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Power Outages in 2003

Task Force Power Outages

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EXECUTIVE SUMMARY

A series of significant power outages during 2003 has drawn political and public attention to the issue of secure electricity supply. These events coincided with the adoption of the 2nd Internal Electricity Market Directive, at a time when a degree of scepticism towards market liberalisation was already being manifested among citizens and politicians in some quarters of Europe. While system operators launched a thorough evaluation of the events, the European Commission reacted by tabling a package of measures intended to ensure security of supply. EURELECTRIC has decided to examine the recent blackouts from a liberalisation point of view, and discover whether any direct link between the parallel opening and integrating of the European electricity markets and such events can be established.

EURELECTRIC's main finding is that **liberalisation did not** in itself **lead to the recent blackouts**. Blackouts have always occurred from time to time since the beginnings of electrification. Market liberalisation and the creation of a single European market have indeed changed the environment in which a secure electricity supply must continue to be ensured. The "traditional" integrated planning of power generation and transmission has disappeared; the European networks, originally designed for mutual assistance, are now hosting transit of commercial flows over long distances, driving system operators to become more and more inter-dependent, while at the same time substantial commercial interests have appeared and the number of market actors has significantly increased. These new challenges must be duly evaluated, the necessary technical, organisational and functional adjustments need to be defined, and appropriate measures must be taken. These measures can and should be defined via an intensive dialogue between system operators, regulators and other actors in the electricity market. EURELECTRIC is ready and willing to participate in and contribute to this dialogue.

EURELECTRIC's conclusions and recommendations (not intended to be exhaustive) include:

- The independence and strength of system operators did not play a direct role in the recent power outages in Europe.
- The evolution of the European electricity system due to liberalisation must be duly examined and evaluated, through the widest possible consultation, involving effective representation of all parties in the European electricity market.
- Already ongoing investigations on more dynamic system security criteria, complementary to the broadly applied n-1 principle, should continue.
- Involvement of interruptible customers should be encouraged. Voltage sensitive actions need further development, also including load shedding techniques, as a last resort.
- Strategic distribution of active and reactive power along the grid, co-ordinated with load centres, would make a major contribution towards reducing risks of serious disturbances on the network. However, any such measure must be critically scrutinised so as to avoid distortions in the market.
- Based on the experiences, defence plans must be updated. This includes the performance of generators and network components during transients, and also the restoration and re-energising of systems following a power outage. Black-start capability and house-load operation should be specified and contracted between system operators and generators.
- A prudent and responsible regulatory framework is needed in order to facilitate the necessary network investments and reinforcements.[1]

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[1] "Ensuring Investment in a Liberalised Electricity Sector", EURELECTRIC report, March 2004

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1. Introduction and summary of events

Europe has enjoyed a secure electricity supply for decades. Minor and major blackouts did happen, yet the overall reliability of supply has been very high. However, a coincidental series of unforeseen major blackouts in America and Europe during 2003 raised public awareness of the issue of security of supply, and has also driven public's and politicians' sensitivity in this regard higher. All of it occurred, when the overall process of liberalisation and particularly its ability to provide long-term security of supply was being questioned by some organisations and fora.

EURELECTRIC members acknowledge that major power outages are viewed by consumers as a failure of the whole electricity industry, irrespective of the actual reasons and contributing factors. The society will hardly tolerate interruptions in the extent of those have occurred since the summer of 2003. Hence, although they cannot be avoided altogether, the probability of blackouts should be minimised and their consequences must be mitigated as much as reasonably achievable.

The power outage events may increase scepticism to liberalisation in citizens, and have already done so in some officials both at national and European levels. Right after the events, EURELECTRIC believed that it would have been far too early to draw conclusions on the successfulness of liberalisation process, before – or instead – properly examining the actual causes and contributing factors. In order to gain full understanding, the recent events must be thoroughly examined. EURELECTRIC has established a special task force to undertake the task of uncovering the relationship between liberalisation and recent outages, and exploring how system security issues shall be handled within the frame of the fully liberalised market. The task force left the technical evaluations to the relevant organisations (e.g. UCTE and NORDEL, and also the involved TSOs and national regulators); but at the same time fully took account of and built on their results.

The list of events examined by the task force is arbitrary and not exhaustive. The aim was to contain events that happened to get into the political focus during 2003, both in Europe and worldwide. Some further events, which might have skipped attention but provide edifying lessons to be learnt, are also included, even if they did not all lead to actual power outages. More detailed summaries of the individual events can be found in the Annex.

The events in this report are referred to by a short, single-country name; even if they involved more countries (e.g. the power outage on September 23, 2003 in Southern Sweden and Eastern Denmark is referred to as "Sweden"), so as make reading easier.

Spain – December 17, 2001

As a result of combination of extremely cold weather conditions and a highly drought year, on Monday 17th December, the Spanish system was running under emergency conditions from 17:30 till 19:30.

Not only the peak load has increased constantly since 1998, the generation capacity has not practically grown up in the last three years (except renewables and cogeneration under the "Special Regime").

That day the availability of thermal generating units was lower than usual and the hydropower stations were not able to offer the energy they normally provide. The TSO was obliged to adopt severe measures to keep the system running: to cancel exports; to ask the clients under special tariff for interrupting their consumption; to import so much energy as the neighbours (France Morocco and Portugal) were able to offer at those hours; to request producers for maximum generation and so on.

Lastly at 18:45, in view of the seriousness of the situation in two specific areas of the system, the TSO requested the load shedding of some 500 MW in Madrid and Levante regions. A 50 % of the shed load was restored at 19:40 and the 100 % at 19:55.

Good co-ordination between the TSO and distribution companies, and use of well-established operation procedures (e.g. load shedding and interruptible supply mechanisms) played key roles in avoiding the voltage collapse, and in quickly recovering normal operation of the system.

Unsupplied energy was about 300 MWh.

Denmark – December 28, 2002

In an otherwise calm operational situation on a Saturday morning, a relay failure led to a disconnection of a million customers in Western and Northern Jutland. The situation seemed to be sustainable, when a second relay error tripped one of the two 150 kV transmission lines from East to West, leading to overloading the second line, which then also tripped. Eventually, the Northern part of the grid was islanded. Load shedding and other emergency measures were not able to prevent a collapse.

While the initiator of the event was two independent relay errors, unsuccessful house load-operation of two units and failure to automatically start up an emergency supply unit have possibly contributed to the final extension of the blackout.

The event involved the loss of 800 MW domestic consumption and 1,800 MW export. In three hours, the supply was fully recovered. Lost production is estimated at 2,200 MWh.

US/Canada – August 14, 2003

The electric system of Northern Ohio was in a reliable operational state, though being operated near prescribed limits, due to moderately high demand to serve air conditioning. High imports and unavailability of units depleted the critical voltage support. Tripping of a 345 kV transmission line due to tree contact, combined with a lack of adequate assessment of system conditions for three hours, led to overloading several other transmission lines without appropriate warnings and operational instructions. A combination of lack of sense of emergency in control room personnel, loss of alarm function, loss of remote control consoles, loss of even the primary server computer without being noticed for an hour, let condition of the electrical system degrade, with the control room's personnel being unaware. In half an hour, three 345 kV lines tripped due to tree contacts. Overloading caused a cascade tripping of several remaining lines.

The numerous causes and contributing factors can be grouped into three categories:

- inadequate situational awareness of TSO;
- inadequate management of tree growth in transmission rights-of-way;

- inadequate diagnostic support.

61,800 MW of load were lost at 4 p.m. on August 14; at 8 a.m. the following morning (16 hours later) 48,800 MW were restored. Hence, some 16,000 MW experienced a longer than 16 hour outage.

The restoration varied between the utilities:
- Consolidated Edison fully restored service after 29 hours;
- FirstEnergy restored service to a vast majority of its customers within 36 hours;
- Long Island Power Authority needed 3 days;
- Ontario had full service restored at 8 p.m. on Friday, August 22 (8 full days after the blackout).

The event involved loss of 263 power plants (531 individual units) and left 50 million customers without power in the US and Canada (unsupplied energy: circa 350,000 MWh).

Austria – August 27, 2003 (no loss of supply)

An automatic scram of Krsko Nuclear Power Plant in Slovenia was in half a second followed by an overcurrent trip of a 400 kV transmission line between Hungary and Croatia (welded contact of line protection). Thermal limits overrun by 15% led to tripping of 3 lines between Austria and Czech Republic. Finally the current fell below 115%, preventing a tripping of all lines between Austria and Hungary by only 2 seconds. During the event, many of the transmission lines in the Germany – Austria – Czech Republic – Slovakia – Hungary – Slovenia – Croatia area were overloaded, and several cross-border flows changed direction.

The normal operational situation was recovered in 20 minutes to 2 hours.

The event did not impose any loss of supply.

United Kingdom – August 28, 2003

Following an alarm caused by low oil level in a shunt reactor, a transformer was disconnected from the distribution system, as the normal practice in this case. Unexpectedly, automatic protection equipment interpreted the change of power flows, due to the transformer disconnection, as a fault, and disconnected 410,000 customers, including parts of London Underground and Network Rail. Supply was recovered in half an hour (though the restoration of underground operation took longer for safety reasons).

The cause of the incident was the incorrect rating of a protection relay, undiscovered by the extensive quality control and commissioning procedures.

The event involved the loss of 433 MWh supply.

Sweden – September 23, 2003

During a situation with certain import, a number of interconnectors and power lines in maintenance and four nuclear units out of operation, the electric system in Southern Sweden experienced the loss of a large nuclear unit, which was a normal n-1 contingency. Approximately 5 minutes after the loss of the large nuclear unit, a double bus-bar fault in a substation on the West coast disconnected four out of five 400 kV transmission lines. Two of the lines provided connection between Central and Southern Sweden, while the two others connected two large nuclear units to the grid. Increasing flows on the remaining lines and low voltage in Southern Sweden was interpreted by protection relays as a remote short circuit, and Southern Sweden and Eastern Denmark were completely disconnected from the Central after 90 seconds. This happened approximately 5 minutes after the loss of the large nuclear unit and approximately 90 seconds after the bus-bar fault.

Restoration in Denmark was slower than in Sweden, because the black-start facilities in the central power plants on Zeeland failed to operate. The units on Zeeland were disconnected after the collapse of the islanded Southern Sweden – Eastern Denmark subsystem, and did at that time not go into house load operation. The 400 kV grid in Southern Sweden was restored in about an hour. The recovery of the supply took one to six hours in Sweden and Denmark.

The root cause of the incident was the combination of the initial loss of the large nuclear unit with the double bus-bar fault in the substation on the West coast, which drove the system beyond its security criteria (n-3 situation).

The lost supply was about 10,000 MWh in Sweden and 8,000 MWh in Eastern Denmark.

Italy – September 28, 2003

Italy was importing about a quarter of the domestic consumption (including big pumped storage plants) through fifteen transmission lines from France, Switzerland, Slovenia and Austria, when a line tripped due to tree contact. After re-connection failed, the Swiss grid operator called for a 300 MW decrease in import (in order to return to the actually scheduled import), failing to recognise the overloading of the remaining lines. In twenty minutes, a second line tripped, initiating a cascade tripping of all transmission lines along the Italian border. In two and a half minutes, the islanded Italy went into a total blackout (except Sardine).

4 root causes were identified:

- line-trippings due to tree flash-over;
- unsuccessful re-closing of the first tripped line;
- lack of sense of urgency regarding the overload of the second line;
- angle instability and voltage collapse in Italy.

