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TECHNICAL BROCHURE
WG C1.2

Maintenance of Acceptable Reliability in an Uncertain Environment

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The full list of members may be found in the brochure

Abstract

This technical brochure considers the issues associated with the occurrence of major system unreliability events in power systems that can be related to planning factors. These issues are examined in the context of the growing complexity of power system operations and electricity trading arrangements. Thirteen major unreliability event incidents spanning the last eight years have been studied. Specific events have been selected which in many cases have led to partial blackouts.

Some of the major events studied have included part or total loss of supply to major cities and it is useful to review network planning standards in the context of events that have occurred. This brochure therefore includes the results of a survey of planning standards in cities. This was deemed appropriate because of the relationship between reliability performance and the coordination of transmission and distribution planning. The survey was conducted among members of CIGRE Study Committee C1 and replies were received from 10 countries.

The analysis of the incidents and survey results identified a number of lead indicators of susceptibility of a particular power system to major unreliability events.

INTRODUCTION

Although major system unreliability events have a low probability of occurrence, their potential impacts on customers have far reaching effects and implications socially, politically and economically. While the causes of these major events are often multifaceted, these events are reviewed in this brochure at a high level before the planning implications are considered in more detail.

In most countries today, power system companies are faced with increasing pressure to provide a low cost and efficient service. While the required infrastructure is usually dictated by technical codes and prescribed planning criteria, there is often pressure to delay investment to the last minute and to revise planning criteria so that more risk is taken on the system. In addition, desegregation of power system utilities may lead to an elongation in the chain of communication and decreased transparency that may impact adversely on planning for reliability.

In this report, thirteen major unreliability event incidents spanning the last eight years have been studied. Economic, planning, operational and social factors have been identified in relation to each of the case studies. Possible lead indicators of unreliability have been identified to establish the risk of future major unreliability events. These can be broadly classified as economic pressures, impaired communications and system limitations. The report suggests possible solutions to these indicators in order to optimize system development and maintain and improve system reliability.

In regard to the original scope of work for the Working Group, it was decided to group the areas for investigation into three broad areas: investment for general reliability – avoiding major unreliability events; investment for local area reliability; and investment to support the market. These areas are categorized below: •••

Table 1: Areas For Investigation

Area	Probability of incident	Potential impact on reliability
Avoiding major unreliability events	Very low	Very high
Local area reliability	Low	High
Market operation	Med/high	Med/low

The work described in this brochure focuses on major unreliability events. The remaining areas are recommended for study by future working groups.

There was discussion about the roles and requirements of NERC, NPCC, UCTE and ETSO. It was concluded that direct comparison is not always straightforward or possible because some requirements are presented as interconnection rules for parallel operation, whereas other documents apply only internally to a particular power system, technical jurisdiction or member of an interconnection.

Given the importance of supply to large urban centres, particularly to their central business districts, it was decided to survey planning standards in cities. The results show the use of distribution systems to back up outages in the transmission system. A trade-off is partial utilisation of back-up assets during normal system operation.

Changing function of the transmission grid

Probably one of the main causes of a number of recent major unreliability events lies in the changing function of the transmission grid and delays in adapting to change.

For over 50 years before the deregulation and development of electricity markets, interconnected transmission infrastructure had been built for the purpose of assuring mutual assistance between national subsystems. Typically a single utility controlled generation, transmission and distribution of electrical energy in a given geographical area and such a utility generally maintained sufficient generation capacity to meet the needs of its customers. Interconnections with neighbours and long distance power transfers were generally used for emergencies, for example to provide assistance immediately following an unexpected generator outage.

Such practices contributed to system reliability aided by the laws of physics that govern the flow of electricity. To avoid line overload and tripping, the amount of power flow across each line must be kept below its capacity at all times. The difficulty in controlling individual power flows rises rapidly with the distance and complexity of the network (for example, the number of lines) along the path of an interconnection. Any change in generation or topology of the transmission network will change loads on all other generators and transmission lines in a manner that may not be anticipated or that is difficult to control.

