System Impact of the Loss of Major Components

A sophisticated saboteur or major natural disaster can readily cause widespread power outages. The time and effort needed for a system to recover could range from seconds to months, depending on which components are damaged, the system's basic characteristics, and the availability of spare parts. Even if a power failure is avoided or lasts only seconds, costs may be high as less efficient reserve generating capacity replaces low cost units, and sensitive consumer equipment such as computers are disabled. This chapter addresses the resilience of current bulk power systems to equipment outages, examining both reliability and economic impacts.

U.S. utilities have been highly successful in maintaining very high levels of bulk power system[1] reliability. Bulk power systems in the United States are designed and operated to be reliable and economical in the face of normal events including occasional equipment failure. Utilities are also prepared to minimize the impact of some highly unlikely events such as multiple simultaneous equipment failures at a single site. However, sabotage or major natural disaster can inflict damage well beyond what utilities plan for. Because U.S. utilities have performed so reliably and have only rarely faced widespread and multiple equipment failures, there is uncertainty about how bulk systems will actually behave in extreme circumstances.

One factor leading to reliability and resilience is the highly interconnected network common to modern power systems (see box E). Because of the vast size of most power systems, no individual powerplant or transmission component is critical to the operation of any power system. An electric system typically has many powerplants, in some cases several dozen. An individual powerplant, even a large multi-unit one, supplies only a small fraction of the total demand of most control areas. There are some very small control areas in the Midwest, but each powerplant provides only a small fraction of the total capacity in the interconnection.

Distribution systems are not designed to have such a high level of reliability as the bulk system. In fact, the great majority of outages that customers experience result from distribution system problems, not from the bulk system (around 80 percent by one estimate).[2] However, unlike bulk system failures, distribution-caused outages are localized, and utilities have considerable experience in responding to them.

SHORT-TERM BULK POWER SYSTEM IMPACTS

The Importance of Any One Component: Preparing for Normal Failure[3]

Some of the thousands of components in any system occasionally fail or operate improperly, or are disabled by natural events such as lightning strikes. Because these events are common and inevitable, utilities consider them to be normal. Most bulk power systems in the United States are designed and operated to continue operation following the failure of any one device without interrupting customer service or overloading other equipment.[4] This is commonly referred to as the "n-1 operating criterion. Some utilities prepare for two such contingencies (called the n-2 operating criterion). Systems west of the Rockies make some exceptions to the n-1 criterion for certain major facilities. In those systems, some customers may be briefly interrupted following certain outages, but with no overloading of other equipment leading to uncontrolled or cascading outages.

Preparing for equipment failure involves two main functions. These are: 1) holding sufficient generation and transmission capacity in reserve to

[1]Bulk power systems include the generation and transmission, but not distribution (see U.S. Congress, Office of Technology Assessment, *Electric Power Wheeling and Dealing*, OZ4-E-41O (Washington, DC: U.S. Government Printing Office, May 1989), ch 4). This chapter focuses on bulk systems since damage to them may be far more widespread and difficult to repair than distribution damage.

[2]U.S. Department of Energy, "The National Electric Reliability Study: Executive Summary," DOE/EP-0003, April 1981, as cited in: *Power System Reliability Evaluation,* Institute of Electrical and Electronics Engineers, 1982, p. 42.

[3]See Office of Technology Assessment, op. cit., footnote 1.

[4]North American Electric Reliability Council, *Overview of Planning and Reliability Criteria of the Regional Reliability Councils of NERC* (Princeton, NJ: April 1988).

[5]See Office of Technology Assessment, op. cit., footnote 1.

Box E—The Organization of Electric Systems: Utilities, Control Areas, Power Pools, and Interconnections

The electric power industry today is a diverse and heterogeneous amalgamation of investor and publicly owned utilities, government agencies, cogenerators, and independent power producers.[2] In most of the country, individual utilities are highly interconnected and operate under a variety of formal or informal coordination agreements. The level of power transfers and coordination between utilities is determined largely by control areas, power pooling arrangements, and physical interconnections.

