction between two independent, unrelated subsystems), and 'indirect information.' Then he specifies that "complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible." And the opposite condition is the presence of linear interactions which are visible and comprehensible(Perrow, 1999).

14) If two parts are quite dependent each other, this dependence is known as tight coupling; and if two events occur independently, these are loosely coupled events because although they are involved in the same accident in the same time, one was not caused by the other(Perrow, 1999).

15) By Perrow's definition, "an accident is a failure in a subsystem, or the system as a whole, that damages more than one unit and in doing so disrupts the ongoing or future output of the system. An incident involves damage that is limited to parts of a unit, whether the failure disrupts the system or not"(Perrow, 1999).

16) Lee regards the two concepts as properties of organizational configurations, while Roberts understands them as properties of technological systems, and argues that Perrow takes an engineering perspective(Clarke and Short, 1993; Roberts, 1990: 160-176; LaPorte and Rochlin, 1994: 221-227; 223).

systems that are interactively complex and tightly coupled. To deal with tightly coupled systems, operators need centralized systems to check everything within a limited period, but to reduce the unexpected interaction of small failures in interactively complex systems, operators need decentralized systems(Perrow, 1999). However, he argues that it is incompatible to both centralize and decentralize system operation – "both local autonomy and centralized control" – at the same time under tightly coupled, interactively complex systems(Perrow, 1986: 150). Therefore, there is no real solution regarding the dilemma of a centralized-and-decentralized system design under tightly coupled, interactively complex systems. But he also argues that both centralization and decentralization in decision-making processes of an organization should exist simultaneously by controlling "the cognitive premises underlying action"(Perrow, 1977; Perrow, 1986: 129). I argue that this is true for organizational reliability or safety. To reduce the possibility of large scale technological accidents, his solution is to reorganize decision-making systems which support social rationality – social bonds or social cooperation – and to redesign high-risk systems(Perrow, 1999).

Perrow extends his argument to the role of powerful groups and individuals who give more attention to efficiency for profit maximization than safety and reliability, which are regarded as production costs. The problem of organizational failure is not the culture of the organizations, but the power of decision makers both inside and outside the organization. Perrow defines organizations as tools to achieve group goals and interests within and between organizations. There are various groups who utilize organizations for their own ends which are not consistent with official goals or the public interest(Perrow, 1999). As a result, the interests of influential decision makers may manipulate the primary goal of safety or reliability in organizations(Sagan, 1993). In his book Limits of Safety, Sagan identifies that 'redundancy' to improve reliability in a system or an organization simultaneously has a possibility to inadvertently reduce its reliability, and that 'organizational learning' usually reflects the narrow interests of influential organizations as the record or collective memory is filtered by powerful past members(Sagan, 1993; Sagan, 1994). Powerful individuals within and without the organization may influence the construction of reliability, making system failure more probable. This perspective can be extended at the institutional level; the exercise of power in establishing institutions affects organizational performance for reliability.

So far, the two perspectives are important in analyzing structural aspects of interconnected power systems: concepts of centralization-and-decentralization and the role of power groups. According to NAT, large scale blackouts are a kind of normal accident,[17] when it is considered that transmission networks are too tightly coupled with a complex organization made up of a

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[17] In fact, Perrow assumes that electric grids are tightly coupled and linear systems with predictable interactions, not interactively complex ones. Thus, he excludes large scale blackouts from his analysis(Perrow, 1999). But the grid systems consist of a variety of components with various organizations involved, which makes the system complexly interactive. In later work he categorizes large scale blackouts as normal accidents(Perrow, 2007).

variety of utilities and power pools in the market. However, the theory misses processes by which operators act to trigger a small failure or fail to recover from small failures in grid systems. Operators are not a static entity in the chain of systems, and could maximize or minimize system failures in accordance with their given conditions. Thus, to get a more integrated perspective of large scale blackouts, we need an analysis that includes the explanations of how human errors linked to surrounding conditions amplify the outcomes of systems failure.