The development of electricity markets over the past decade or two brought a fundamental change to that paradigm. Major transmission infrastructure has become no longer just a tool for mutual assistance, but a platform for shifting ever growing power volumes across the entirety of interconnected networks. Deregulation has resulted in higher cross-border and long distance energy exchanges, which are driven by short-term objectives of individual market participants. Other across-interconnection power flows result from an increasing number of major wind energy generation sources. These flows were usually not anticipated in the original designs of power systems, and difficulties now arise each time they reach and potentially exceed transmission capacity. The likelihood of this is compounded by delays in obtaining new transmission corridors, market-driven load and generation patterns, volatile wind generation infeeds and unusual network topologies.

Due to increased long distance and cross border trading across most national systems, individual Transmission System Operators (TSO) are becoming increasingly interdependent. Interconnected power systems are operated ever closer to their limits for increasingly longer times. Operation under higher stress for longer periods of time will inevitably result in more severe and more frequent incidents.

Impact on TSO Control

The changing functions of the transmission system, higher system stress, volatility of wind generation, and trading volumes changing hourly by thousands of megawatts, make daily operation of power systems much more challenging today. ●●●

At the same time as these challenges have been increasing, the range of actions available to system operators has become generally constrained by short term electricity market rules and it was noted [UCTE, "Final Report: System Disturbance on 4 November 2006", 2007] that "The need for a more complex management of interconnected grids is obvious, but has so far not always been supported by regulators and main stakeholders when TSO operators have requested more generation data and intervention rights, particularly in emergency situations."

Impact on Market Participants

Deregulation created the opportunity for greater competition between participants and this weakened the traditional spirit of cooperation that had been the hallmark of the industry for more than 50 years.

Focused mainly on profits and short term objectives, companies started to withhold information of perceived commercial value to their competitors, which was also important for coordination to achieve reliability of supply. This increased uncertainty and the probability of major unreliability events, some of which are documented in this technical brochure. Where possible, regulations mandating the sharing of information for the use of the network operators are being used to overcome confidentiality and conflict of interest issues.

Complexity

The intrinsic complexity of major unreliability events, the causes of which extend well beyond technical considerations, led to a decision to explore economic, planning, operational and social factors in relation to each of the case studies. The results, based on the available information, can be summarized as follows.

Economic

The reported electricity markets are fully or partially deregulated and unbundled. Two important findings were that deregulation changed the function of the transmission grid and that market rules may interfere with system operation. This leads to a conclusion that the regulatory framework and various incentives should take closer consideration of the impact they create on the grid and infrastructure, and should be directed towards alleviating congestion and stress of the electricity grid.

There is a need to coordinate regulatory regimes for gas and electricity, particularly when they both potentially have a major impact on the power system.

Commercial arrangements for reducing the spinning reserve are quite common. Maintaining the balance of active power in the system includes the use of interruptible loads as a substitute for spinning reserve. These loads can cover a wide range of contracted capacity, ranging from tens of megawatts (industrial customers) to thousands of megawatts (pumped storage). A more recent development is that of contracts with commercial customers for grid peak load reduction, either by disconnection of non-critical loads or by transferring all or part of demand to emergency generators.

Participation in under frequency load shedding protection appears to be mandatory in all juris- • • •

dictions. The same applies for under voltage load shedding, although these schemes do not seem to have been so commonly used.

Operational

Two response times are of concern: the time from the trigger event to blackout, and the time for restoration. These times varied substantially in the events reviewed.

It took about 4 hours for the USA/Canadian blackout to develop after the SCADA system became ineffective (about 2 hours after the loss of generation). The UCTE blackout occurred after 32 minutes of insecure operation, those in Italy and Greece occurred after 27 minutes and the one in Sweden/Denmark after 5 minutes. Nearly instantaneous loss of supply occurred in Algeria, Australia, Finland, Great Britain, Iran, Libya and Singapore.

