Extraordinary events: understanding sequence, causes, and remedies

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ABSTRACT: Increased understanding of extraordinary events in the electrical power system is vital in order to develop and assign appropriate remedies to limit the presence and consequences of such events in the future. In this paper, extraordinary events are analysed in order to identify general patterns in the sequence of event, causes, and potential remedies. The generalised discussion is supported by a case study of historical events from the U.S. – Canadian and continental European power systems. Results show that there are correlating factors between the proposed generalised structure of events and the events analysed in the case study, supporting the generalisation of extraordinary events. Improvements of monitoring systems and controlled islanding schemes are remedial actions identified to have high potentials for decreasing vulnerability of extraordinary events. Such actions may lead to increased situational awareness and limitation of disturbance propagation and consequences of extraordinary events.

1 INTRODUCTION

Increased understanding of extraordinary events in the electric power system is vital in order to develop and assign appropriate remedies to limit the consequences of future extraordinary events in the power system. An extraordinary event is here referred to as a contingency in the power system with a low probability to occur and a potentially high societal impact, such as a major blackout (wide-area interruption) resulting in considerable socio-economic costs.

This paper describes the result of an attempt towards further understanding of extraordinary events on a generalised level, with examples from a case study of historical events.

The motivation behind this paper is to serve as input for further research and development in the area of countermeasures to reduce the risk of extraordinary events, in terms of enhanced monitoring, protection and control.

This paper is organised in two main parts. In Part I, extraordinary events are discussed on a generalised level, where sequences of event, causes, and potential remedies are in focus. Part II holds a case study where three historical events are analysed, identifying similarities and differences to the generalised discussion. At the end, a summary is included of result and conclusions, together with suggestions for further work .

2 PART I: SEQUENCE, CAUSES, AND REMEDIES

In this part of the paper, an attempt is made to define a generalised sequence of extraordinary events, and to identify common causes and potential remedies to extraordinary events.

2.1 *Sequence of extraordinary events*

The sequence of events leading to a blackout in the power system varies widely between events. In many cases, however, there are similarities, and attempts have been made to identify a generalised sequence to describe extraordinary events.

Such a generalised sequence of events is depicted in Figure 1. This structure is established on a basis found in (Knight 1989), (Pourbeik 2006), and (IEEE 2007), and can be described as:

1 The event is triggered by a failure with high impact on the operation of the power system.
2 Depending on the nature of the failure, the system shifts into an insecure (also called alert or abnormal) state, or even to an emergency operating state, where fast and proper remedial actions are needed in order to save the system from further deterioration.
3 Insufficient remedial actions (or even a second independent failure) lead to further deterioration of the system.

4 This is followed by fast cascaded tripping due to overload or instability.
5 Resulting in system sectioning, or disconnection of major load centres or significant generation capacity.
6 The system, or part of the system, experiences significant imbalance between demand and generation.
7 Inadequate control actions, or insufficient island operation procedures, lead to instability problems and partial or total blackout of the power system.