Control Areas

Responsibility for the operation of the Nation's generating facilities and transmission networks is divided among more than 140 ''control areas. In an operational sense, control areas are the smallest units of the interconnected power system. A control area can consist of a single utility, or two or more utilities tied together by contractual arrangements. The key characteristic is that all generating utilities within the control area operate and control their combined resources to meet their loads as if they were one system. Control areas coordinate transmission transactions among electric power systems through neighboring control areas. Control areas maintain frequent communications about operating conditions, incremental costs, and transmission line loadings.

Power Pools

There are two types of power pool arrangements-tight power pools, which include holding company power pools; and loose power pools. Tight power pools are highly interconnected, centrally dispatched, and have established arrangements for joint planning on a single-system basis. Four of these tight pools consist of utility holding companies with operations in more than one State; the others are mostly multi-utility pools. Together, the tight power pools account for about a quarter of the industry's total generating capacity. Arrangements among utilities in loose power pools are quite varied and range from generalized agreements that coordinate generation and transmission planning to accommodate overall needs to more structured arrangements for interchanges, shared reserve capacity, and transmission services.

Interconnections

North America's interconnected utilities create four physically separate, synchronously operated transmission networks: the Eastern Interconnection (or Seven Council Interconnection); the Texas Interconnection; the Western Systems Coordinating Council (WSCC); and the Hydro Quebec System. DC and AC transmission interties between the networks are limited in location and capacity, with the result that the transmission systems in the United States do not forma single national grid, but rather form three huge, separate grids. However, even the smallest one, the Texas Interconnection, is very large with installed generating capacity of over 50,000 MW comprised of scores of generating units.

[1] See U.S. Congress, Office of Technology Assessment, *Electric Power Wheeling and Dealing*, OTA-E-410 (Washington, DC: U.S. Government Printing Office, May 1989, ch. 4.

[2] At present, the Nation's utility industry includes 203 investor-owned operating companies; 1,988 local publicly owned systems; 994 rural electric cooperatives; 59 public joint-action agencies, and 6 Federal power agencies, In addition, there are several hundred cogeneration and small power producers selling power to utilities.

respond immediately; and 2) designing circuit breakers and relays to protect and isolate equipment in a controlled manner.

Reserve Generation and Transmission

Utilities keep enough generation, transmission and substation capacity on-line and ready for operation to replace any operating components that fail. Generating units must be warmed up and rotating in synchronism with the 60 Hz of the power system before operating. Generating units which are synchronized and ready to serve additional demand immediately are called spinning reserves. Utilities select "unit commitment plans" specifying which units will be warmed up and cooled down to follow the cycle of loads over the course of a day, week or season. Unit commitment schedules are chosen which minimize the total expected costs of operation and Spinning reserves required to maintain reliability and meet expected changes in demand.

Unlike generating units, transmission circuits and substations don't require any warm-up time and are instantly available as long as they are connected to the system. The flow of power in a transmission network is dictated by the laws of physics. One of the key laws is that power flows on all available paths between a generator and a load. This is called parallel path flow. After a generator or transmission circuit fails, the power flow on the remaining circuits responds immediately. To ensure that resulting flows don't exceed emergency ratings, "security-constrained dispatch' techniques are used to ensure sufficient transmission reserves. Control center operators typicallyexamine a series of contingency cases to determine the most severe contingency and the resulting transmission loadings. When they find a contingency would create unacceptably high loadings, the generation dispatch is adjusted to reduce the resulting flows to acceptable levels.