The blackouts typically lasted between 6 minutes and 2 hours. The times for full restoration of loads ranged from 6 minutes (Australia) to between 2 to 18 hours. Extremely long timeframes were recorded in New Zealand, where it took 29 days for a blackout to develop and 3 weeks to restore supply via a temporary 110kV overhead line.

Poor communication between participants contributed to many incidents, particularly poor pre-incident inter-TSO coordination. Poor inter-TSO and TSO/DSO coordination hampered system restoration.

The lack of visibility beyond 'own borders' and lack of effective operational procedures to manage 'system-wide' disturbances were identified as problems in large interconnections. The establishment of an information platform to allow TSOs to observe in real time the actual state of the whole interconnection was recommended following a major incident.

Other reported communication problems included operator failure to record topological changes from ongoing work and TSOs having no on-line information on the total amount of connected distributed generation.

Poor communication of operational planning data and general planning assumptions to operators was also a contributing factor in many incidents. The risk of inadequate communication is high when different parties are involved and when accessing data beyond 'own borders'. For example, in one case a TSO didn't take into consideration lower protection settings on the opposite side of the interconnecting line, owned by another TSO, although this information was critical due to the very high flows on that line. In another case pre-existing line outages were not communicated to the system operator, causing the state estimator to operate incorrectly.

Planning

Planning for low probability events

The reported practices in relation to low probability contingency plans can be summarized in three broad categories:

✔ Contingency plans existed and were successfully executed. For example, the action of under frequency load shedding in Australia.

✔ Contingency plans existed but not for the severity of events that occurred, for example, there was a contingency plan for the loss of two cables in New Zealand, however four cables failed.

✔ There were no contingency plans for the type of disturbance that occurred or developed. For example one independent system operator did not measure system voltages and there were no operational procedures to shed large amounts of load in a matter of minutes (it was later found that the incident could have been avoided by containing the initial disturbance from spreading by under voltage shedding 1,500MW of load). Similarly, circuit breaker failure protection could have prevented another incident. In another case diesel fuel was used as a backup fuel, however there was no contingency plan if the transition failed.

It should also be noted that inappropriate resynchronization procedures delayed restoration in some cases.

All incidents led to the review of planning and operating practices and contingency plans.

Operational management of risks

The lack of an overall picture and poor visibility beyond a particular jurisdiction is an issue for transmission system operators in large interconnected systems.

In some cases heuristic security assessments proved unreliable in identifying N-1 insecure operation and in predicting the immediate effect of planned switching strategies. For these cases, incidents developed after the system was operated in an N-1 ●●●

insecure state or after a switching operation produced the opposite effect from that desired.

The range of actions available to system operators is generally constrained by the short term electricity market rules. The adequacy and effectiveness of such rules is not always supported by the management of specific conditions, for example those that occurred on 4 November 2006 in Europe. In another case, in Western Australia, a large wind farm, located at the far end of a longitudinal system supplied via two lines, produced unacceptable voltage fluctuations at a nearby city, however the wind farm operator was unavailable. The market rules did not allow the system operator to disconnect the line to which the wind farm was connected, as that would have brought the system into an N-1 insecure operating state. This led to a conclusion that, although the actions of the operators may impact the free operation of the market, operators must be given enough intervention rights, under certain conditions, to quickly bring the system back into the normal operating state.

Relation between design assumptions and operational behaviour

Operators generally run equipment up to assigned ratings. Actual ratings lower than assigned ratings have contributed to several incidents. In one case assumptions to calculate cable ratings were found to be inadequate. In another, inadequate clearances reduced the assigned line emergency rating. In a third case, inaccurate old cable impedance data led to incorrect protection settings. In a fourth case, a lack of spinning reserve assistance available from neighbours was a key cause. In a fifth, there was an explosion of an under-rated circuit breaker located at a key transmission installation. There was no circuit breaker failure protection to contain the disturbance. This indicates flaws in the system design. Similar design shortfalls in relation to the voltage stability contributed to two other incidents. In a few cases, generators were disconnected before the last stage of under frequency load shedding operated. This included mass disconnection of small generators connected to the distribution systems.