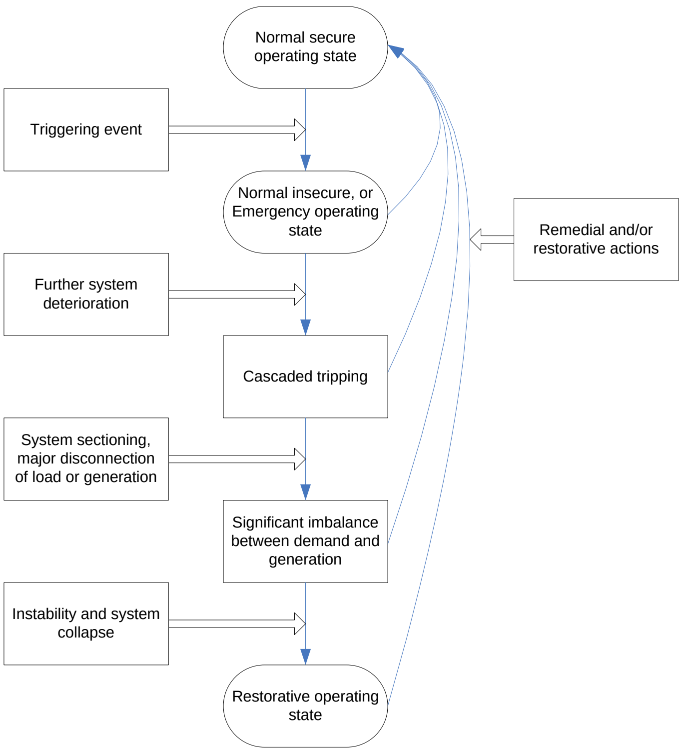

Figure 1. Generalised sequence of extraordinary events

As indicated in the figure, remedial actions are an important part at every stage of the event in order to limit consequences and to maintain the integrity of the power system. Integrity of a power system means the ability of a power system to preserve interconnected operation (IEC 1990).

It is important to realise that a generalised sequence of events, such as the one discussed here, cannot be assumed to be valid for all possible extraordinary events. Exceptions are for example events related to extreme weather, where vast tripping and/or destruction of power system components are common in the region of the weather phenomenon.

Nevertheless, this generalised view can be beneficial when analysing remedial solutions to mitigate future extraordinary events.

2.2 *Causes of extraordinary events*

Causes of extraordinary events are typically complex, with many factors influencing the final consequence. In this study, causes of extraordinary events are separated into: triggering event, root cause and contributing causes.

2.2.1 *Triggering event*

Often, a relatively uncomplicated fault, together with a negatively influencing factor, is the triggering event of a sequence leading to an extraordinary event (Knight 1989; Pourbeik 2006; IEEE 2007). As described by Figure 1, this triggering event is the factor that shifts the operational state from a normal and secure state to an insecure (alert / abnormal) or even to an emergency operating state.

Factors that the triggering event might be composed by are e.g.:

– Failure of equipment (often due to aging)
– Malfunctioning of protective devices
– Lightning
– Human error
– Insufficient cooperation between TSOs,
– Operational planning error
– Control system error

2.2.2 *Contributing and root cause*

A contributing cause is in (DOE 1992) defined as: *"a cause that contributed to an occurrence but, by itself, would not have caused the occurrence"*. I.e. a contributing cause is a factor that affects the consequence of the event. If corrected, it would not prevent the event from occurring.

Root cause, on the other hand, is identified as the most fundamental aspect of the cause of an event, and can be defined as: *"the cause that, if corrected, would prevent recurrence of this and similar occurrences"* (DOE 1992).

The list of contributing causes can typically be made long to almost any event, while there are often only one single or only a few root causes. Hence, the identification of true root causes is an important part of the work in order to mitigate future events.

A list of causes of extraordinary events is summarised from the three studies (EURELECTRIC 2004), (IEEE 2007), and (Andersson 2005):

– Maloperation of protection, especially transmission protection
– Increased failure probability of aging equipment
– Insufficient requirements on design and control of production units
– Inappropriate distribution of active and reactive power generation
– Lack of defence plans and demand control
– Increased and changed power flow and system utilisation
– Inadequate system dimensioning criteria
– Insufficient system investments
– Insufficient availability and adequacy of monitoring and control tools
– Insufficient automation and coordination of protection and controls
– Inadequate training and maintenance

– Lack of coordination, cooperation, communication, responsibilities, and situational awareness by involved TSOs

Differentiation between root and contributing causes is not an easy task and is very case specific. There are however some general aspects of root and contributing cause:

– Root causes are more often related to system operation than to actual equipment failure.
– Contributing causes are often directly related to failure and excessive or premature disconnection of equipment.