Circuit Breakers and Relay System Design

Relaying techniques and circuit breakers to isolate and protect equipment are essential to maintaining reliable service. Circuit breakers are installed at each end of every circuit and transformer in the system to provide protection in the event of a short circuit. Under normal conditions the breakers perform routine switching operations such as disconnecting and isolating equipment for maintenance or inspection, transferring loads among circuits and disconnecting generators when not needed. When relays sense a short circuit, they cause the circuit breakers to operate, isolating the faulted component. Most breakers on the bulk power system operate in no more than five cycles (1/12 second in the U.S. 60-Hz system), and three cycle (1/20 second) operation is common. Prompt isolation of faulted components is critical to ensuring that the remaining equipment is not damaged and is able to continue operation.

Increasingly, many power systems are using elaborate relaying schemes for protection.[6] These involve coordinated operation of multiple circuit breakers simultaneously in different locations rather than merely isolating individual failed components. For example, in the Pacific Intertie, which connects the Pacific Northwest with southern California, a complex scheme is employed which isolates generation in Oregon and transmission circuits in Arizona when certain circuits in California fail. This system, which enables California to reliably import large amounts of power, ensures that a transmission failure in California will not cause damaging imbalances in neighboring States.

Impacts of Multiple Failures: Islands and Cascading Outages

While the failure of any single generating unit, transmission line or substation normally should not cause significant outages, simultaneous failure of more than one major component generally will result in interruption of service.[7] When abnormal, multiple failures occur, a power system typically undergoes ''system separation, " in which portions of the system disconnect from each other.[8] Some of these isolated portions, called "electrical islands," may have an imbalance of supply and loads. Those islands have either more generation than load or more load than generation, causing the system frequency to deviate from its normal value of 60 Hz and transmission voltages to exceed design limits. In turn, protective relays would cause several generators and transmission circuits to disconnect from the island, resulting in a blackout. Other islands may have a balance of supply and demand, allowing continued operation even though disconnected from the rest of the system.

"Cascading outages" occur when the failure of one or more components causes the overloading and failure of other equipment and breakup of the system into islands in an uncontrolled fashion. It is not possible to accurately predict the way a system will break up after a major disturbance-there are too many variable factors.[9] Utilities do analyze their systems and implement plans to help anticipate and control the likely pattern of islands. Their analyses show that the pattern of islands will vary depending on the location of loads, which units are operating, how much each unit is generating, the configuration of the transmission network, and the specific second-by-second sequence of events causing the disturbance. However, one can predict that cascad-

[6] North American Electric Reliability Council, *1987 Reliability Assessment—The Future of Bulk Electric System Reliability in North America, 1987-1996* (Princeton NJ: October 1987).

[7] This assumes that the system is operated for n-l contingencies. A system operated for n-2 should be expected to have significant impacts only when more than two major components fail.

[8] Westinghouse Electric Corp., *Utility Survey of Methods for Minimizing the Number and Severity of System Separations,* EPRI EL-3437 (Palo Alto, CA: Electric Power Research Institute, March 1984).

[9] Ibid.

ing failures will extend over large areas, in some cases over a multistate region.

Preparing for Extreme Contingencies

Because uncontrolled, cascading outages can be so widespread and difficult to recover from, U.S. utilities have made special provisions to avoid them even though the circumstances leading to them are viewed as highly unlikely. In addition to planning for ‘normal” contingencies, U.S. utilities also plan for ‘extreme’ contingencies.[10] The reliability criteria of each of the NERC regional reliability councils specify that bulk power systems shall be planned and operated in a reamer to avoid uncontrolled, area-wide interruptions under certain extreme contingencies. Under extreme contingencies, substantial outages will occur, but should not extend across an entire system.

Typical extreme contingencies examined include the loss of an entire multi-unit generating station, multi-circuit transmission substation, or loss of all circuits on a common right-of-way. Thus, the failure of all units in a large multiple-unit plant would cause serious, although perhaps temporary, blackouts in most systems. While customer interruptions would be expected in the immediate area, cascading failures resulting from overloading of remaining equipment should not occur if the extreme contingency planning has been performed properly.