Many incidents occurred during a weakened state due to plant maintenance, indicating the need to study these situations in planning and operational planning timeframes. Several incidents occurred because of events well beyond the planning criteria, for which the performance of automatic remedial schemes was crucial.

Use of automatic remedial schemes

Under frequency load shedding protection (UFLS) was not always effective because it either shed less load than expected or because a large amount of generation disconnected before its last stage was activated.

System restoration problems included uncontrolled reconnection of wind generators into an island with a surplus of generation.

Social

The impact of widespread disturbances

Three of the largest incidents in Europe and North America affected between 50 and 60 million people and resulted in disconnection of between 20 and 70 thousand megawatts of load. A regional incident in the south of Sweden and Denmark affected 4 million people and 6,500 MW of load was lost. Outside these large interconnections, incidents in Algeria and Iran respectively affected 98% and 50% (22 million) of population where 5,200 MW and 7,000 MW of load was lost. Two major capital city incidents resulted in the loss of supply to 800,000 people in Helsinki and 410,000 customers in London, however many more people in London were affected due to the loss of supply to the underground railway transport services.

Governing bodies / Control hierarchy. The reported governing bodies and control hierarchy appear to be unique for each technical and legal jurisdiction to the extent that no useful comparison could be made.

Planning standards for cities

The importance of supply to large urban centres, particularly to central business districts, led to a decision to review planning standards for cities and how they safeguard against major unreliability events. A survey was emailed to members of CIGRE Study Committee C.1 in 2005. Replies were received from 10 countries.

In summary, the survey identified that, despite vastly differing practices and historical constraints, powering of major cities generally requires simultaneous consideration and coordination of the local transmission and distribution network design and operating practices. An important finding for planning for reliability is the desire to target location of generation sources in close proximity to major urban centres.

Lead indicators

Some of the early warning signs of susceptibility of a power system to major unreliability events include the number, magnitude, frequency, duration or cumulative time of events when the:

• Area Control Error (regulating error or the system frequency error) is outside the permitted dead band

• Voltages at key locations are outside their normal band

• The system is in an insecure state (risk of overload/instability following the next contingency)

• The system is in an 'unusual' state

• The number of incidents (near misses) is high

• The number of transmission load relief procedures, as a proxy for 'near miss' situations are significant

• Bulk transmission system utilisation change (%) increases over the past few years defined as the ratio between yearly electricity load demand [TWh] and equivalent EHV transmission grid extension [km]

• Percentage of time near critical transfer limits increases

• Maximum loading of key interconnectors (transmission corridors), particularly relative to the load growth, and their load duration curve is approached

• The maximum number of generating and other plant in the system that went on maintenance simultaneously is significant

• Use of equipment for duties beyond their assigned short circuit level occurs

• Percentage of disconnected load increases

• The number of projects delayed, perhaps weighted by the delay time increases, and

• Lack of clear responsibility for power system security occurs.

The analysis of incidents and planning standards in cities identified a list of key possible lead indicators of risk of major unreliability events. These can be broadly classified as economic pressures, impaired communications and system limitations. The more salient indicators are listed below:

Economic Pressures

• It is frequently difficult to obtain permission for new or upgraded infrastructure, which results in undue pressure to run systems harder.

• The development of electricity markets seems to be running ahead of the ability of power systems to support them.

• Liberalisation of network tariffs has resulted in unforseen changes to patterns of generation and line flows

• Inter-regional trading places pressure on interconnectors originally intended only for interchange of mutual support power. Insufficient knowledge of changes to generation and the network in neighbouring systems has exacerbated this problem.

• The ability of TSO's to manage critical events is often constrained by short-term market rules that place market purity ahead of system security.

• The economic incentives/penalties for generators to contribute to reliability may be inadequate.

• Following a large disturbance, the automatic reconnection of unscheduled generation such as wind must be balanced by decreased generation from other plant. This has not always happened and the question arises whether market rules facilitate this.

• There has been insufficient enforcement of technical standards that contribute to reliability.