This implies that, on a general level, the first three causes listed above (which are related to protection, equipment and production units) could be considered to be contributing causes, while the other causes could be regarded as root causes.

2.3 *Potential remedies against extraordinary events*

Mitigating extraordinary events is a complex task, both since the events have much diversity, and due to the fact that the very low probability of occurrence limits the level of economically viable investments to prevent such events.

Through analysis of historical events, it is possible to identify vulnerabilities in the power system, which, if properly improved, could prevent a similar event from occurring. As concluded in (IEEE 2007): *"it is not possible to eliminate the risk of blackouts, since extreme contingencies, though highly improbable, are always possible"*.

In the following subsections, mitigating solutions suggested in the literature are discussed.

2.3.1 *Reliability standards and best practices*

Many studies provide recommendations on standards, policies, and best practices to improve the reliability and reduce risk of future blackouts.

(Cooke 2007) focuses on the operational security of the transmission system, giving recommendations on various security strengthening policies ranging from legal arrangements to the importance of investing in people.

(IEEE 2007) suggests several best practices related to the dynamic performance of the power system, with the intention that these should act as an *"additional layer of protection"* behind other necessary improvements, needed to reduce risk of blackouts. Best practices are suggested within various disciplines, such as: power plant equipment, reactive power compensation, special protection systems, and reliability standards.

In (Andersson 2005), the following recommendations are made:

– Periodically reviewed, mandatory and enforceable reliability standards
– Clear investment plans to maintain appropriate reliability levels
– Continue promotion of research in the fields of power systems engineering

2.3.2 *Automatic control*

For many extraordinary events, the time period available for implementation of appropriate remedial actions is short. Therefore, several solutions are directly related to automatic control actions.

Applications for automatic control (and/or protection) to mitigate extraordinary events can be referred to as: emergency control, system integrity protection schemes, system protection schemes, special protection systems, remedial action schemes, defence plan, wide area protection systems, etc. A common attribute of such applications is the focus on system integrity, with the key objective to: *"maintain the integrity of the interconnected grid, in spite of the loss of a number of elements"* (CIGRE 2007a). In this paper the term "special protection systems" (SPS) is used when describing these kinds of applications.

Effective measures to improve operational security and reliability, with suggestions on how to mitigate extreme contingencies using special protection system are described in (CIGRE 2007a) and (Knight 1989), where also the value of selecting proper protective action is discussed.

A distinction should be made between the two different applications, or main objectives, to implement a special protection system:

– Preserve the system integrity (related to extraordinary events)
– Increase system utilisation (i.e. an alternative to system capacity)

When designing a special protection system for either objective, it is important to consider the impacts the SPS might have on the other objective. For example, in the case where the main objective is to enhance the system utilisation, if not properly designed the SPS could easily increase the system vulnerability to extraordinary events. Therefore, careful design of SPS, with clear distinctions between normal and emergency operation, is needed in order to avoid adverse effects and to serve both objectives.

2.3.3 *Future development*

Implementation of various wide area monitoring system (WAMS) applications into the power system is an ongoing process. WAMS utilise phasor measurement units to provide highly accurate, time synchronised, and almost real-time data from a widely dispersed system. Augmented measurement data have uses in many application areas, such as e.g. system state estimation, power oscillation control and phase angles monitoring, implying the usefulness of WAMS in improving power system security.

Suggestions are made on possible improvements of classical special protection systems by integration of WAMS. Typically SPS are designed to take predefined actions to preserve the integrity of the power system during abnormal conditions. Many special protection systems (e.g. remote load shedding and generator rejection) are event-based system protections, which (in contrast to response-based) acts directly on the detection of a defined event. These special protection systems are fast and often related to the transient rotor angle stability and short-term voltage stability of the power system. However, as a consequence of being event-based they do not protect against unforeseen events. Data from a WAMS could be used to enhance the use of such special protection systems to decrease the vulnerability of unforeseen extraordinary events.