High Reliability Organizations Theory

A group of scholars have studied complex organizations and have reacted to the normal accidents theory by proposing the High Reliability Organizations theory. Todd La Porte and his colleagues start with a set of components - interactive complexity and tight coupling. They argue that some potentially hazardous organizations - aircraft carriers, U.S. air traffic control systems, and international banking - deal with these components successfully without any accident(Rochlin, Porte et al. 1987; Roberts, 1990). The properties of these high reliability organizations include good organizational design and management, safety as the organization's primary goal, redundancy, decentralized decision-making, a culture of reliability, continuous training of their employees and trial-and-error learning. In other words, without these properties, complex organizations could experience large scale system failure. In table 1, Sagan compares the two theories.[18]

<Table 1> Competing Perspectives on Safety with Hazardous Technologies

High Reliability Organizations theory	Normal Accident theory
Accidents can be prevented through good organizational design and management	Accidents are inevitable in complex and tightly coupled systems
Safety is the priority organizational objective	Safety is one of a number competing objectives
Redundancy enhances safety: duplication and overlap can make 'a reliable system out of unreliable parts'	Redundancy often reduces safety: it increases interactive complexity and opaqueness and encourages risk-taking
Decentralized decision-making needed to permit prompt and flexible field-level responses to surprises	Organizational contradiction: decentralization for complexity but centralization for tightly coupled systems
A 'culture of reliability' will enhance safety by encouraging uniform and appropriate responses by field-level operators	A military model of intense discipline, socialization and isolation is incompatible with democratic values
Continuous operations, training, and simulations can create and maintain high reliability operations	Organizations cannot train for unimagined, highly dangerous, or politically unpalatable operations
Trial and error learning from accidents can be effective and can be supplemented by anticipation and simulations	Denial of responsibility, faulty reporting, and reconstruction of history cripple learning efforts

※ Source: Sagan(1993: 46).

The HROs theory suggests some constructive solutions to improve organizational reliability,

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[18] Perrow also discusses that Sagan identifies four critical features regarding high reliable organizations: "1) political elites and organization leaders put safety and reliability first as a goal; 2) high levels of redundancy in personnel and technical safety measures; 3) the development of a 'high reliability culture' in decentralized and continually practiced operations; and 4) sophisticated forms of trial and error organizational learning"(Perrow, 1994: 212-220; 214).

while the normal accidents theory is pessimistic about technological systems. The HROs approach focuses on the conditions of organizational performance for high reliability, while NAT identifies specific properties of high-risk systems. In this sense, La Porte argues that he and his colleagues are interested in properties of high reliability organizations, not the causes of technological accidents(LaPorte and Rochlin, 1994). Therefore, the HROs theory selects those cases of error-avoiding or failure-free "organizations," while NAT usually analyzes error-inducing or already failure-experiencing "systems." Roberts argues that the normal accident theory deals with the characteristics of technical systems, not the properties for high reliability organizations, and proposes that the high reliability of hazardous organizations can be enhanced by adding the above properties to their performance(Roberts, 1990). Accordingly, La Porte explains that their HROs can be complementary to the normal accidents perspectives(LaPorte, 1994). And he wants to reveal more practical, abundant properties of high reliability organizations, challenging current theoretical limits in analyzing large scale technical systems(LaPorte and Consolini, 1991).

One of the issues La Porte raises is that he and his colleagues concentrate on a set of common organizational and structural factors within high reliability organizations(LaPorte and Rochlin, 1994). NAT also generally gives attention to the inside properties of high-risk systems. However, neither theory considers the conditions of inter-organizational relationships and the properties of the networked systems that are organizational features of interconnected transmission systems in the electricity industry. It is necessary to extend the HROs theory by including a relevant framework of explaining the inter-organizational relationships in which large scale blackouts occur. The inter-organizational relationship is beyond the authority of one organization and should be managed and regulated at the institutional level. Hence, an institutional approach can be a relevant framework to improve our understanding of the conditions of inter-organizational relationships which bring about large scale blackouts.[19] Another issue is that the HROs group does not consider the role of power in their explanation of constructing a culture of reliability, while NAT significantly discusses it in regard to the process of decision-making and technological system design. In the electricity industry, different interests conflict with one another in the process of constructing institutions, which should be considered in explaining inter-organizational relationships. A culture of reliability between organizations may not be created without cooperation between utilities and regulatory bodies.

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[19] Studies on inter-organizational relationship have been dealt with by various approaches and theories. They are "industrial economics, organizational economics, industrial marketing and purchasing, organizational sociology, game theory, resource dependence theory, population ecology, institutional theory, and social network approaches." Ebers, M.(1997). Explaining Inter-Organizational Network Formation. The Formation of Inter-Organizational Networks. M. Ebers. New York, Oxford University Press., pp 5-15. Their research mostly focuses on the motives for cooperation among organizations at the actor level, and socio-economic conditions for the formation of inter-organizational networks at the institutional level. However, they rarely pay attention to how an inter-organizational network produces flip side of itself.