The event involved some thousand citizens in Switzerland for 1 to 2 hours; and 55 million citizens in Italy for up to 20 hours (unsupplied energy: circa 200,000 MWh).

2. Common elements and their root causes

EURELECTRIC thoroughly and critically studied the available reports on the different events (power outages and load shedding), and, based on its own expertise, has developed the following understanding of their contributing factors.

	SPAIN	DENMARK	USA	AUSTRIA	UK	SWEDEN	ITALY
1. Outside the dimensioning criteria	○	●	○	●	○	●	◉
2. Not foreseen event in dimensioning criteria of the system	◉	●	○	○	○	●	○
3. Inadequate management of rights-of-way	○	○	●	○	○	○	◉
4. Lack of investment in network	○	○	◉	●	○	○	○
5. Inadequate demands on co-ordination, co-operation or communication	○	○	◉	◉	○	○	◉
6. TSOs did not meet demands on co-ordination, co-operation or communication; lacked situational awareness	○	○	●	○	○	○	◉
7. Inadequate defence plans or inefficient manual or automatic load shedding	○	○	◉	◉	○	○	●
8. Inadequate distribution of active or reactive generation	◉	○	◉	◉	○	◉	◉
9. Inadequate operational requirements on generation plants	○	◉	○	○	○	○	●
10. Generating plants did not meet operational requirements							
11. Has distributed generation capacity increased the scope of the event	○	○	○	○	○	◉	◉
12. Has intermittent generation (e.g. wind power) capacity increased the scope of the event	○	◉	○	○	○	◉	○
13. Would better demand response have decreased the scope of the event	○	◉	○	○	◉	◉	●
14. Would reinforcement of the grid have had positive impact	○	●	○	●	○	●	◉
15. Would higher strength, independence or responsibility of involved TSOs have had positive impact	○	○	●	○	○	○	○
16. Large and long-distance commercial flows	○	◉	◉	●	○	○	●
17. Protection maloperation	○	●	◉	●	●	○	○
18. Education and training	○	◉	●	○	○	○	◉
19. Availability of adequate IT-tools for information evaluation	○	◉	●	●	○	○	○

Legend: ● strong contribution ◉ some contribution ○ no contribution

Some of the factors are briefly discussed below (the corresponding row of the table is indicated between brackets).

***Dimensioning criteria* (1, 2)**

It appears that the n-1 criterion was met before all events. However, the fulfilment of the n-1 criterion induces that in a limited period of time after an incident, it is necessary to come back to a situation allowing the loss of a system element. This means that no malfunction should happen during that time and that adequate actions have to be taken by the grid operators. In most of the studied cases, this requirement was not fulfilled: relays malfunctioned, inadequate countermeasures were taken, etc. In some cases, events outside the dimensioning criteria caused the outage (e.g. simultaneous loss of 2 lines).

***Lack of investment in and reinforcement of networks* (4, 14)**

There is no evidence, for the studied events, that the lack of investment in networks was a direct cause in power outages. Some lines were operated clearly close to their technical (thermal) limits. It is obvious that a reinforcement of the grid would have had a positive impact. It must be noted that the actual effect of reinforcement depends on whether it increases the reserve capacity of the line, and is not simply used to increase the flows in normal conditions.

***Co-operation and communication among TSOs* (5, 6)**

It has been noticed that in the most important events, the lack of correct information exchange and/or coordination between TSOs contributed to the extent of the power outage. In some cases, it may have been caused by a lack of situational awareness.

***Inadequate defence plan or load shedding* (7)**

The inadequacy (or the lack of preparedness) of a defence plan played a major role in contributing to the final extent of the outage in Italy. In some other cases, this impact was lower, yet present.

***Inadequate distribution of active or reactive power* (8)**

The adequacy of this distribution can be questioned in some instances. In several cases, the ability to maintain voltage seemed to be close to its limits.

***Inadequate operational instructions and early tripping of generation plants* (9, 10)**

The behaviour of power plants during the events needs deep investigations, regarding whether the plants:

- were not set to sustain the conditions such as low voltages, high instability, etc.;
- did not succeed to go into house-load operation despite their design;
- were exactly designed to protect themselves.

These investigations are still ongoing. The evolution of safety conditions of the grid following a fault to a great extent depends on the protection philosophy of units (i.e. a compromise between the capability to sustain the conditions and to keep on-line; and the need to protect the unit from the potentially damaging disturbances). Following a blackout, a rapid restoration of the grid can be more successful and rapid, when some units are designed for house-load operation (and they actually succeed to go into house-load operation).

***Impact of distributed generation* (11)**

No direct conclusions regarding the effects of distributed generation can be drawn from the examined events. In general, an increase of distributed capacity reduces the amount of reactive power in the area, making the area more susceptible to voltage collapse. The proper installation of reactive power components, such as synchronous generators, can reduce this problem. If no adequate requirements for such generators are developed, their unselective tripping can contribute to system instability,

***Impact of the response of intermittent generation* (12)**

The behaviour or the potential effects of intermittent generation (particularly that of windpower), shows a limited impact during these events. If no adequate requirements for such generators are developed, their unselective tripping can contribute to system instability,

***Demand response* (13)**

A better response or a better control of the demand, taking into account the limits of the lines, could have limited the extent of the events, or even helped to avoid them in most cases.

***Independence of TSOs* (15)**

It seems that it was not a factor in the European incidents. The case of US/Canada, however, indicates an important impact linked to a lack of clear responsibility of the TSO.

***Large and long-distance commercial flows* (16)**

Such flows may induce instability and difficulties for the power plants to cope with that situation (e.g. Italy, US), as well as for system operators (e.g. to reconnect lines due to angle differences in Italian case).

***Protection maloperation* (17)**

The incidents have often shown a negative impact of the protections:

- Relays with wrong set point (e.g. UK).
- Distance relays interpreting low voltage as a short circuit (e.g. US/Canada) and opening lines. This action could lead to an increase of the scope of the outage or, on the other hand, limit the area affected. This point needs further investigation.

***Education and training* (18)**

Human errors or wrong human behaviour have led to an increase of the consequences of the initial event. The lack of preparedness of emergency plans was obvious in some power outages such as in Italy or US/Canada. Most of these problems could be solved or reduced by adequate education or training.

***Adequate IT-tools* (19)**

In particular in the US/Canada power outage, the problems of the IT tool in the dispatching room (systems not available and lack of alarms to alert the operators) were an important contributor to the degradation of the event.

Some other common elements can be identified in the analysed reports, such as:

- Lack of maintenance: tree cutting, etc. (e.g. US/Canada, Italy).
- Usage of the lines close to the limits (e.g. US/Canada, Austria, Italy).

3. Financial consequences of blackouts

The outages cost more and more for the society. One consequence of this is that the public administration lays higher requirements for the operators. Furthermore, customers try to claim more and more compensation referring to blackouts. This tendency will be amplified along completing liberalisation of the market (cf. eligible consumers).

Different studies, mainly based on customers' own evaluations, provide widely ranging estimates for the cost of an unsupplied kWh. Shorter outages for industrial customers are valued the highest levels (e.g. 1,000 €/kWh), while long outages (over 24 hours) are put by residential customers around 5€/kWh, and in cases below 1€/kWh. It must be noted that these estimations are to a great extent uncertain; partly due to a lack of objective approximation of actually incurred costs, and partly due to the difficulties of drawing an appropriate balance between including and excluding directly and indirectly associated damages (e.g. a longer outage of the London Underground due to safety considerations was a consequence of the otherwise short UK event).

Due to their increasing financial consequences, it is of vital importance to take the necessary measures to contain the already occurred power outages in both geographical terms and in time. This includes adequately calibrated protective measures to "seal" the already involved areas and also the ability of certain network entities to operate as islands; and the quickest possible restoration of the system and power supply afterwards.

4. Recommendations

The events examined in this report show a wide range of root causes and contributing factors. The contribution of these factors varies for case to case, but each of them either played a significant role in at least some of the events, or was seen as of major importance by the task force. Hence, the task force deemed it desirable to individually examine these factors to unveil what roles they actually played in the events. Where appropriate, the group also tried to identify areas of possible improvements.

The following issues – which were approved of by EURELECTRIC's Board of Directors on November 13, 2003 – are grouped along the following lines:

- role and co-operation of TSOs;
- security criteria currently in use;
- handling of load;
- ancillary services;
- investments.

Strength, responsibility and functional independence of TSOs

In extreme grid fault situations, the TSO is expected to take actions to minimise the impact and to limit disruption of supply to regions. When a blackout has occurred it is up to TSO to restore supply and smooth operation as quickly as possible. In this context, technical and especially organisational requirements have to be fulfilled. These are: responsibility, ability and authority to take corrective action in grid operation and last but not least independence when making decisions.

Firstly, it is of fundamental importance having well-defined responsibility. This is given in Europe. When the latest European blackouts happened, responsibilities of TSOs were clearly defined. Even with hindsight, there is no need for correction in this regard. This was different with the blackout in the US/Canada. When liberalised market came into being there has been an independent system operator (ISO) established on top. Regarding the August 2003 blackout it is criticised that responsibilities, organisations and system management were coordinated in inappropriate manner.

Furthermore even if responsibilities are clearly defined it is indispensable to have TSOs being able to intervene directly e.g. using remote control access or giving orders by phone to permanent operated control rooms. Again, this was not given with the US/Canada blackout; while the Midwest Independent System Operator (MISO) performed supervisory functions, it could not intervene directly and use appropriate technical measures. In contrast, European TSOs are authorised to take decisions. Adequately trained staff and technical equipment should be used.

Moreover, TSOs have to be independent, when taking a decision. Specific interests of affiliated companies (functional and organisational unbundling), or other groups of market participants must not influence them. The Regulation on conditions for access to network for cross border exchanges ensures that there is no commercial conflict in congestion management, as it controls the use of congestions revenues in a way that TSOs will have no advantage (revenues to be used for construction of new lines, maintenance, reducing use of system charges). There is, however, a strong pressure from market participants with trading activities. These groups force TSOs to maximise Available Transmission Capacities (ATC), which in turn leads to reducing reliability margins. TSOs have to be obliged to take an adequate reliability margin into account ("security first"). Information regarding available capacities on congested interconnectors should be handled in a transparent manner.

Further on taking corrective action on physical load flows might be a measure which could be criticised by market participants. If thereby a disturbance was avoided, it is the TSO's dilemma to prove *ex post* that the particular measure taken was indeed needed to prevent a blackout.

Conclusion

Apparently, TSOs' responsibility and independency did not play a direct role in the recent blackouts in Europe.

Recommendation

Against the background of increasing long-distance load flows, it is important to assert TSOs' position, to take adequate reliability margins into account and to make sure that today's well proven system will be continually developed in future.

Communication, coordination and co-operation among TSOs

Rules

The mission of the TSOs is to ensure the transmission of electricity from generators to the distribution system. It means:

- ensure physical flows, without compromising the security of the grid;
- facilitate commercial flows.

Most of the existing cross-border lines connecting in Europe were designed in the past to realise a large network improving global safety, socialising reserves and providing mutual assistance in case of emergency (generation or grid faults). Today, as the single European electricity market is developing, the transmission networks are more frequently used for commercial exchange of electricity and thus operated closer to their technical limits, whilst their security margins are reduced. This trend is encouraged by regulators, who aim at stimulating competition among Member States. In addition, with the increasing cross-border trade of electricity, transmission system operators are becoming more dependent on each other. At the same time, TSOs in the UCTE area are still applying non-binding recommendations, which were developed before liberalisation (since 1999, a binding System Operation Agreement is in force between the NORDEL TSOs; requiring *inter alia* the currently valid security criteria to observed in daily operations). Hence, the strategies for defence, restoration and information exchange must be updated according to the development of the power system and the market.