The types of equipment failure that a terrorist attack or major natural disaster may cause are far more severe than those considered by utilities as extreme contingencies. The extreme contingencies planned for by utilities today are limited to failures at a single site. However, natural disaster or attack could well affect two or more major sites. The simultaneous failure of any combination of two or more large multi-unit powerplants, or multi-circuit transmission corridors or substations may well lead to cascading failures. While the extent of the impact (e.g., the characteristics of the electrical islands) can’t be accurately predicted, it can be very large.

LONG-TERM BULK SYSTEM IMPACTS

The Importance of Any Few Components: Large Reserves and Peak Capacity

Most of the time, U.S. utilities have large amounts of generating capacity in excess of demand. Anything less than the failure of much of this generation reserve should cause outages lasting no longer than the few hours required to start idle capacity and restart the system. However, there may be a daily cycle of shortages or rotating outages during hours of peak demand. The large surplus of generating capacity over demand results from two factors: 1) installing sufficient capacity to meet peak loads; and 2) planned reserve margins in excess of peak demand.

Power systems are designed to meet widely fluctuating loads which reach their peak for only a few hours in any year. Peaks usually occur in the late afternoons of hot summer days when air-conditioners add to normal loads, or on very cold winter days when space heating is uncommonly high. Because capacity is installed to meet the peak demand, a large amount of capacity operates at partial output or is idle except during those peak periods. Off-peak-period loads may be as little as one-third of daily peak. On average, demand throughout a year is around 60 percent of peak demand.[11] Thus, on average, the power plants in a system operate at no more than around 60 percent of capacity.

Furthermore, even at peak periods, there is generally a large amount of reserve generating capacity. Most utilities plan to install generation reserve margins of 15 to 20 percent.[12] Utilities install reserve capacity in order to accommodate both planned and unplanned needs such as scheduled maintenance, unexpectedly high load growth and equipment outages. Because loads grew much slower than anticipated during much of the 1970s and 1980s, many areas of the country now have far higher reserves than planned, too, with over 35 percent in some NERC regional reliability councils.

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[10] North American Electric Reliability Council, *Overview of Planning and Reliability Criteria of the Regional Reliability Councils of NERC* (Princeton, NJ: April 1988).

[11] U.S. Department of Energy, *Electric Power Supply and Demand for the Contiguous United States 1988-1997*, DOE/IE-0013, January 1989, tables C1-C9.

[12] U.S. Congress, Library of Congress, Congressional Research Service “Do We Really Need All Those Electric Plants?” August 1982.

As loads continue to grow, however, this excess capacity gradually is being reduced. Other regions of the country, on the other hand, are beginning to experience relatively small reserve margins.[13]

Transmission systems are planned to accommodate both the geographical distribution of powerplants as well as the changing patterns of loads. Thus, the reserves of generation are necessarily accompanied by similar reserves of transmission. Transmission networks also link the many utilities in the Nation's three interconnections (see box E). NERC reports that some transmission systems are heavily loaded by economy energy transfers both within and among regions, and will continue to be during the 1988-97 forecast period. These transfers are driven by fuel price differentials rather than reliability requirements. For example, the Pacific Intertie carries low-cost hydroelectricity from the Pacific Northwest to displace expensive natural gas-or oil-fired generation in California. However, on some occasions, large, long-distance transmission lines carry power which is essential for reliability, not just for minimizing electricity costs.

Because there generally are large reserves of transmission just as there are of generation, it would take the destruction of the transmission capacity associated with several powerplants to keep any system down for an extended period of time over a wide area. However, at certain times such as extreme peak periods or when scheduled maintenance or unplanned outages have reduced actual reserve margins, failure of only a few key generation or transmission components units could significantly disrupt service.