Institutional Imbalance and Power Relations

Culture and Organizational Failure

In investigating technological failure or large scale blackouts, both perspectives should be considered simultaneously - culture and power relations. First, I emphasize the importance of culture, because a culture of reliability will guide timely and appropriate decision-making during emergencies. Organizational safety culture after the accident at Chernobyl becomes an important factor to be considered in technological failure(Pidgeon, 1997). A culture is generally defined as a system of symbols or meanings through which a group of people understand the world(Pidgeon, 1997), and also a set of solutions which is institutionalized and passed on as the rules, rituals, and values of the group(Vaughan, 1996). Weick points out that technological accidents occur because human beings are not sufficiently complex to discern and predict problems generated by the complex systems they operate and manage(Weick, 1987). In his macro-micro analysis of the Tenerife air disaster, Weick(1990) discovers that communication among and within groups is critical in improving high-reliability performance, and insists on developing a “collective mind” in an organization through social skills(Weick, 1993).

Human actions, when they meet with external factors such as production pressure and a changing environment, can increase the possibility to bring about errors, thereafter triggering and magnifying the failure along with the structural problems - sloppy management,[20] conflicting goals, poor design and defective organizational settings - in the organization. That is, it is the organizational culture that should be considered in technological failure. Cultures in an organization, which are influenced by its environment, are more broadly discussed in the New Institutional approach.

Second, as Perrow argues, “a cultural approach is necessary, but it must be informed by an awareness of political and organizational power”(Perrow, 1986: 265). Just focusing on socio-cultural factors in analyzing technological accidents, however, might miss another aspect of how institutions to support a culture of reliability are created and maintained in an arena with conflicting interests. Powerful groups or decision makers are located in the position to set organizational goals and create organizational cultures that may not be sufficient for organizational

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[20] A simple meaning of sloppy management is the disregard of safety rules and instructions, ignoring warnings, lack of adequate communication. From the sloppy management perspective, Turner has developed an incubation model of disaster according to which there are six phases of disaster development: “[1]a notionally normal starting point; [2]an incubation period; [3]terminated by a precipitating event; [4]which leads to the onset of the disaster; [5]rescue and salvage dealing with the immediate problems after the disaster; and [6]a final stage of full cultural readjustment to the surprise associated with the precipitating event”(Turner, and Pidgeon, 1997: 83).

reliability. The two concepts - power and culture - should be treated equally in examining large scale blackouts.

Institutional Imbalance and Power

A(new) institutional approach in the social sciences has revived in recent decades. As Scott (1998) defines, organizations are seen as socio-cultural and open systems which interact with their institutional environment. A group of organizational theorists pay attention to institutions in order to observe cultural aspects of organizations(Scott, 2001) and examine inter-organizational relationships(Meyer and Scott, 1992). Institutional environments bound the behavior of actors and organizations through regulative, normative, and cultural-cognitive elements[21](Scott 2001). Institutions as a form of external pressure have an influence on the internal formation of organizational behavior. Institutions provide individuals and organizations with meaning and stability so that social life can continue(Scott, 2001).

Concerning the unique conditions of the electricity industry - with interconnected transmission lines and tightly networked systems - the industry should be expected to need holistic management of its systems. This could be achieved by drawing upon two perspectives from the HROs theory so as to create reliability management of the interconnected systems(Table 1). One is a 'strong organizational culture' of centralizing similar premises and assumptions – recruiting, socialization, incentives for organizational mission(LaPorte, 1991) - and another is 'decentralized decision making' for flexible field-level responses to emergency situations. Weick clearly describes this process of centralization-decentralization. That is;

> Before you can decentralize, you first have to centralize so that people are socialized to use similar decision premises and assumptions so that when they operate their own units, those decentralized operations are equivalent and coordinated. This is precisely what culture does. It creates a homogeneous set of assumptions and decision premises which, when they are invoked on a local and decentralized basis, preserve coordination and centralization(Weick, 1987: 117).