EURELECTRIC acknowledges and supports that system operators (UCTE, NORDEL, etc.) already started – well before the recent blackouts – and currently work on the abovementioned update, eventually aiming at elaborating a binding compilation of operational rules for transmission system operators.

Communication and data exchange among TSOs are crucial in ensuring a smooth operation of a single European electricity market, through ensuring greater transparency and better understanding of potentially critical situations. In such cases (e.g. a threatening or actual power outage), the fast, open and effective communication is vital in both avoiding the event and containing it, if happens; as well as in restoring the system. This communication must be based on the clear understanding of mutual benefits.

Scheduling

Transmission of large flows on long distances needs to be carefully studied. It raises specific technical problems depending on the continuously changing situations of the system.

Consequence of a fault may lead to blackouts due to the *cascade effect*, whose extent is rather unforeseeable. Under the guidance of the regulators, TSOs have the expertise to make it possible to authorise or to forbid increasing international transmission on their own grid. For cross border-flows, the studies must be coordinated between the concerned TSOs. Due to potentially serious consequences of a failure on the grid, they must be accountable for bringing the sufficient technical guarantees.

Real time operation

In order to be able to respect the security rules (e.g. n-1 criterion), TSOs must exchange technical data. Exchange of information on active and reactive power flows on cross-border lines are a minimum requirement. But the respect of safety rules across boundaries induces the respect of safety rules inside the countries involved. (e.g.: in Italy, the initially tripping lines were Swiss, not cross-border interconnectors). TSOs have to share the necessary data about the grid, which enables an efficient control of security rules by each of them. A great level of transparency regarding grid data is recommended. However, some data may be commercially (economically) valuable and may lead to confidentiality difficulties; therefore, TSOs must ensure the confidentiality of these data.

Solutions for a commercial handling of re-dispatch measures in emergency situations should be developed.

Lack of situational awareness

Under real time operation, available information has to be provided in a useable way (see adequate IT-tools). The staff needs to be aware of the situation also in the surrounding systems to draw the right conclusions and to take appropriate countermeasures – also in situations that yield stress to the staff. In the Italian blackout it seems there was a lack of sense of urgency.

Conclusion

The lack or inadequacy of communication, co-ordination and/or data exchange between system operators seems to have played a major role in the escalation of some of the examined events.

In some cases, there was a lack of sense of urgency, so that the designed procedures were not applied.

Recommendation

Binding rules for coordination among system operators both in normal operation and in other situations are desirable. These rules must take account of the new challenges imposed by the liberalisation and integration of the European markets (larger cross-border flows, appearance of commercial interests, etc.).

Tools and means to intensify collection and availability of real-time data should be examined and established.

Dimensioning criterion

The n-1 principle

The n-1 criterion means that loss of a single element of the network does not cause unmanageable (and thus escalating) disturbances, because the other elements could replace the lost function ("single loss security"). The transmission network by itself has to satisfy the n-1 criterion.

This principle is commonly applied, although it is not the only principle in use. On the highest voltage levels it implies that the grid must be meshed and the necessary spare capacity in generation and transmission must be observed. The n-1 rule also implies that after a first incident, measures should be taken within a specified period (e.g. in 15 minutes in NORDEL) to return the system normal security situation (i.e. where a loss of a single element is manageable). In particular, the n-1 principle aims at avoiding *cascade effects* (which happened in Italy).

The realisation of the n-1 principle depends on the local situation of the interconnected networks.

Probabilistic methods

During some of the events, the system was being recovered from an "n-1 situation" and being brought back to normal operation, when a further event compromised the stability of the system. Such events raise the question what "n-1" actually means. There are different definitions in use for "1" (i.e. what is the single item of the system whose loss must be handled), as well as for how quickly the system must return to normal operation. However, this required quickness should depend on what item has been lost (e.g. a cross-border transmission line on a congested border should definitely be made available quickly, compared to a less highly stressed transmission component). Hence, a more dynamic criterion to define the permissible time of loss for individual items in different operational scenarios is desirable to be developed. Such a system should take account of the following aspects (not exhaustive):

- expectable loss of further elements as a consequence of the failure;
- number of customers expected to lose supply;
- profile of customers expected to lose supply;
- time and efforts needed to recover from the failure;
- possibilities to by-pass the failure;
- etc.

Conclusion

The n-1 security level proved irrelevant as defence in Sweden and Denmark, where the combination of contingencies appeared to be at a n-3 level (the actual security level prior to the events has been estimated from simulations to be at n-2 level).
Inappropriate application of the n-1 principle (i.e. recovering of the normal operation within a certain period of time) clearly contributed to the events in the US/Canada and Italy.

Recommendation

Although the deepening of defence beyond n-1 level (n-2, n-3, etc.) could enhance system security, its cost effectiveness is questionable.
Already ongoing investigations on a more flexible probability-based approach, in addition to the n-1 principle, should continue; where the duration, profile and consequences of a blackout can be taken into account in defining the necessary level of defence.

Involvement of demand response in balancing

In theory there are many ways of involving demand response in balancing or ways which can be considered as demand response. Arbitrarily, they can be grouped into two categories:

Price sensitive customers

The buyers can demand electricity as a function of the price in the spot market. This facility is well used by industries in e.g. Norway and UK et al., and is also used by the system operator in e.g. Sweden as peak capacity. Also in Denmark trials are carried out, where customers decrease consumption as a reaction to prices in the spot market. These initiatives are probably used or planned to be used in a number of other countries. In this report, in the definition of balancing we do not consider this demand response to prices in the spot market to be demand response in balancing. This type of response started out to be more intended to decrease consumption and substitute reserve or peak capacity more than it was a tool in critical situations with risk of a blackout.

Recent developments and investigations have shown that TSOs also contract these customers to be shut down in the event of overload of lines, critically insufficient supply and other situations, which could pose a threat to system security. The customers are then paid the agreed price to be disconnected in the critical situations, which means that the TSO has more tools in critical situations, where he will have to choose primarily the safest response and secondarily the cheapest necessary response.

The price of demand reductions must in a fair, objective and transparent manner be compared with the price of reserve capacity and other measures.

Interruptible customers

In some countries there is at certain times not enough production or transmission capacity to operate certain areas safely. In these areas certain groups of customers can be cut off for short periods. For this, they are sometimes offered compensation. The interruption of the power supply is planned and is carried out with relatively long notice. In this report, these interruptible customers are not considered as demand response in order to avoid blackouts. It could be argued that had the system operator not planned these rolling black-outs, the risk of black-outs would have increased as the system probably could not have been operated within the n-1 criteria.

Customers with consumption can participate in tenders in the balancing market, together with suppliers with emergency power supply (e.g. Denmark). These customers put their consumption or production at the disposal of the system operator. They can be activated within 5 to 15 minutes and are activated on one button. The second controlling layer has coded the amount and gradient of regulating power for the different suppliers.

Conclusion

Contracts between TSO and large customers in order to reduce consumption, as a function of price or as demand reduction in critical situation, can increase system security in a number of situations and thereby in the end reduce the number of blackouts. The contract must however be easy to manage for the TSO and must be ordered in a manner that is safe and does not increase the complexity of the task of the TSO to the extent, where there is a risk that appropriate measures are not taken when critical situations arise.

Recommendation

TSOs should continue the work of contracting large customers to reduce consumption in critical situations or as price sensitive customers to the extent that these contracts are more cost efficient than peak capacity and to the extent that they can reduce the risk of blackouts.
TSOs should collaborate on the experiences gained in the areas and cooperate on new measures so that they are integrated appropriately and most efficiently.

Manual and automatic load shedding

In the case of overload and/or low voltage levels manual or automatic load shedding can considerably reduce the risk of a complete blackout and support the fast restoration of supply. For deliberate shedding of selected industrial consumers such measures might be agreed upon by contracts.

As long as the whole synchronous area stays linked together, frequencies near 49.0 Hz are far out of reach and thus frequency load shedding can only take place after splitting of networks and during island operation of parts of the grid (e.g. losing a load of 6,600 MW in Italy caused the frequency to rise by 0.2 Hz in the rest of the UCTE area). Though maintenance and testing of the related frequency sensitive devices is difficult and risky, it should be performed regularly according to defence plans.

TSOs should focus their attention on additional actions to avoid voltage collapse. Performance of these measures can also be done by manual switching, but this can sometimes be too late for remedial action depending on the dynamics of the collapse.

Voltage sensitive actions would include:
- automatic shut down of shunt reactors and storage pumps;
- (automatic) increase of active and reactive power of generators;
- automatic blocking of on-load tap changers (supplying customers with reduced voltage and thus relieving load of the endangered area);
- automatic (delayed) load shedding if voltage in transmission system remains below approximately 85% of nominal value; same as with frequency load shedding, certain customers (e.g. hospitals) may be excluded from this measure.

All measures must be coordinated within the areas under each TSO’s responsibility because major parts of these actions have to be performed within distribution networks at lower voltage levels.

Conclusion

Frequency load shedding will be decisive for successful island operation following disturbances that cause the European grid to split into smaller parts.

Long distance transport of active and reactive power will increase voltage problems in case of contingencies. This may cause voltage collapse within areas, which have not experienced this kind of blackout up to now.

Recommendation

Taking account of the frequency stability of the current European networks, re-evaluating the adequacy of the starting point of frequency load shedding should be considered (nowadays a threshold of 49.0 Hz is in common use).

Voltage sensitive actions – particularly blocking of tap changers and load shedding – should be studied and eventually included into international emergency procedures and/or into national grid codes.

Periodic testing of devices related to emergency actions should be part of defence plans.

Ancillary services

Transmission of large flows on long distance is critical for grid safety. In case of fault of one or several elements of the system, generation unit or line, it is desirable that the grid be able to withstand transients of power, voltage and frequency. In these cases, grid safety depends a lot on generation unit performances.

As part of their daily operation, TSOs have to define specifically the unit performances they need to ensure operational safety, taking into account the large number of competing generation companies. They have to re-dispatch the power among their grid. If these performances induce additional costs for generators, TSOs have to compensate them.

The specifications for ancillary services should be harmonised, where appropriate. Depending on their proportion of the generation fleet, distributed generators, connected at medium and low voltage levels, may have a significant influence on the safety of the grid. Therefore, their participation in ancillary services and their design requirements should be examined.

TSOs and generators usually contract upon the commitment expected depending on the grid characteristics: standard commitment for the whole grid, specific if necessary for cross-border interconnections.

In case of a blackout, TSO has to restore the grid as fast as possible. The duration mainly depends on the unit capacity to restart. The restoration is easier, when some units are designed for black-start. But generally, only small units have the black-start capability. For large power plants, house-load operation is the normal practice, in order to allow the TSO to organise the grid with generation and consumption on small regions immediately after the blackout (US thermal power plants are not designed for house-load operation – the restoration took 50 hours).

Black-start and house-load operation capabilities for long enough periods are ancillary services, for which TSOs and generators have to contract.

Conclusion

Ancillary services are vital in safely managing grids, and also in restoration following a blackout.