Integration between wide area monitoring systems and special protection systems is seen as one of the future solutions for system integrity and reliability improvements, (CIGRE 2001) and (CIGRE 2007b).

3 PART II: CASE STUDY OF HISTORICAL EVENTS

In this part, three historical events are studied to identify similarities and differences to the general discussion of Part I. The events studied here occurred in:

- Germany, November 4, 2006
- U.S. and Canada, August 14, 2003
- Italy, September 28, 2003

The reasons for selecting these events are their relative recentness, the availability of literature, as well as their diversities.

3.1 *Event: Germany, November 4, 2006*

This disturbance is reported in (UCTE 2007), where a description is given of the sequence of events, causes and critical factors. The report also provides recommendations towards an enhancement of the power system operational security. Further identified lessons to be learnt are reported in (ERGEG 2007), together with recommendations related to operational guidelines and rules for improvement of the security and reliability of the continental European power system.

3.1.1 *Identified sequence of events*

The event originated from a planned de-energisation of overhead lines which, when shifted to an earlier time slot, was not sufficiently analysed in advance. This led to overload and tripping of other lines, and system splitting of the continental European power system, with loss of load in several areas due to load shedding (UCTE 2007).

The sequence of event can be described as:

1. Disconnection of transmission lines, without executing sufficient security analysis.
2. System experienced high load, however still considered secure, hence no remedial actions were taken.
3. Increased load combined with manual remedial actions with adverse effect, led to overload and automatic tripping of a transmission line, however with peculiar protection settings.
4. This triggered a fast cascaded tripping of other overloaded transmission lines.
5. Stability problems led to sectioning of the continental European power system into three asynchronous areas.
6. Frequency deviation led to unwanted generator tripping (and reconnection), especially of wind generation.
7. Unbalance between load and generation in the three areas led to shedding of loads and pump stations.
8. Adequate controlled islanding and emergency procedures limited further deterioration and led to successful resynchronisation of the system.

3.1.2 *Identified causes*

The two reports identify three main causes of the disturbance:

- Non-fulfilment of the N-1 criterion
- Inadequate cooperation between TSOs
- Insufficient controllability of distributed generation

The non-fulfilment of the N-1 security criterion relates to a human error and/or inadequate operating guidelines. If sufficient analyses had been carried out, identifying that the system would no longer operate in a normal and secure state, this event could have been prevented from occurring. The inadequacy of operating procedures and/or guidelines is considered a root cause of this event.

The inadequate cooperation between TSOs can be identified to originate from insufficient emergency and communication procedures. Factors such as lack of information exchange, common emergency procedures, communication routines, and over-all coordination led to insufficient or untimely actions taken to limit the consequences of the event. Timely and accurate mitigating actions could have prevented this event from occurring. The inadequacy of emergency and communication procedures is also considered a root cause of this event.

The last main cause identified in (UCTE 2007) and (ERGEG 2007), insufficient controllability of distributed generation, originated from a lack of monitoring and control by TSOs as well as from inappropriate under-frequency tripping. This cause is recognised to have worsened the consequences of the event, and is considered a contributing cause, and not a root cause, since, if corrected it would not have prevented the event from occurring.

With a time period of around 33 minutes, between the triggering event and cascaded tripping, predefined manual emergency actions should have been able to be implemented. However, since it took 25 minutes for the operators to realise the insecure operating state, the time left was too short for any manual intervention. This implies a lack of situational awareness, which should also be seen as a root cause of this event.

Thus, recognised root causes to this event are:

– Inadequate operating, emergency, and communication procedures
– Lack of situational awareness

3.1.3 *Potential remedial solutions*

Main recommendations given in (UCTE 2007) and (ERGEG 2007) can be summarised as:

– Review and improvement of the UCTE Operation Handbook
– Improved operational security guidelines
– Development of standards to improve TSO coordination
– Improve real time system information to TSOs
– Adaptations in regulatory and legal frameworks related to connection and operation of generation units

In order to improve the situational awareness there are remedies that could play an important role in giving the operator enough time to implement proper actions. Improvements of the monitoring system could provide better estimations of operating state, security level and operator awareness. Another solution could be to implement automatic emergency actions, controlled by an enhanced monitoring, control, and protection system, such as a special protection system in combination with a wide area monitoring system.