Therefore, I believe that the electricity industry must develop a culture of reliability by centralizing basic premises and assumptions and at the same time by decentralizing decision making at each utility level. In particular, a centralization-and-decentralization is necessary during

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[21] Cultural-cognitive elements refers to "the shared conceptions that constitute the nature of social reality and the frames through which meaning is made" including symbols - words, signs, and gestures; normative elements refers to prescriptive, evaluative, and obligatory dimensions of institutions - that is, how things should be done; and regulative elements, such as rules, laws and sanctions, are to constrain and regularize behaviors. Scott, W. R.(2001). Institutions and Organizations. California, Sage Publications, Inc: 51-58.

emergency situations. If one of utilities experiences a system failure, then it must share the information with other neighboring utilities, so that they can prevent the spread of the initial failure to other systems. Although they coordinate tightly interconnected power systems, however, they control their interconnected systems in a loosely coupled way, without much sharing of premises and assumptions.

Regarding this institutional imbalance, one basic interpretation by the new institutionalist approach is to see institutions as rationalized myths. Formal organizations are constructed under the domain of rationalized institutions. And these institutions are merely cultural symbols and rationalized myths,[22] because they do not reflect real demands of the organization's work(Meyer and Rowan, 1977). Organizations usually adapt to their institutional environments which are created by the force of powerful organizations(Meyer and Rowan, 1977), and assume that the institutions rationalize their structural forms and activities. As a result, organizations' structural forms and practices become isomorphic(DiMaggio and Powell, 1983). Reliability institutions in the United States have developed a formal structure in dealing with reliability standards: planning and system operation tasks. Then major utilities have corresponding sub-organizations which conduct common functions for reliability - usually construction planning, finance, reliability coordination, transmission operating centers, emergency planning, training, and so on. Because the inter-organizational relationships are loosely coupled, however, the electricity industry has not practically developed necessary contents of reliability-related institutions, although it has tried to develop them. In this sense, the reliability institutions exist, to some extent, as rationalized myths masking real situations.

A question is raised. Why do reliability institutions exist to a certain extent as rationalized myths? The question can be considered in the conditions under which the goals and interests of utilities conflict with those of federal(central) government regarding inter-organizational relationships. Then power relations[23] will govern those interests, and therefore those who dominate the industry will decide the structure of inter-organizational relationships that affect the culture of reliability. The new institutionalists, although focusing on the taken-for-granted nature of organizational forms and practices which are not affected by the interests of politically influential actors(DiMaggio, 1988: 4), point out the power relations which affect institutional properties. "The success of an attempt at institutional change depends not simply on the resources controlled by its proponents, but on the nature of power and the institutionally specific rules by which resources are produced, allocated, and controlled"(Friedland and Alford, 1991: 254).

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[22] The conceptualization of institutions as myths comes from the study of education systems and hospitals conducted by John W. Meyer, Brian Rowan and W. Richard Scott in the early 1970s. And they generalize what they have found(Perrow, 1985:151-155; Meyer, and Rowan, 1992).

[23] In organization theory, power is defined as the capability of one social actor or group to overcome resistance and thus to extract a desired objective or outcome from a given system where each interest conflicts with another(Pfeffer, 1981; Perrow, 1986).

Organizations are capable of responding to institutional influences creatively and strategically. Not only do they shape their structure and culture according to their institutional settings, but also can they create or modify their institutional environments. Scott perceives that even if institutional environments are endogenously created by social actors, they act as an external force, regulating the social actors(Scott, *et. al.*, 2000). Organizations internalize their institutional environments – the external forces – through the process of institutionalization, which, in DiMaggio's terms, "is profoundly political and reflects the relative power of organized interests"(DiMaggio, 1988: 9). With the power relations perspective, the new institutionalism articulates the relationships between private firms and the state; "private-sector firms use the state to organize their [organizational] fields in a fashion that supports the interests of the already existing organizations"(Fligstein, 1991: 314).

The perspective of power relations can explain much about the construction of institutions in the field of the electricity industry. Powerful groups – or leading utilities – construct organizational forms and institutional settings, and stabilize a certain structure of inter-organizational relationships. As other large scale industries do, the electricity industry has grown with its technological development. In the United States, with a certain scale of expansion, the unregulated electricity industry takes on the form of a regulated business, creating an institutional environment on the industry's behalf. Electricity organizations, especially investor owned utilities(IOUs), take the initiative to form institutions to reduce uncertainty. In Russia, State, political leaders, facing a challenge of constructing a socialist state against capitalist ones, promoted electrification for specific their political interests(Lawton, 1932; Lagendijk, 2008). Sublevel decision makers will give priority to the interests of their chief decision makers within the organizations. And their decisions are affected by a context that reflects the interests of leading utilities.