Recommendation

Black-start and house-load operation capabilities should be considered ancillary services, for which system operators and generators can contract. Other ancillary services, as and where appropriate, should be procured in market conditions.[2]

The role distributed and/or intermittent generation can play in ensuring operational safety of the grid should be examined.

Distribution of active and reactive power sources

Power systems must ensure in every consumption node the required quality characteristics, namely frequency and voltage. Frequency is a common feature in the entire network, but voltage has a local behaviour. The main tool to regulate voltage is the "correct" localisation of active and reactive power (i.e. active and reactive power should – as much as possible – be build near the big consumption centres, where the voltage problems are more intense). On the other hand, the difficulties encountered to build new power plants in these particular areas are usually considerable and the economical incentives are rather negative. To build reactive power in the "correct" places (by system operators) is certainly easier, because it is possible to install static reactive power in existing substations and, of course, the cost can be recovered through system tariffs.

There are several options to attract new generation in areas where it is needed. One of the options is to apply economic incentives, e.g. to differentiate the connection fees according to the location along the grid (locational signals). These locational signals are only one of the factors among various "non-electrical" locational factors, such as taxes, environmental laws, activities of local authorities in order to hinder or promote investments on certain purposes. These factors are not harmonised and can to a great extent strengthen or diminish the effect of "electrical" locational signals.

In fact, there is natural affinity in new generation units to prioritising places close to importing groups, for the reason that the possibly necessary reinforcements of the grid are less extensive, hence the connection can be relatively easier, less expensive and more rapid.

Conclusion

The correct localisation of active and reactive power can certainly improve the quality characteristics in consumption centres and, furthermore, can contribute to diminishing the probability of blackouts.

Recommendation

According to the national legal environment, regulators can adopt certain tools, so as to facilitate such localisation of active and reactive power. However, any measures of that kind must be critically scrutinised to avoid distortions in the market.

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[2] Ancillary services – An emerging market, EURELECTRIC 2004

Defence plans and operational requirements for generating plants

As already indicated, the ability of generators to ride through power system disturbances is crucial to successful post fault recovery. Typically disturbances such as electrical faults on the network, particularly close to the generator terminals, will readily provide severe short-term transient conditions. However generators must also ride through disturbances of a wider nature, such as network splits, which create significant frequency or voltage disturbances. Whilst islanded systems will by their very nature regularly see wider frequency deviations, mainland Europe networks can also suffer splits leading to operational requirements down to around 47 Hz.

Defence plans for generating equipment against wider network disturbances will normally be dealt with in the following ways:

Specification

The formal conditions for connection of a generator to the grid (e.g. network code or generator specification) will typically set out the requirements for maintaining active power output under continuous conditions (e.g. for Europe 49.5 Hz to 50.5 Hz) and for transient conditions (e.g. down to 47 Hz) with associated time limits. In addition output of active and reactive power will be specified under a range of voltage conditions.

Procurement/Construction

Usually the generator manufacturer will provide details of how the specification will be met. This may include design diagrams, governor and excitation system block diagrams, and test evidence which may include control system tuning studies and simulations.

Pre-commissioning

System operators will perform power system studies to include parameters provided by the manufacturer.

Commissioning

As part of the final stage before entering commercial service it is possible to check the performance of the generator (e.g. steady state and transient power output) although only against steady state frequency and nominal voltage perturbations.

Service performance

By undertaking a post event review of generator dynamic stability following a network fault it may be possible to verify performance but limited by the conditions at the time.

Whilst frequency defence measures are relatively well established, tested and understood, this is not necessarily the case for defence against voltage collapse. With systems now moving much closer to their design limits voltage performance is becoming more brittle. Performance of generators (particularly their auxiliaries) and of network reactive compensation under low voltage conditions is becoming more critical. With the Italian blackout there is evidence that falling voltage conditions caused generators to trip and this accelerated the eventual blackout. Furthermore the link needs to be drawn to defence plans which disconnect demand under voltage collapse conditions. The conclusion is that further work is desirable in the area of defence plans (both network and generator) for voltage collapse conditions.

The final requirement is for a restoration plan with the ability to restart the network after a blackout. Usually network operators deal with this by having black-start contingency plans with certain generators and through black-start plans, procedures and simulation tests for system operators. Evidence from all European blackouts is that each recovery was generally efficient, assisted in many cases by the availability of cross-border energy supplies which help to resynchronise disconnected generation.

Conclusion

It is important that generators are able to respond to network disturbances and provide a defence against transient and system collapse conditions, without sustaining damage.

Further work is desirable in the area of defence plans (both network and generator) for voltage collapse conditions.

Recommendation

The required dynamic performance of generation plants should be assessed and proven via adequate specification, commissioning and in-service testing.

Further studies should be undertaken to examine the performance of networks and network components (e.g. generation, reactive compensation, protection distance relays) under progressive voltage collapse conditions.

The effect of intermittent generation, particularly wind-power

Energy systems have been steadily developed for over hundred years; however, launch of big number of small and distributed sources of energy, which could be observed in recent years, as well as their dynamic development, creates a great challenge for managing energy systems. The influence that distributed sources have on operation and functioning of these systems will increase proportionally to their number and capacity they have. Analysis of this impact contribute in better preparing of these systems to work in new conditions, in adjusting the characteristics of these sources for the needs of final customers as well as in proper way the regulations and technical requirements linked to the functioning of these systems are formulated.

The renewables, particularly wind generation, have an important effect on the management of the power systems, as well as on the security and reliability of the networks. The development of this technology is mainly determined by subsidies and political agreements.

The technical integration of renewables, particularly wind energy, requires solving of three basic problems:

- balance between supply and demand of electricity;
- rules for the connection to the grid;
- grid extension.

The wind generation has some specific characteristics, which influence the grid, due to:

- technical aspects (protections, inductions machines, etc);
- no-predictable behaviour of the primary source;
- number of wind farms connected to the distribution network.

EU legislation promotes the generation of energy with the use of renewable sources. Sources like these can originate both as distributed sources characterised by low capacity and sporadically they can have large capacity. A significant number of distributed sources have not been equipped with the central management systems thus their work is uneasy to be adjusted to the functioning of energy systems. Difficulties with balancing the generation level and the demand create special problems. Additionally the functioning of part of these sources depends in large extend on external conditions limitedly predictable – wind, clouds or water level, etc. Dependence of energy generation, in case of some sources that are unpredictable and impossible to regulate, seems to be difficult to overcome in the context of managing the energy system, the more so as in recent years wind farms with large installed capacity have been built. In practice, intermittent sources require back-up of quick reserve, generated by other technologies.

Functioning of distributed energy sources influences the quality of energy in grid, the stable and secure work of the energy system and also the ecological generation of electricity. The most important task is to ensure a stable functioning of the energy system, which means continuous balancing between energy generated and energy used by the customers in accordance to their needs. The imbalance causes certain costs; in certain situations even the base load units may have to reduce the generation in order to keep the system in balance.

Operation of renewable sources may also influence voltage parameters such as: frequency, shape of flow, phase symmetry and change of value. Power shedding, changes in level of generation as well as introduction of new sources of that type may cause changes of frequency. It means that reserves should be kept for the regulatory purposes in the conventional power stations.

In some cases distributed sources may also decrease the safety of supply leading to power outages. Limitation of negative influence that distributed sources and wind farms have on energy system is possible with the implementation of technical, regulatory, organisational means, and also with adequate investments made in the power grid. Disturbances can be eliminated both by system power stations as well as by some part of the distributed sources, provided they are managed properly and centrally controlled (cf. virtual power plants).

Energy, which is generated with the use of distributed sources, may be used for ancillary services that are usually provided for the energy system. It may be regulation and power reserve, regulation of reactive power, voltage control as well black-start capability to participate in rebuilding of a system in case of its collapse.

Functioning of distributed energy generates costs that result from the big number of additional activities, which have to be periodically executed by system operators as from technical requirements that have to be fulfilled. Making forecast regarding the level of generation in distributed sources is a very complex process, which involves the implementation of sophisticated computing models which take into consideration both the technical and the atmospheric parameters.

The integration of huge new renewables wind farms makes new harmonised connecting rules and proper incentives necessary to avoid negative effects on the stability of existing electrical systems across Europe.

Conclusion

The growing capacity of intermittent sources, particularly wind energy, makes new harmonised connecting rules necessary.
The installed and planned intermittent sources in large scale requires extension of existing and erection of new grid infrastructure.
The increasing share of intermittent generation increases the need for ancillary services.

Recommendation

The potential effects of intermittent generation on system security must be evaluated. Harmonisation of connection rules and the future development of ancillary services must reflect the outcome of this evaluation.

Realisation of the necessary investments in generation

With the help of the electricity market Directives 96/92/EC and 2003/54/EC, the European Union is in the process of changing its electricity markets into one single liberalised market. This reform is expected to lead to greater efficiency and lower prices but maintaining the very high security of electricity supply that Europe has enjoyed for many years. With a few exemptions there is still overcapacity in generation in most European countries and the single electricity market with more exchange of power between countries gives automatically a higher reserve margin since national reserve capacities become available for all countries if sufficient transmission capacity is installed. How much higher reserve margin that can be achieved depends on differences in national load patterns, climate differences and economical factors but the impact is clearly limited due to small time differences within the European Union and physical constraints in transmission.

Despite that there is mainly sufficient generation capacity available short-term, there is a growing concern that adequate level of investments in generation will not take place in a liberalised electricity market. Lower electricity prices, increased investment risks, long lead times, unclear regulation and increasing environmental requirements might slow down the investment plans. In combination with a growing demand and ageing power plants, which soon will be retired, there is a risk that the balance between demand and supply could be difficult to obtain. The increased interest in distributed generation might improve the situation but will not be enough to meet the huge need for new generation capacity (estimated to 500-600 GW in the period 2000-2030). Therefore some actors sometimes request other incentives than pure market forces in order to secure an adequate level of generation. Examples of possible incentives besides the electricity price are:

- Central planning and market intervention
- Direct or indirect subsidies as investment support
- Feed-in tariffs
- Green certificates for RES
- Emission trading
- Capacity fees
- Regulation

Perhaps the most important incentive (or hindrance) for new investments is the design of regulation. In order to stimulate investments, regulation must be stable, clear, predictable, fair, transparent and adequately harmonised. Furthermore, it must ensure that lead times for obtaining permits are shortened and the consequences for the industry of any new regulatory interventions must be carefully analysed before implementation.

Incentive schemes such as green certificates for RES, emission trading and capacity fees can be designed in a market-based way but will always introduce some kind of distortion in a liberalised market compared to just having the electricity price as the driving force for new investments in generation. Other incentives mentioned above would severely distort the market.

It should be noted that the 2nd Internal Electricity Market Directive provides an impressive list of tools for market surveillance. It allows governments to organise direct tendering procedures where judged appropriate to ensure security of supply.

Some other conclusions from a new EURELECTRIC study[3] regarding ensuring investments in generation are these:

- The internal electricity market should be allowed to mature into a fully functioning free open market before new Directives and rules are introduced. Existing instruments in the newly approved IEM Directive such as capacity tendering should be used (but only in exceptional situations) in order to secure enough capacity in local areas where there is some lack of capacity.
- The electricity price is the best signal for investments. Price caps would damage the market and incentives for investments. All energy options should be left open, so that a balanced portfolio of renewables, gas, coal, hydropower and nuclear energy can be maintained.
- Longer-term contracts could stabilise the market and protect the customers. A suitable mixture of spot market and longer-term contracts could develop a liberalised market with reduced risks and attractive for investments
- Interaction of the customers is important in order to obtain a good balance of demand and supply. The use of interruptible contracts is a way of reducing the demand peak and the shortage of supply.
- In order to guarantee **reserve capacity margins** for short-term security of supply, the responsible authority could put in place systems using market mechanisms, such as capacity auctions, in exceptional cases when enough capacity is not available. However, EURELECTRIC believes that these mechanisms and tendering processes for **new power plants** must be specifically designed for the said purpose of security of supply, and must be properly calibrated; otherwise they would distort the price signals and weaken the incentive for using peak and building new capacity.