• Not all markets provide sufficient incentive for reliable generation of reactive power.

• Responsibilities for system adequacy are not always clear.

• The mass proliferation of distributed sources of generation has contributed significantly to the pool of generation but there has been a lack of knowledge of the momentary status of these generators and their performance during power system disturbances, especially their fault ride-through capability.

Impaired Communication Channels

• Between planners and system operators there has been a lack of transparency in communication of accepted emergency procedures, and amongst system operators, information flow has been impaired by structural and hierarchical changes

• Generators have been reluctant to share information such as dynamic models to protect perceived competitive advantages – an issue at the planning stage. In some countries this information is required to be placed in the public domain.

• Inter TSO and TSO/DSO coordination is essential in operational timeframes. Limited visibility inhibits the ability to prepare contingency plans for emergency situations.

• A need has been established for limited visibility beyond the boundary of owned assets in order to manage disturbances that spread across the boundaries.

• Effective operator communication is required along the entire path of flow of electricity inclusive of neighbours that can significantly alter the path. ● ● ●

System Limitations

• Difficulty in obtaining approval for new lines has substantially increased the utilisation of some systems with a consequent reduction in redundant capacity.

• System limitations must be identified along the whole path of electricity flow between trading partners eg action in one country may transfer the problem to another. Condensed models of a neighbouring system have not always proven adequate.

• Unpredictability of output of large wind generation installations increases complexity of operational planning, especially security assessment.

• The occurrence of cascade events is very difficult to predict.

• Inadequate protection methods may have system-wide consequences.

• There is a need for defence plans that may include sacrificing parts of the system to save others (when absolutely necessary).

Possible solutions

Some of the possible solutions proposed by this study are:

• Clarify the responsibility for power system security.

• The regulatory framework for electricity and gas and various incentives should take closer consideration of the impact they create on the grid and infrastructure, and should be directed towards alleviating congestion and stress of the electricity grid.

• Promote the placement of new generation in close proximity to load centres thereby eliminating the need for long power transfers.

• Rather than confining to a particular jurisdiction, conduct planning and real-time contingency assessment studies to encompass the entire paths of major normal and emergency power flows.

• Increase co-ordination of system planning and emergency procedures and training of operators to handle emergencies.

• Increase stakeholder awareness of system limitations and economic/reliability trade-offs.

• Devise protection systems to contain the spread of the initial disturbance for low probability events.

• Co-ordinate maintenance across jurisdictions.

• Consider introducing a new planning criterion that addresses the impact of multiple maintenance events during off-peak times.

• Install Wide Area Protection (WAP), Wide Area Measurement System (WAMS) and synchronised high speed data recorders.

• Establish an information platform to allow TSOs to observe in real time the actual state of the whole interconnection.

• Investigate the formulation of maintenance congestion as an indicator of system stress at off-peak times and develop local planning criteria based on this.

• Mandate plant performance characteristics for all generators, including non-synchronous and distributed generation, in the areas of fault ride through capability and the duration and magnitude of the generator fault current contributions that are sufficient for protections to see the fault and provide adequate voltage support.

• In systems with high penetration of distributed generation, TSOs should have on-line access to their status, schedules and changes to the schedules, at least one minute data in the form of aggregate generation data provided by individual DSOs.

• Investigate the practicality of intelligent household appliances (e.g. storage hot water) that would self load-shed during major under-frequency events.

Conclusions

There is great industry interest in major unreliability events. The gravest concerns are in relation to those that occur in major population centres or are spread over a vast area. Thirteen recent major unreliability events have been documented in this report and planning standards for cities have been surveyed. Economic, planning, operational and social aspects of major unreliability events were identified which led to the development of proposals for lead indicators of susceptibility of power systems to these events.

Economic pressures, impaired communication channels and system limitations were identified as the key lead indicators. Other contributing factors fall under the headings of social, economic, planning and operational complexity. This has led to a conclusion that underlying causes may have originated in rules and regulations governing electricity markets and power system operations but their consequences have been exacerbated by subsequent planning and operational decisions. ■