In sum, we can interpret some rationalized institutions(or imbalanced institutions), which affect preference of decision-makers in organizations and the shapes of organizations, as myths which do not reflect real demand of the society.

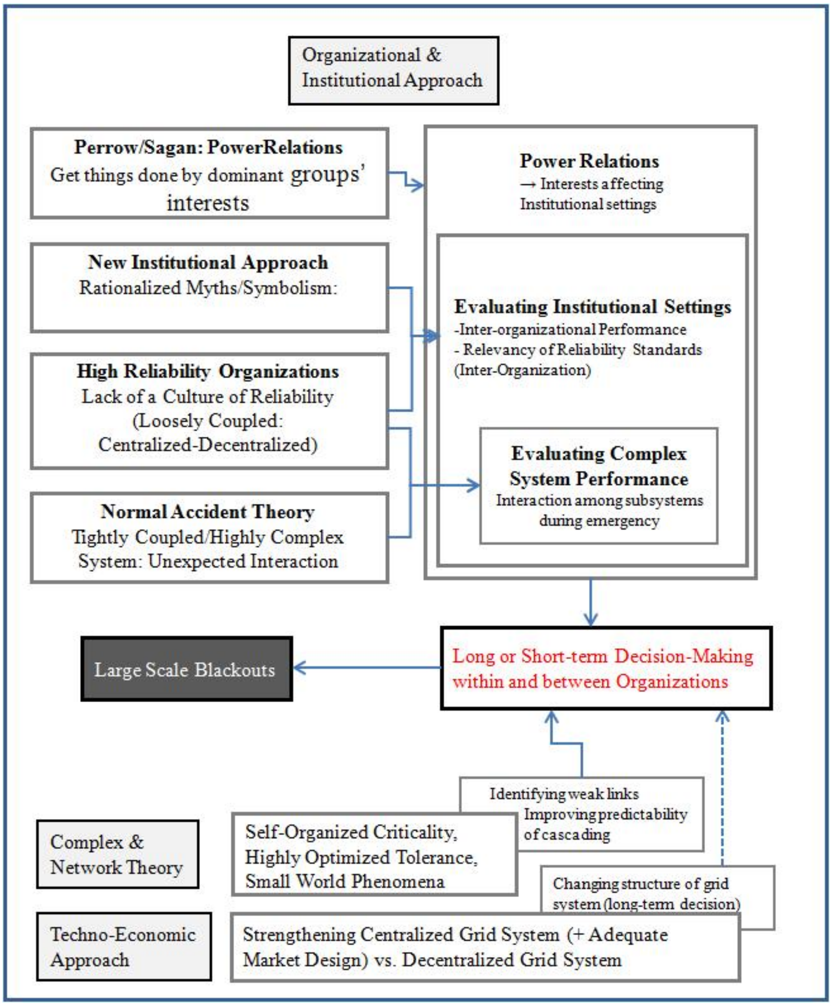
Conclusion

an Analytic Framework for Large Scale Blackouts: Interorganizational Reliability

In fact, organizational theorists who have developed social theories on technological failure do not place the large scale blackouts in the scope of their analysis. After the 2003 blackout, some scholars and electrical engineers discussed organizational and institutional issues regarding large scale blackouts. A group of scholars at Carnegie Melon University pointed out system problems of the electricity industry and organizational issues(Apt, *et. al.*, 2004; 2006). Concerning the interrelationships in the electricity industry, some engineers in this field have raised institutional issues of electrical blackouts, particularly focusing on deregulation and restructuring(Casazza, *et. al.* 2005; Casazza, *et. al.*, 2005). The organizational issues are explained in detail by Mark de Bruijne(2006) in a more organized manner, applying Normal Accident Theory and High Reliability Organizations Theory to the case of the California energy crisis. He argues that in the process of deregulation, institutional settings for reliable operation of electricity systems as a whole have become fragmented, and thus organizational performance does not work well as it did before(Bruijne, 2006).