EURELECTRIC has strong confidence in the ability of the liberalised market to ensure both security of supply and the necessary investments in a sustainable manner, i.e. providing economic savings, if an attractive investment climate is created.

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[3] Ensuring Investment in a Liberalised Electricity Sector, EURELECTRIC 2004

Conclusion

There will soon be a great need for investments in new power plants. In a liberalised market the electricity price is the best signal for investments and all types of price caps would damage the market and weaken the incentives for investments. In order to solve exceptional capacity problems in local areas, existing instruments in the IEM Directive such as tendering process could be used for building new power plants and market-based mechanisms such as capacity auctions used to guarantee reserve capacity margins for short-term security of supply.

Recommendation

The implementation of the IEM Directive and creation of a fully liberalised single market should be speeded up. In order to stimulate investments in generation a clear, stable and efficient regulatory system and attractive investment climate must be created. If incentives for RES and/or CHP are introduced, they must be market-based and applied equally across Europe.

Grid reinforcements and investment into networks

The analyses made by the task force shows different root causes and contributing factors of the recent blackouts in Europe and US/Canada: human errors, *force majeure*, regional lack of balance between active/reactive power generation and demand, technical problems with power system management, unclear responsibilities and communication between transmission system operators or lack of maintenance (especially tree-cutting), and also network topology itself.

It has to be taken into account that the existent transmission grids in Europe were planned for supplying regional markets and not for European-wide commercial load flows. Existing interconnections were mainly planned for temporary support between TSOs in emergency circumstances. So, in some cases more interconnection capacity can be one of the contributions to reduce the possibility for outages as the system has to cope with an increasing European electricity market and, as a consequence, an increasing interstate load-flow. However, it should not be neglected that power production close to the load centres is still the best solution from a system security point of view.

Actually, in many countries there are no appropriate incentives for TSOs to invest in cross-border lines, where the return on investment is not sufficiently ensured by the regulation. There is no clear and stable framework for national grid-fees, cross-border tariffs and capacity auctions, which would secure an acceptable rate of return on investment. Close co-operation regarding the need of the interconnection and its financing between TSOs, the regulators and/or governments involved (even at European level, if necessary) must precede the decision on the development of interconnections. In this context, TSOs dispose of the necessary technical knowledge to carry out technical planning activities. Furthermore, TSOs have to bear all the risks associated with the interconnector investment and should therefore be in charge of the actual financial planning.

It has also to be mentioned that delays in the construction of new lines are normally not due to the TSO but to local opposition. Unfortunately, there is often no finalising of the licensing procedure within acceptable time limits possible. Approval procedures have to be faster and easier. For infrastructure-projects a close co-operation and coordination between involved TSOs and competent authorities for approval following a tight time schedule is necessary. There has to be a mutual understanding concerning rights and duties of every involved party. In this respect, building underground cables instead of overhead lines is in most cases not an alternative due to technical and commercial reasons.

Conclusion

Actually, in many countries there are no appropriate incentives for TSOs to invest in cross-border lines, where the return on investment is not sufficiently ensured by the regulation.

Recommendation

Stable framework is necessary for national grid-fees, cross-border tariffs and capacity auctions in order to secure an acceptable rate of return on investment.

5. Conclusions: the impact of liberalisation and the role of regulation

It would be very wrong to blame market liberalisation itself for the blackouts that have occurred recently, but liberalisation has changed the rules of the game, increasing the number of actors. Planning and operation of transmission systems need to take account of this new complexity.

The unbundling of generation and transmission breaks the earlier planning link for an integrated company, where there was a choice between reinforcement of interconnection and more power generation to cover increases in electricity demand within an area. In today’s liberalised market, the transmission system operator has limited influence on the localisation of new generation, other than via the tariffs for connection and for feeding electricity into the network.

Liberalisation also means that the earlier planning method, where each integrated generation and transmission company was normally self-sufficient, is being replaced by a system in which electricity is localised and generated where it is most economic to do so. This means that transit flows are increasing and that the transmission links are more often being operated close to their limits. Blackouts have also become more difficult to contain within smaller areas. TSOs have to take that into account in their planning, and this may mean for instance that they have to strengthen the dimensioning criteria. They may also have to find adequate ways to procure necessary services from generators in order to bring the system into operation again much more rapidly, after a blackout occurs.

Market liberalisation and the increased transit flows make transmission system operators more inter-dependent and thus put much higher demands on cooperation and coordination among TSOs. Systems can no longer be operated as if they were independent.

Liberalisation itself and the regulatory system have to be designed in such a way as to give the TSOs the right incentives to maintain optimum capacity and reliability of the transmission system. This means that the regulation should provide incentives to carry out appropriate expansion of the transmission system with respect to the anticipated flows that arise due to the economic operation of the power generation system. The organisation of the operations should also be done in such a way as to facilitate the best possible functioning of the market.

There should be strong incentives to maintain high availability of the system, i.e.:

- make necessary investments in equipment and IT systems in order to develop and maintain best possible knowledge of the conditions in the system,
- carry out necessary maintenance to keep high standards – tree pruning, etc
- train the personnel to cope with the ever-more complicated working environment

The unbundling of generation and transmission should be carried out in such a way that:

- organisation within company groups is such that there are no incentives to compromise system security by prioritising or by taking into account the interests of for example trade for another business unit in the group
- operational personnel feel confident that the system security is the overarching goal even though this may sometimes lead to reductions in transit. Operational personnel should be able to make such reductions without risk of being unduly criticised.

ANNEX
Review of major events

The summaries are based on the reports from different organisations, listed on the last page. They reflect the task force's understanding of those reports, and are not intended to deliver any judgement on responsibilities of any kind.

1. Spain – December 17, 2001

1.1 Description

Date: 17 December 2001.

a) As a result of combination of extremely cold weather conditions and a highly drought year, on Monday the 17th December, the Spanish system was running under emergency conditions from 17:30 to 19:30. The unavailability of 2147 MW of thermal generating units, of which 1656 MW located in south and east regions and the hydropower stations were not able to offer the energy they normally are, led to NW to SE high transmission flows. Several thermal power plants reduced the active power output, in order to increase the reactive power output. The action increased more the NW-SE power flows and very low voltages were recorded especially in Levante and Madrid regions.

b) After adoption of all available preventive and corrective measures, and with all available power generation in operation at full load –and, simultaneously, growing the demand up to an historical peak value-, the risk of voltage collapse was becoming imminent. At 18:45 hour the TSO requires to Iberdrola and Unión-Fenosa (distribution companies) to apply load shedding in Madrid (300 MW) and Levante (200 MW) regions, in order to recovery voltage nominal values in Levante.

c) From 18:45 to 19:55, restoration of the system was carried out. At 19:40 50% of load shaded was reconnected. At 19:55 instruction was given by the TSO to reconnect 50% of remaining load.

1.2 Reasons of the event

No reserve margin, to face to extreme unfavourable circumstances. In this case:

low hydro reserves –low sustainable hydro power out put- as a consequence of extreme dry season,

high unavailability of thermal generation mix –mainly as a consequence of changes in operation regime that the wholesale market brought out-, and

historical peak demands, simultaneously to adverse meteorological circumstances all over Europe –that led to singular difficulties in receiving support from the European grid-.

The impact of the described event was reduced to a manageable level as a consequence of a well co-ordinated operation of TSO and dispatches of the generation and distribution companies. (A part of the traditional 'co-operative culture' in grid operation –compatible with the increasing competitive environment- seems to have been ‘put to work’ during the described event, supporting actions and leading to the most convenient behaviour of all players in such circumstances).

A well established sequential use of **operational procedures** –including activation of interruptible supply mechanism and clearly established load shedding procedures- in order to avoid dramatic generation-demand unbalance, and permanent actualised **regional and national grid recovery planning**, were also very useful –indispensable- tools to face such an extremely unfavourable scenario.

2. Denmark – December 28, 2002

2.1 Short description of the event and consequences

System breakdown in Western and Northern Jutland, Saturday 28 December 2002

On Saturday 28 December at 06:45 the overall grid in Western Denmark was subject to a double relay error which caused a black out in Western and Northern Jutland within seven seconds. One million inhabitants did not have any power. It was fortunate that the breakdown happened early Saturday morning between Christmas and New Year. Ahead of the breakdown Saturday morning the situation in the power system was very calm.

From Jutland and Funen 1,180 MW was exported to the North (Norway 940 MW and Sweden 240 MW) and 590 MW was imported from Germany. Due to a dry year situation in the North there was thus a large transport on the 150 and 400 kV-grid towards the North. The consumption was approx. 1,900 MW. The total power production in Jutland and on Funen was 2,490 MW (wind power approx. 330 MW, decentralised combined heat and power plants approx. 880 MW and centralised plants approx. 1,280 MW).

The breakdown started at 06:45:10 when the 400 kV T-connection Kassø-Endrup-Tjele was interrupted because of an error in the relay protection in Kassø and Endrup. The error was a data-transfer delay. The T-connection was only decoupled in the south. If the relays had been set up differently, the whole 400 kV could have set out and power to Norway would have been cut of.

Since the Norhtern end remained operative, the transit to the North went for the other lines in the transmission system and the transport to Noway did not decrease). The load on the two 150 kV cables between Trige and Tange was approx. 90% of their transmission capacity, which they ought to be dimensioned for. Due to a latent relay error in Tange, one of the cables was tripped, and then things happened very quickly. The second l50 kV-line from east to west is overloaded and tripped on relay protection. The last line from south to north was closed down after another two seconds. The northern part of Jutland had large power deficit and frequency dropped fast. Emergency power measures on DC-links to Sweden and Norway and load shedding of other consumers (frequency) was not enough to stabilize the system. Seven seconds after the first error the northern part of Jutland was without power.

Two units in the area did not successfully go into turbine house load-operation. and one smaller unit to support black start did not start. These incidents have possibly prolonged the extension of the black-out, but would not have prevented it.

The situation shortly after the breakdown:

800 MW local consumption and 1,180 MW export was lost.
The production from 310 MW wind power, 470 MW decentralised combined heat and power plants and 350 MW from centralised plants was stopped. This led to a power surplus in the rest of Jutland and Funen and to avoid a too large export for Germany the other centralised plants in Jutland and on Funen had to regulate down.

At 07:04 the reestablishment of the grid started and at 09:50 the transmission grid and the supply to the distribution grid was re-established. Lost production is estimated to 2200 MWh.

2.2 Reasons according to investigator

Relay error 1 trips the 400 kV T-connection Kassø-Endrup-Tjele.
Relay error 2 trips the 150 kV line Tjele-Tange and then the northern part of Jutland trips.

3. US/Canada – August 14, 2003

3.1 Short description of the event and consequences

This summary is derived from U.S.-Canada Power System Outage Task Force Interim Report: Causes of the August 14th Blackout in the United States and Canada. The report investigates the sequence of events that lead to the outage when more than 60,000 MW of load was lost and 50 million people were affected, and analyzes the reasons.