System Impact When No Outages Occur: Higher Costs and Lower Reliability

Even if a blackout is brief or avoided altogether, the loss of damaged or destroyed base-load generating units is very expensive for the duration of the outage. Base-load units, fueled by uranium, coal, or hydropower, have the lowest operating costs of any units in a power system and are typically the largest units. If they are damaged, the energy they would have produced must be replaced by other more expensive units such as inefficient peaking units using natural gas or oil. In the case of a large nuclear unit replaced by natural gas-fired turbines, the additional cost can be well over one-half million dollars daily.[14]

The lost use of the transmission capacity necessary to deliver the power from a generating unit to consumers is similarly costly. The capacity to transfer power while remaining within voltage and load flow limits on the system is a constraint on economic dispatch. When sufficient transmission is not available to deliver power from the lowest cost generators to loads, other generators must be operated instead.

Any loss of generation and transmission capacity reduces the reliability of a system somewhat. The destruction of one or more major generating or transmission components reduces a system's reserves, leading to fewer options and less resilience for any further component outages. The degree to which reliability is reduced depends on the level of installed reserve margins.

BULK SYSTEM RECOVERY FROM OUTAGES

There has been little experience with the types of widespread, carefully planned and executed acts of aggression addressed in this report. However, the utility industry has a long history of responding to various kinds of emergencies, whether they are relatively small, such as an outage of a transmission circuit or a generator unit, or more serious, due to tornado damage, hurricanes or earthquakes. Most utilities have some plans in place for restoring service after a total shutdown. However, few have had to test those plans recently—in the 1980s, Florida, Texas, South Carolina, and California provide the notable examples.

Restoring service involves starting generation or reclosing circuit breakers and adding load in small increments, slowly piecing the system back together. For customers in small islands adjacent to an area that remains interconnected, power may be restored in a few minutes. Isolated islands will take

[13] U.S. Department Of Energy, *Electric Power Supply and Demand for the* Contiguous *United States* 19&1997, DOE/IIE-0013, January 1989, tables C1-C9.

[14] This estimate is based on a 1,000-MW unit outage and the average operating costs of nuclear units and gas turbines reported in U.S. Department of Energy, *Historical Plant Cost and Annual Production Expenses for Selected Electric Plants 1987,* DOE/EIA-0455(87) (Washington, DC: U.S. Government Printing Office, May 1989), figure 1. The costs are, respectively, 2.1 and 4.7 cents/kWh.

longer, especially those that were completely blacked out.

Restarting Generating Capacity

If an external source of power is available, restarting a unit is not a problem. However, if no external power sources can be used, the powerplant must have "black start" capability. Black start capability can be provided from a diesel or a self-starting gas turbine unit in the plant. It is also possible to provide black start capability from the interconnections of a system. This is done by disconnecting the interconnections from the load-serving circuits (to avoid overloading the lines) while keeping the generator connected. The interconnections can then be energized to import power from the neighboring system to use in starting the unit.

Restoring Transmission

As generating units are restarted, portions of the transmission system can be energized. The segments energized must be carefully selected to avoid building up excessive voltages due to the capacitive effects of the high-voltage lines. This requires that load be added as line segments are energized. Care must be exercised not to overload the small amount of generation connected.

A power system is restored by successively restarting generators, connecting transmission lines, and connecting load until significant islands of operating load and capacity are available. Then the separate portions of the system are connected to each other. In this way, the portions of the system that are operable can be completely restored and returned to as near normal operation as feasible. Restoration of an outage should begin within minutes of an outage. The length of time to restore full service depends on the design of the system, the severity of the blackout, and the components damaged.

SPECIFIC EXAMPLES OF ATTACKS

To evaluate the impact of sabotage on electric power systems, postulated attacks were developed and reviewed for their effect on six areas in the United States. The impact of these attacks is described below, beginning with the simplest attacks that are most applicable nationwide. Most of the attacks involve transmission circuits (whether at substations or along transmission lines).

The components attacked could be identified by someone generally familiar with power systems, either using published transmission maps or from direct observation. Physically locating the targets would involve modest effort and planning, since they are generally large and highly visible. Anyone familiar with power systems could readily identify the particular transmission facilities that need to be attacked for effective disruption. However, it is possible for unsophisticated saboteurs to mistakenly target small or relatively unimportant facilities.