Some elements of NAT, the HROs theory, and the new institutional approach deliver insights in analyzing large scale blackouts. These insights are; 1) institutional settings for reliability are decided by powerful groups; 2) reliability institutions exist as rationalized myths or symbolism due to cultural persistence to change and loosely coupled relationships among utilities, reliability coordinators and reliability institutions; and 3) there are unintended interactions of human errors and equipment failure and a lack of an effective culture of reliability in interorganizational relationships. Even though the electricity industry has had great technological achievements in improving the quality of life, at the interorganizational level it has not possessed an attentive ability to avoid spreading blackouts from local power disturbances.

Now we may synchronize those theories - techno-economic approach, complex & network theory, and organizational & institutional approach - in explaining causes of large scale blackouts. Figure 4 show the locations of theories in explaining causes of large scale blackouts. Their explanations are necessary for long or short-term decision-making process. From the organizational and institutional perspective, NAT can help us explain unexpected interactions of subsystems while HROs can identify unstandardized or irrelevant reliability criteria during an emergency. The deficiency of reliability standards should be reviewed through a lens of the new institutional approach. Controlling interconnected power systems needs a level of coordination among utilities that is beyond any individual organization's authority. Therefore, an institutional approach can be a relevant framework to improve our understanding of the conditions of inter-organizational relationships. Then we can identify that reliability institutions, which have developed reliability standards, to a certain extent, do not reflect real demands or situations in preventing large scale blackouts. Sometimes they exist as rationalized myths or symbolism, masking some deficiencies of reliability standards. The institutional deficiencies are an outcome of power relations, reflecting dominant organizations' interests rather than real demands for power systems control. As a result, during an emergency, system operators in each local unit may make different decisions which will lead to large scale blackouts. The complex & network theories can identify weak links in the interconnected transmission systems and increase predictability of large scale blackouts. They can help system operators and decision makers find problems of interconnected power systems before an initial failure of power systems at the local level develops into a cascading stage. Through the techno-economic approaches, system operators and decision makers may determine the basic structure of inter-connected power systems; whether they strengthen the current centralized grid systems or change them into decentralized ones. Using information obtained through the complex & network theories, decision makers can reconsider which power system structure - centralized or decentralized - is relevant to the prevention of large scale blackouts. Or they may also select technologies of delivering power, that is, direct current[24] rather than alternate one, between two power systems if they want to prevent a cascade under the current structure of centralized power systems. Because the techno-economic approaches can provide us with basic information for deciding the fundamental structure of electrical power systems, they will be useful for a long-term decision.



<Figure 5> Location of the Theories in an Analytic Framework

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[24] Unlike alternate current, direct current can isolate power disturbances which occur at the local level, and therefore can prevent cascading outages.

The theories discussed above are currently explaining large scale blackouts in different ways in the different fields. There should be a concerted effort by the experts in the different fields; so that their integrated explanations can help decision makers prevent future large scale blackouts. Korea is facing a crisis of a very potential large scale blackout as well as power shortages, because interconnected power systems are more complicated nowadays. Technical solutions could not be enough. As the experts and decision makers of the electricity industry and the central government in Korea review all the dimensions as introduced above including organizational & institutional perspectives, they need to establish an integrated approach in order to prevent a future large scale blackout. Future research on blackouts in Korea, therefore, would analyze both technical and organizational aspects based on the framework as proposed above. In particular, how we can create a culture of reliability within and between organizations should be discussed as we study blackout cases in Korea.

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Theories of Explaining Causes of Large Scale Blackouts
- Current Literature and a Future Research Framework -

Hyun Soo Park

Recently large scale blackouts have been a global issue to be addressed. Korea also faces highly unlikely but catastrophic large scale blackouts due to the complexity of its interconnected grid systems. There are different explanations on the causes of large scale blackouts in different fields. At first, therefore, this article categorizes them as techno-economic approaches and complex & network theories. The latter observe the cascading outage itself as a physical phenomenon independent of the social organization of technological events, while the former searches for the causes of large scale blackouts in the physical structure of interconnected transmission systems and market design. Because they do not deal with organizational and institutional problems in their explanations, this paper includes organizational & institutional approaches - Normal Accident theory, High Reliability Organizational theory, and New Institutionalism - to explain social causes of large scale blackouts. Finally, a theoretical framework is outlined that makes an attempt to synchronize different theories in different fields to show multi-dimensions of explaining large scale blackouts and to guide future policy direction.

Key words: large scale blackout, normal accident, a culture of reliability, symbolism, power relations