Status of the Northeastern Power Grid Before the Blackout Sequence Began

The Task Force's investigators found that at 15:05 Eastern Daylight Time, immediately before the tripping of FirstEnergy's (FE) Harding-Chamberlin 345-kV transmission line, the system was able to be operated reliably following the occurrence of any of more than 800 contingencies, including the loss of the Harding-Chamberlin line. At that point the system was being operated near (but still within) prescribed limits and in compliance with NERC's (North American Elictric Reliability Council) operating policies.

Determining that the system was in a reliable operational state at that time is extremely significant for understanding the causes of the blackout. It means that none of the electrical conditions on the system before 15:05 was a direct cause of the blackout. This eliminates a number of possible causes of the blackout, whether individually or in
combination with one another, such as:

- High power flows to Canada
- System frequency variations
- Low voltages earlier in the day or on prior days
- Low reactive power output from Independent Power Producers (IPPs)
- Unavailability of individual generators or transmission lines.

Phase 1: A normal afternoon degrades

Northern Ohio was experiencing an ordinary August afternoon, with loads moderately high to serve air conditioning demand. FirstEnergy (FE) was importing approximately 2,000 MW into its service territory, causing its system to consume high levels of reactive power. With two of Cleveland's active and reactive power production anchors already shut down (Davis-Besse and Eastlake 4), the loss of the Eastlake 5 unit at 13:31 further depleted critical voltage support for the Cleveland-Akron area. With Eastlake 5 gone, transmission line loadings were notably higher. Loss of Eastlake 5, however, did not initiate the blackout. At 14:02, Dayton Power & Light's (DPL) Stuart-Atlanta 345-kV line tripped off-line due to a tree contact. This line had no direct electrical effect on FE's system — but it did affect MISO's (Midwest Independent System Operator) performance as reliability coordinator, even though PJM is the reliability coordinator for the DPL line. One of MISO's primary system condition evaluation tools, its state estimator, was unable to assess system conditions for most of the period between 12:37 and 15:34, due to a combination of human error and the effect of the loss of DPL's Stuart-Atlanta line on other MISO lines as reflected in the state estimator's calculations. Without an effective state estimator, MISO was unable to perform contingency analyses of generation and line losses within its reliability zone. Therefore, through 15:34 MISO could not determine that with Eastlake 5 down, other transmission lines would overload if FE lost a major transmission line, and could not issue appropriate warnings and operational instructions.

Following the loss of Eastlake 5 at 13:31, FE's operators' concern about voltage levels was heightened. They called Bayshore at 13:41 and Perry at 13:43 to ask the plants for more voltage support. Again, while there was substantial effort to support voltages in the Ohio area, First Energy personnel characterized the conditions not being unusual for a peak load day, although this was not an all-time (or record) peak load day.

Phase 2: FE's computer failures

Starting around 14:14, FE's control room operators lost the alarm function that provided audible and visual indications when a significant piece of equipment changed from an acceptable to problematic condition. Shortly thereafter, the Energy Management System (EMS) lost a number of its remote control consoles. Next it lost the primary server computer that was hosting the alarm function, and then the backup server such that all functions that were being supported on these servers were stopped at 14:54. However, for over an hour no one in FE's control room grasped that their computer systems were not operating properly, even though FE's Information Technology support staff knew of the problems and were working to solve them, and the absence of alarms and other symptoms offered many clues to the operators of the EMS system's impaired state. Thus, without a functioning EMS or the knowledge that it had failed, FE's system operators remained unaware that their electrical system condition was beginning to degrade. Unknowingly, they used the outdated system condition information they did have to discount information from others about growing system problems.

Phase 3: Three FE 345-kV transmission line failures and many phone calls

From 15:05:41 to 15:41:35, three 345-kV lines failed with power flows at or below each transmission line's emergency rating. Each was the result of a contact between a line and a tree that had grown so tall that, over a period of years, it encroached into the required clearance height for the line. As each line failed, its outage increased the loading on the remaining lines. As each of the transmission lines failed, and power flows shifted to other transmission paths, voltages on the rest of FE's system degraded further.

Beginning no earlier than 14:14 when their EMS alarms failed, and until at least 15:42 when they began to recognize their situation, FE operators did not understand how much of their system was being lost, and did not realize the degree to which their perception of their system was in error versus true system conditions, despite receiving clues via phone calls from AEP, PJM and MISO, and customers. The FE operators were not aware of line outages that occurred after the trip of Eastlake 5 at 13:31 until approximately 15:45, although they were beginning to get external input describing aspects of the system's weakening condition. Since FE's operators were not aware and did not recognize events as they were occurring, they took no actions to return the system to a reliable state.

FE's operators did not believe the transmission line failures reported by AEP and MISO were real until 15:42 after FE conversations with AEP and MISO control rooms and calls from FE IT staff to report the failure of their alarms. At that point of time, FE operators began to think that their system might be in jeopardy but they did not act to restore any of the lost transmission lines, clearly alert their reliability coordinator or neighbours about their situations or take other possible remedial measures (such as load-shedding) to stabilise their system..

By around 15:46 when MISO and neighbouring utilities had also begun to realize that the FE system was in jeopardy, the only way that the blackout might have been averted would have been to drop at least 1,500 to 2,500 MW of load around Cleveland and Akron, and at this time the amount of load reduction required was increasing rapidly. No such effort was made, however, and by 15:46 it may already have been too late regardless of any such effort.

Phase 4: The collapse of the FE 138-kV system and loss of the Sammis-Star line

After 15:46, the loss of some of FE's key 345-kV lines in northern Ohio caused its underlying network of 138-kV lines to begin to fail, leading in turn to the loss of FE's Sammis-Star 345-kV line at 16:06.

As each of FE's 345-kV lines in the Cleveland area tripped out, it increased loading and decreased voltage on the underlying 138-kV system serving Cleveland and Akron, pushing those lines into overload. Starting at 15:39, the first of an eventual sixteen 138-kV lines began to fail. As these lines failed, the voltage drops caused a number of large industrial customers with voltage sensitive equipment to go off-line automatically to protect their operations. As the 138-kV lines opened, they blacked out customers in Akron and the areas west and south of the city, ultimately dropping about 600 MW of load. The Sammis-Star 345-kV line stayed in service until it tripped at 16:05:57. The loss of FE's Sammis-Star line was the event that triggered the uncontrollable cascade portion of the blackout sequence. The loss of the Sammis-Star line triggered the cascade because it shut down the 345-kV path into northern Ohio from eastern Ohio After16:06, the cascade evolved in three distinct phases:

Phase 5. The collapse of FE's transmission system induced unplanned power surges across the region. Shortly before the collapse, large electricity flows were moving across FE's system from generators in the south (Tennessee, Kentucky, Missouri) to load centers in northern Ohio, eastern Michigan, and Ontario. This pathway in northeastern Ohio became unavailable with the collapse of FE's transmission system. The electricity then took alternative paths to the load centers located along the shore of Lake Erie. Power surged in from western Ohio and Indiana on one side and from Pennsylvania through New York and Ontario around the northern side of Lake Erie. Transmission lines in these areas, however, were already heavily loaded with normal flows, and some of them began to trip.

Phase 6. The northeast then separated from the rest of the Eastern Interconnection due to these additional power surges. The power surges resulting from the FE system failures caused lines in neighboring areas to see overloads that caused impedance relays to operate. The result was a wave of line trips through western Ohio that separated AEP from FE. Then the line trips progressed northward into Michigan separating western and eastern Michigan. With paths cut from the west, a massive power surge flowed from PJM into New York and Ontario in a counter-clockwise flow around Lake Erie to serve the load still connected in eastern Michigan and northern Ohio. The relays on the lines between PJM and New York saw this massive power surge as faults and tripped those lines. Lines in western Ontario also became overloaded and tripped. The entire northeastern United States and the province of Ontario then became a large electrical island separated from the rest of the Eastern Interconnection. This large island, which had been importing power prior to the cascade, quickly became unstable as there was not sufficient generation in operation within it to meet electricity demand. Systems to the south and west of the split, such as PJM, AEP and others further away remained intact and were mostly unaffected by the outage. Once the northeast split from the rest of the Eastern Interconnection, the cascade was isolated.

Phase 7. In the final phase, the large electrical island in the northeast was deficient in generation and unstable with large power surges and swings in frequency and voltage. As a result, many lines and generators across the disturbance area tripped, breaking the area into several electrical islands. Generation and load within these smaller islands was often unbalanced, leading to further tripping of lines and generating units until equilibrium was established in each island. Although much of the disturbance area was fully blacked out in this process, some islands were able to reach equilibrium without total loss of service. For example, most of New England was stabilized and generation and load restored to balance. Approximately half of the generation and load remained on in western New York, which has an abundance of generation. By comparison, other areas with large load centers and insufficient generation nearby to meet that load collapsed into a blackout condition.

By 16:13, more than 263 power plants (531 individual generating units) had been lost, and tens of millions of people in the United States and Canada were without electric power.

Restoration

61,800 MW of load were lost at 4 p.m. on August 14; at 8 a.m. the following morning (16 hours later) 48,800 MW were restored. Hence, some 16,000 MW experienced a longer than 16 hour outage.

The restoration varied between the utilities:

- Consolidated Edison fully restored service after 29 hours;
- FirstEnergy restored service to a vast majority of its customers within 36 hours;
- Long Island Power Authority needed 3 days;
- Ontario had full service restored at 8 p.m. on Friday, August 22 (8 full days after the blackout).

3.2 Reasons according to investigator

The initiation of the August 14, 2003, blackout was caused by deficiencies in specific practices, equipment, and human decisions that coincided that afternoon. There were three groups of causes:

Group 1: Inadequate situational awareness at FirstEnergy Corporation (FE)

In particular:

- FE failed to ensure the security of its transmission system after significant unforeseen contingencies because it did not use an effective contingency analysis capability on a routine basis.
- FE lacked procedures to ensure that their operators were continually aware of the functional state of their critical monitoring tools.
- FE lacked procedures to test effectively the functional state of these tools after repairs were made.
- FE did not have additional monitoring tools for high-level visualization of the status of their transmission system to facilitate its operators' understanding of transmission system conditions after the failure of their primary monitoring/alarming systems.
-

Group 2: FE failed to manage adequately tree growth in its transmission rights-of-way

This failure was the common cause of the outage of three FE 345-kV transmission lines.

Group 3: Failure of the interconnected grid's reliability organizations to provide effective diagnostic support

In particular:

- MISO did not have real-time data from Dayton Power and Light's Stuart-Atlanta 345-kV line incorporated into its state estimator (a system monitoring tool). This precluded MISO from becoming aware of FE's system problems earlier and providing diagnostic assistance to FE.
- MISO's reliability coordinators were using non-real-time data to support real-time "flowgate" monitoring. This prevented MISO from detecting an N-1 security violation in FE's system and from assisting FE in necessary relief actions.
- MISO lacked an effective means of identifying the location and significance of transmission line breaker operations reported by their Energy Management System (EMS). Such information would have enabled MISO operators to become aware earlier of important line outages.
- PJM and MISO lacked joint procedures or guidelines on when and how to coordinate a security limit violation observed by one of them in the other's area due to a contingency near their common boundary.

4. Austria –August 27, 2003

4.1 Short description of the event and consequences

The event can be divided into three stages. First, the Krsko Nuclear Power Plant in Slovenia tripped. Then, a transmission line between Hungary and Croatia opened due to a tripping at Tumbri substation, caused by a welded contact of line protection. As a result, an automatic disconnection device in Austria triggered and caused severe load flow changes in the neighbouring systems. The minimum voltage level was reached in Southern Austria and Slovenia within 5 minutes.