These cases assume that the attack occurs at a load level of about 80 percent of annual peak load. It is also assumed that about 20 percent of the total generating capacity is undergoing maintenance or forced outage. In all of the cases, the extent of the initial interruption would not be affected by the time of day or load level. That is because the amount of reserves which are warmed up and ready to operate is sufficient to handle only one (or in some cases two) contingencies, as is standard utility practice. The near- and long-term impacts would be lessened, however, if the attacks occurred during the spring or fall when system loads are lower. In most cases, rolling blackouts would be necessary only during certain hours, e.g., between 10 a.m. and 6 p.m. on weekdays, when loads are typically their highest.

Destruction of Any One Generator, Transmission Circuit, or Transformer

As has been noted above, U.S. power systems are operated to withstand the loss of any single piece of equipment without interrupting customer load. Therefore, the destruction of any one of these would not cause a blackout. The loss of any of these may signtificantly increase a utility's operating costs, if it made replacement of low-cost baseload generators with high-cost peaking units necessary.

Destruction of One Major Multi-Circuit Transmission Substation or Multi-Unit Powerplant

As noted above, U.S. utilities generally plan for the loss of an entire multi-circuit transmission corridor, substation, or multi-unit powerplant. For such a loss, the system should not experience cascading outages. However, customer interruptions should be expected. No case was found in which such an attack would seriously disrupt the bulk power system or affect more than a subarea of a utility.

Immediately after the loss of a transmission substation (or of the multi-circuit corridor supplying it), the customers served directly and some others would be interrupted. Some more distant customers might be affected by the operation of protective relays as a result of power transients. The more distant customers interrupted would be restored in several minutes as the operators reconnected the circuit breakers and adjusted generation output. Customers in the immediate area of the failed substation would experience a longer power outage, lasting on the order of one day. Customers served by a distribution circuit powered directly from a destroyed substation might not return to service for several days or even weeks.

If a powerplant was taken out of service (whether by attacking the generating units themselves, the generation substation, or the transmission circuits leading from it to the network), the impacts would be less severe. While the outages could cover large areas, service should be restored in several minutes as operators reconnected the circuit breakers and adjusted generation output. Costs of replacement power could be high, particularly if the plant was a large, low-cost baseload unit replaced by inefficient peaking units.

Destruction of Two or Three Major Transmission Substations

Inmost cases, the nearly simultaneous destruction of two or three transmission substations would cause a serious blackout of a region or utility, although of short duration where there is an approximate balance of load and supply in the isolated areas. It is almost certain that the transmission system would have too little capacity to continue operation after the second loss, resulting in separation of the system and the interruption of customer load in several areas. Most customers would be restored within 30 minutes, after undamaged interconnections were restored. For most systems, there would be a sufficient balance of generation and load to restore all customers as soon as generation could be warmed up and brought on-line.

There are some areas of the country where failure of key substations could cause long-term disruptions. Two particularly vulnerable cities would be isolated by the loss of two or three substations, because of a serious shortage of generation. Rolling blackouts during high-load times (e.g., daytime) would occur for several weeks until temporary repairs were made.

Destruction of Four or More Major Transmission Substations

The destruction of more than three transmission substations would cause long-term blackouts in many areas of the country. Only a few areas have a good enough geographic balance of load and generation to survive this very severe test. For example, one city is served by a ring of nine evenly spaced transmission substations. Nearly all the interconnections serving this major metropolitan area would be destroyed by attacking the seven largest and easiest to identify transmission substations. The other two are smaller and of little importance during normal conditions. There is enough local generation in this case to restore service to most customers quickly, although it is considerably more expensive than the imported power. This case represents the best case of a multiple-substation attack.

A final example is a city served by eight transmission substations spread along a 250-mile line and located in five States. A knowledgeable saboteur would be needed to identify and find the eight transmission substations. A highly organized attack would also be required. However, the damage would be enormous, blacking out a four-State region, with severe degradation of both reliability and economy for months.