Outage of Krsko Nuclear Power Plant
During a test procedure of some safety valves, an improper setting of a switch led to an automatic switch-off of the unit at 9:15.

Outage of line Hévíz-Tumbri
Half a second after the NPP trip, a 400 kV breaker feeder was tripped by CBF protection, due to a welded contact. Following the trip of the Krsko NPP, load flow of Hévíz lines increased to up to more than 1300 A (overcurrent trigger level). CBF protection sent tripping command not only to all breakers in Tumbri station (where all feeders were connected to one busbar system due to scheduled maintenance works), but also to Hévíz through the telecommunication system.

Automatic disconnection of tie-lines in Austria
Following the NPP trip and the disconnection of Tumbri-Hévíz line, the load flow in Austria increased in such a way that the double circuit line Wien-Südost – Ternitz reached a current approximately 110% of thermal rating, and then in a few minutes exceeded 115%. The automatic disconnection device tripped 2 lines at Bisamberg (to Sokolnice) and 1 line at Dürnrohr (to Slavetice), 4 minutes after the NPP trip. With these three lines disconnected, the current fell below 115% and the tripping sequence stopped – preventing the tripping of all tie-lines with Hungary just by 2 seconds.

Recover
Line Hévíz-Tumbri was closed 2 hours and 6 minutes after the initiating NPP trip. The three Austrian lines were closed after 2 hours and 30 minutes.

Disturbances during the event

Czech Republic
Power flows started to flow from Czech Republic to Germany, instead of the schedule Germany to Czech Republic (a change from -3 MW to +297 MW). Flow between Czech Republic and Germany increased from 1100 MW to 1500 MW, and 1260 MW to 1600 MW between Czech Republic and Slovakia. The n-1 criterion was not fulfilled between Czech Republic and Germany.

Slovenia
Flow directions Hungary-Croatia-Slovenia-Italy and Austria-Slovenia-Italy changed to Austria-Slovenia-Croatia and Italy-Slovenia-Croatia. The reactive power flow increased from Croatia and Slovenia towards Austria. A large voltage drop was detected, especially at Krško substation,

where the voltage was below the lowest permissible level (imposing a danger of a voltage collapse).

Germany
The 110 kV network experienced a maximally 108% overload, due to increased cross-border flows. The n-1 criterion was not met for transformer tripping at Pleinting and network failure between Etzenricht and Pleinting.

Hungary
After the tripping of the Czech-Austrian interconnections, the power flow from Slovakia to Austria through Hungary considerably increased. The total power flow from Slovakia reached 1650 MW (TTC was 1150 MW), and from Hungary to Austria reached 1260 MW (TTC was 900 MW). Later, the flow from Slovakia increased to 1950 MW, imposing a 10% overload on Gabčíkovo-Győr line for more than 20 minutes.

Slovakia
During the event the system was not able to fulfil the n-1 criterion and the North-South interconnection was seriously endangered.

Austria
The loss of Tumbri line significantly increased the import from Hungary (import on 380 kV line Győr–Wien-Südost increased from 90 MW to 384 MW). Southern Austria experienced a voltage drop. The situation was stabilized within 20 minutes by urgent request for additional active and reactive power deliveries from almost all power plants operational in the region.

4.2 Reasons according to investigator

The disturbance was provoked by three independent events:

1. high cross-border flows in North to South direction;
2. unexpected trip of Krsko NPP;
3. welded contact of line protection at Tumbri.

Occurrence of each single event would not have initiated such severe consequences.

The significant North-South power flow is a permanent phenomenon. The real transit flows usually differ by hundreds of megawatts from the schedule.

An additional disconnection of the 220/380 kV Wien-Győr lines (via increased cross-border traffic and a cascade tripping of Germany-Austria interconnections) would most likely have resulted in significant voltage drop in Austria and Slovenia, leading to possible blackouts.

Disconnection of transmission lines in order to avoid overloading of parts of the transmission system does not solve the problem of insufficient transmission capacities, but shifts the overload towards other network elements and may cause cascading outages.

Recommendations from the investigators

1. coordinated NTC values among involved TSOs;
2. reinforcement of North-South interconnection (380 kV);
3. coordinated switching operations;
4. an Electronic Highway to intensify real-time data exchange among TSOs.

5. United Kingdom – August 28, 2003

5.1 Short description of the event and consequences

This summary is derived from National Grid Transcos's 'Investigation Report into the Loss of Supply Incident affecting parts of South London at 18:20 on Thursday, 28 August 2003', a copy of which has been made available to the EURELECTRIC Task Force on Power Outages.

Transmission system in South London
The transmission system in South London consists of four substations at Littlebrook, Hurst, New Cross and Wimbledon (Figure 1). Normal demands of around 1,100MW are drawn by the Distribution Network Operator, EDF Energy, to supply domestic customers and London Underground, together with supplies for other large users including Network Rail. Following the incident supplies were lost from Hurst, New Cross and part of Wimbledon substations. Supplies from the transmission system were restored within 37 minutes.

Maintenance activity in the area
On 28 August 2003, scheduled maintenance was underway on one circuit from Wimbledon to New Cross and one from Littlebrook to Hurst. This level of maintenance is usual during the summer months, when demand for electricity is generally lower. The maintenance had been planned and was being carried out in line with the Security & Quality of Supply Standard (a document approved by the UK electricity industry).
In line with normal procedures, the arrangement of the transmission system to accommodate the maintenance had been agreed well in advance with EDF Energy, the distribution network operator for the London region. Prior to the planned outage at Wimbledon proceeding on 1 July 2003, EDF Energy confirmed that it could arrange its distribution system to accommodate this outage securely.

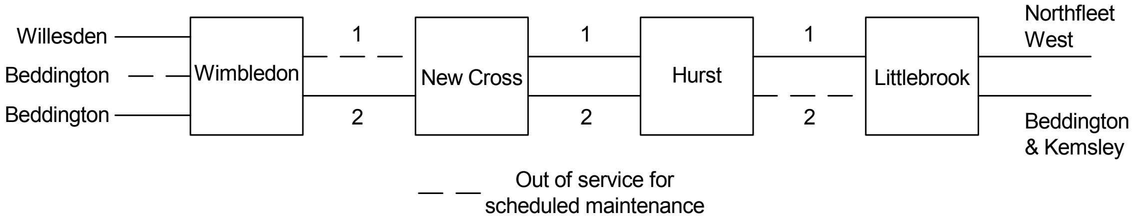


Figure 1: Schematic of the South London transmission system

The first fault: Hurst substation
The sequence of events which led to the loss of supply started at 18:11. The Electricity National Control Centre (National Control) received an indication that a transformer or shunt reactor at Hurst substation was in distress and could fail, with potentially significant safety and environmental impacts. In general, this indication, called a 'Buchholz alarm', tells National Control that gas has accumulated within the oil inside the transformer or shunt reactor, which can lead to equipment failure. It should also be explained that the Buchholz relay is a protection device that has an alarm function for abnormal gas levels or low oil in an oil-filled transformer or shunt reactor. These two possible causes for a Buchholz alarm can only be distinguished by a site inspection. The alarm on 28 August was triggered by a low oil-level in the shunt reactor. National Grid has nearly 900 pieces of oil-filled equipment connected to its transmission system and on average 13 Buchholz alarms are received each year.

Following normal practice, at 18.17 National Control notified EDF Energy of the Buchholz alarm and asked EDF Energy to disconnect the distribution system from the transformer. National Control then initiated a switching sequence to disconnect the transformer from the transmission system. Under National Grid operating procedures a Buchholz alarm is sufficiently serious to warrant the isolation of equipment and reduced security is acceptable for 'switching time' (normally around five to ten minutes).

The switching sequence to remove the transformer began at 18:20, correctly disconnecting Hurst substation from Littlebrook substation. (Note Hurst is a mesh substation requiring disconnection of both transformer and associated mesh corner connected line). This enabled a safe shutdown of the transformer and shunt reactor which had triggered the alarm, but left Hurst supplied from Wimbledon via New Cross.

The second fault: Wimbledon substation
Unexpectedly, a few seconds after the switching, automatic protection equipment on the number two circuit from Wimbledon to New Cross operated, interpreting the change of power flows, due to the switching, as a fault.
The protection operation disconnected the circuit from Wimbledon to New Cross. This disconnected New Cross, Hurst and part of Wimbledon from the rest of the transmission system, causing the loss of supply. 724MW of supplies were lost, amounting to around 20% of total London supplies at that time. This affected around 410,000 of EDF Energy's customers, with supplies being lost to parts of London Underground and Network Rail.

Restoration
Restoration actions began at 18:26, re-energising the Hurst substation from Littlebrook and then isolating the Wimbledon to New Cross circuit, which had automatically disconnected itself, to prevent a recurrence.

At 18:38, 18 minutes after the incident began, National Control offered to restore supplies to Wimbledon for EDF Energy. EDF Energy requested restoration of supply at 18:48 and restoration was completed at 18:51. From this point onwards, London Underground could restore electricity to the underground network, when they considered it was safe to do so.

At 18:41 EDF Energy restored supplies via National Grid's Hurst substation to approximately one third of the affected consumers.

Some 30 switching actions enabled National Grid to restore overall supplies to all substations concluding with New Cross at 18:57 (37 minutes after the incident began), which restored the remaining supplies for Network Rail. No further switching took place to allow a full review of system status to take place until 23.00, during which time the substations remained connected to the rest of the transmission system via a single circuit. At this point normal levels of security were restored.
The total energy unsupplied was estimated to be 433MWh.

5.2 Reasons according to investigator

Initial investigation and subsequent inquiries
National Grid's investigation into this incident found that the second fault, and the loss of power to parts of South London, occurred because an incorrectly rated protection relay was installed on the Wimbledon-New Cross circuit when old equipment was replaced in 2001. A relay rated at 1 amp was supplied, rather than the 5 amp relay specified on the settings sheet. The error was not picked up when the relay was installed and commissioned, despite extensive quality control and commissioning procedures followed by both supplier's and National Grid's specialist staff.

Other key findings were:

- The removal of the Hurst transformer did not itself cause the incident. The consequential increase in flows on the Wimbledon to New Cross circuit were within operational limits. National Grid engineers would not expect that their actions to remove the transformer would cause the loss of supply;
- The impact of the incident on the areas of South London was clearly exacerbated by the loss of supplies to underground and railway transport services;
- From 20 July, EDF Energy's distribution system was arranged such that a significant supply to London Underground was dependent on a single transmission circuit, such that a loss of supply would result from a fault occurring on one of the transformers or associated line at Wimbledon. National Grid understands that EDF Energy had contingency arrangements for immediate restoration of supplies to London Underground in such an eventuality.

Once the cause of the outage had been identified, National Grid undertook an urgent review of the 41,264 similar relays on the transmission system. Each relay has multiple settings which must be checked and this comprehensive survey required the checking of approximately one million separate parameters. The survey was completed within 4 weeks of the incident. It found:

- No cases that replicated the error identified in the South London incident;
- No circuits where the applied relay settings would have caused inadvertent protection operation under any operational load conditions, including operation under short term emergency load conditions;
- A small number of minor discrepancies, none of which could have resulted in the inadvertent tripping of circuits. A programme is being developed to address all remaining discrepancies over a six-month period.

Following publication of the NGT report on the London incident, a number of actions were identified and are being taken forward. In addition to NGTs further investigations, DTI (Department of Trade & Industry) and Ofgem (Regulator) announced separate investigations into the power failures and appointed consultants, PB Power, to undertake joint fact-finding on their behalf.

The investigations by DTI and Ofgem are major exercises and the findings are expected shortly. In the meantime, NGT has taken forward a number of actions in the light of the lessons learned from this incident.

6. Sweden – September 23, 2003

6.1 Short description of the event and consequences

In a situation with certain import, a number of interconnectors and power lines in maintenance and four nuclear units out of operation, the electric system in Southern Sweden experienced a shut-down of Oskarshamn Nuclear Power Plant from 1176 MW to 0 MW within 20 seconds due to a faulty valve. This happened on September 23, 2003 at 12:30.

The frequency was stabilised but voltage in Southern Sweden decreased moderately. The system operator had 15 minutes to bring back the system to n-1 state. After only 5 minutes there was a double bus-bar fault in a substation on the West coast. This disconnected four out of five 400 kV transmissions lines at substation Horred. Two of the lines were parts of the connection between Central Sweden to Southern Sweden and two lines connected two nuclear power units to the transmission grid (Ringhals 3+4 with total production of 1,800 MW). This happened at 12:35.

The situation now became critical. Remaining transmission lines from Central Sweden to Southern Sweden experienced increasing power flows and voltage dropped in the South-Eastern part of the 400 kV grid. The combination of falling voltage and very large flows from north to south caused the protection relays on the transmission lines to detect what seemed to be a remote short circuit and Southern Sweden was disconnected from Central Sweden. This voltage collapse occurred 90 seconds after the bus-bar fault.

Southern Sweden and Eastern Denmark formed hereafter a sub-area without connection to the other Nordic countries. The sub-area had low voltage and large production deficit. A few seconds after the grid separation, the voltage fell to zero in the sub-area and the black-out had occurred. After the voltage dropped to zero, Zeeland was disconnected from Sweden via the zero voltage relays.

The protection relays between Denmark and Sweden did not isolate Denmark East from Sweden because they did not see a low voltage, which mainly is explained by the fact that the production in Zeeland is located far away from where the voltage collapse occurred.

The central power plants on Zeeland did not go into successful turbine house operation when the system broke down.

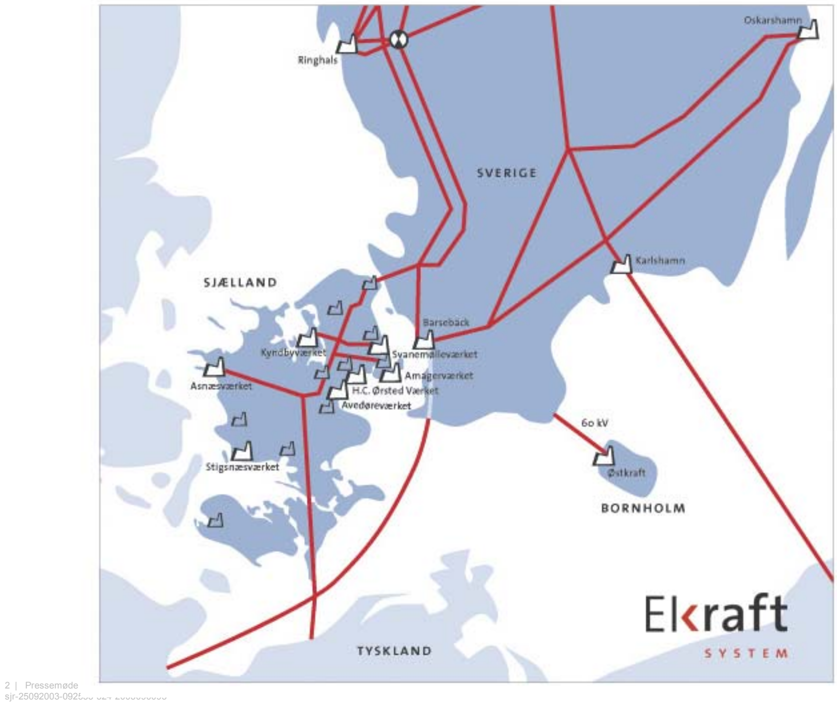
Preparation for restoring the grid began immediately. At 13:47, the 400 kV grid to Southern Sweden was restored and the supply to customers could start to be resumed. At 18:00 all restrictions to full supply were lifted. Zeeland had a slower start and the last consumer was connected on September 23, 2003 at 19:00.

The lost supply is estimated to be 10,000 MWh in Sweden and 8,000 MWh in Eastern Denmark.

6.2 Reasons according to investigator

The shut-down of Oskarshamn was according to the dimensioning of the system operation. The incident at Horred was a double fault which was not foreseen or envisioned. The busbar fault in a switch happened in two steps. The station had been properly overhauled in early spring 2003. Analysis at laboratories revealed that the material had slowly degraded since it had been analysed by thermography. The load was well below nominal current (3150 A) with 1500 A after the fault at Oskarshamn. The switch fell and drew an arc to the next switch which then was short-circuited.

Svk has announced work at Horred to eliminate the risk of a double fault and engaged in planning a strengthening of the transmission lines from Central Sweden to Southern Sweden.



7. Italy – September 28, 2003

7.1 Short description of the event and consequences

Italy imports electricity through fifteen 380kV and 220kV lines crossing the borders with France, Switzerland, Slovenia and Austria.

On September 28, 2003 at 3h00, the total physical import to Italy was 6 651MW. The scheduled program was 6 400MW. At that time, the consumption of Italy (without Sardine) was 24 064MW with extra pump storage load of 3 638MW.

The sequence of events was triggered by a trip of the Swiss 380 kV line Mettlen-Lavorgo (also called the “Lukmanier” line) at 03:01 caused by tree flashover. Several attempts to automatically re-close the line were unsuccessful. A manual attempt at 03:08 also failed. Meanwhile, other lines had taken over the load of the tripped line, as is always the case in similar situations. Due to its proximity, the other Swiss 380 kV line Sils-Soazza (also called the “San Bernardino” line) was overloaded. This overload was acceptable in such emergency circumstances, according to operational standards, only for a short period. The allowable time period for this overload was approximately 15 minutes, according to calculations by the experts.

At 03:11, a phone conversation took place between the Swiss coordination centre of ETRANS in Laufenburg and the GRTN control centre in Rome; the Italian transmission system operator. The purpose of the call was to request from GRTN countermeasures within the Italian system, in order to help relieve the overloads in Switzerland and return the system to a secure state. In essence, the request was to reduce Italian imports by 300 MW, because Italy imported at this time up to 300 MW more than the agreed schedule, which amounted to 6 400 MW on the northern border. The reduction of the Italian import by about 300 MW was, in effect 10 minutes after the phone call at 03:21 and returned Italy close to the agreed schedule. This import reduction, together with some internal countermeasures taken within the Swiss system, was insufficient to relieve the overloads. At 03:25, the line Sils-Soazza also tripped after a tree flashover. This flashover was probably caused by the sag in the line, due to overheating of the conductors. Having lost two important lines, the then created overloads on the remaining lines in the area became intolerable. By an almost simultaneous and automatic trip of the remaining interconnectors towards Italy, the Italian system was isolated from the European network about 12 seconds after the loss of the line Sils-Soazza.

During these 12 seconds of very high overloads, instability phenomena had started in the affected area of the system. The result was an unsatisfactory low voltage level in northern Italy and consequently, the trip of several generation plants in Italy.

After separation from the European network, the fast frequency drop in Italy was temporarily stopped at approximately 49 Hz, by the primary frequency control and the automatic shedding of the pumped storage power plants and part of the load. Subsequently, additional generating units tripped for various reasons: turbine tripping, underfrequency relay operation, high temperature of exhaust gases, loss of excitation, etc. Despite additional load shedding, the frequency continued to decrease and the system collapsed 2 minutes and 30 seconds after the separation of the country, when the frequency reached the threshold of 47,5 Hz.

The analysis of the UCTE system outside Italy after the splitting of the network shows that the primary frequency control performed well, limiting the positive frequency deviation. The early trip of some generation units by overfrequency has been observed. These units were either large centralised plants or smaller decentralised units embedded in the distribution system. Some generation units switched their control mode from load frequency or load control to frequency control. Generally speaking for the UCTE area, there were differences between the control areas in the way the frequency/power control reacted. The event was also observed in the second UCTE synchronous zone, due to the tripping of the HVDC link Greece-Italy.

In Italy, the restoration process started immediately after the blackout. Nearly all of the northern part of Italy was energised before 08:00, the central part around 12:00 and the remaining parts of mainland Italy at 17:00. Sicily was fully energised at 21:40. Although some difficulties were encountered, the restoration process was successfully performed.

7.2 Reasons according to investigator

1. Unsuccessful re-closing of the lukmanier (mettlen–lavorgo) line because of a phase angle difference that was too high
Due to the high loads on the remaining lines, an automatic device, aiming at protecting the equipment, blocked according to its design settings, the possibility of restoring the line back into service.

2. Lacking a sense of urgency regarding the san bernardino (sils-soazza) line overload and call for inadequate countermeasures in italy
The operators were unaware of the fact that the overload on Sils-Soazza was only allowable for about 15 minutes. A single phone call by ETRANS took place 10 minutes after the trip of the first line. ETRANS asked for the imports to be decreased by 300 MW. This measure was completed by GRTN within 10 more minutes. Despite the joint effort with the Swiss internal countermeasures, it was insufficient to relieve the overloads.

3. Angle instability and voltage collapse in italy
As explained in the sequence of events, this was one of the main reasons why the Italian system collapsed after its separation from the UCTE system. It was not the original cause of the event.

4. Right-of-way maintenance practices
Tree cutting, to maintain safe clearances regarding flashover, is subject to national regulation. Therefore, the Committee did not examine these practices. The Swiss Federal Inspectorate for Heavy Current Installations conducted an investigation into the line maintenance practices before the incident. Their findings are that the line inspections and line maintenance practices of the two affected transmission system operators ATEL Netz AG and EGL Grid AG were both in full compliance with the Swiss regulation in this area. Nevertheless, this Swiss Authority decided to review the procedures for maintenance practices and documentation of the conducted inspections. With regard to the increased load flow on specific lines, the assumptions for sag calculation are also subject to evaluation by the authorities.

Features of the blackout

- ❖ Up until the time of the first incident (the loss of the Lukmanier line), the system was in a state compliant with the security criteria: the total level of import towards Italy did not exceed the level that was jointly accepted and its control deviation was within the Transmission Reliability Margin (TRM).
- ❖ The blackout was not caused by some extraordinary "out of criteria" event such as a severe storm, a cyber-attack, simultaneous lightning strikes on several lines, etc…
- ❖ The blackout was triggered by causes in Switzerland. The initial stages in the sequence of events were out of reach for action by the Italian operators.
- ❖ After the first contingency, although the foreseen countermeasures for returning the system to a secure state were available from a purely technical point of view, human, technical and organisational factors prevented the system from returning to a secure state. These factors are related to known principles and available tools of the TSO business. They do not reveal fundamental deficiencies in the existing rule setting of the UCTE system.
- ❖ The behaviour of the UCTE system outside Italy after disconnection did not reveal critical malfunctions on a global level.

- The restoration process of the Italian system was performed successfully. However, its duration might have been reduced should more units have successfully switched to house load operation or have performed black-start capability.

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