3.2 *Event: U.S. and Canada, August 14, 2003*

This event started with the malfunction of a software system, and ended with a blackout affecting the Midwest and Northeast United States and Ontario in Canada. (TaskForce 2004) and (NERC 2004) documents a thorough investigation of the events, describing the sequence of events, as well as causes and consequences. An analysis of similarities with previous historical events in the U.S. - Canadian power systems are also included, as well as an extensive list of recommended actions to decrease probability and consequences of similar future events.

3.2.1 *Identified sequence of events*

At the moment when this event started, parts of the Eastern Interconnection operated with very small security margins on voltage and reactive power, making the system highly vulnerable to voltage instability (TaskForce 2004). With several software systems malfunctioning, the state of the system slowly degraded, without system operators being aware of the situation. Increased loading led to tripping and, because of insufficient vegetation management, several of the overhead lines tripped prematurely, which further increased the deterioration of the system. As the result of insufficient mitigating actions, further disconnections led to instability, cascaded tripping, system separation, and blackout.

The sequence of event can be described as:

1 Malfunction of a software system, leaving the operators without proper knowledge of the system state.
2 Automatic trip of an important production unit led to increased loading of transmission lines.
3 Trip of a highly loaded transmission line and malfunction of other software systems, further deteriorated the state of the system and decreased the situation awareness of the system operator.
4 Increased loading led to further tripping of transmission lines, with insufficient vegetation management as cause of premature tripping of many of the affected lines.
5 Tripping of transmission lines eventually caused instability triggering cascaded tripping of lines and generation.
6 The Eastern Interconnection then separated into two asynchronous parts.
7 Large differences between load and generation, led to instability and blackout of the island consisting of parts of the Midwest and Northeast U.S together with Ontario, Canada, while the rest of the Eastern Interconnection remained largely unaffected.

3.2.2 *Identified causes*

The analysis performed by (TaskForce 2004) and (NERC 2004) describes four identified groups of causes of the blackout:

– Lack of system understanding
– Insufficient situational awareness
– Insufficient real-time analysis support from reliability coordinators
– Inadequate vegetation management

Even though the first event of the disturbance is a software malfunction, the inadequate system understanding is considered a main cause of the event. It was an inadequate system understanding which led to the unfavourable operating state prior to the disturbance and to the insufficient mitigating actions taken in an early stage of the event. This issue is recognised in (TaskForce 2004) but not in (NERC 2004). (TaskForce 2004) identifies several issues (e.g. lack of understanding of critical facilities for voltage and reactive power support, inadequate system planning, and insufficient emergency procedures and automatic remedial actions) which contributed to the vulnerability of the system. Therefore, an inadequate understanding of the power system is considered to be a root cause of this event.

Several software systems malfunctioned, such as: state estimator (hence no proper system state analysis or real-time contingency analysis available), SCADA alarm and logging (leaving operators without information of failures), remote EMS terminals (leading to a lack of updated system measurement data), as well as primary and back-up EMS servers (leading to loss of primary generation controls). It should be noted that the state estimator and real-time contingency analysis software was under development at the time of the event (TaskForce 2004), however without sufficient backup. The malfunction of these software systems, interdependent or not, led to a lack of real-time data for monitoring and contingency analysis, which led to insufficient situation awareness by the reliability coordinators and system operators. Therefore, insufficient situation awareness is considered a root cause of this event.

The unfavourable operating state together with insufficient situation awareness, led to a slowly degrading system situation. Where, due to inadequate vegetation management, several of the overhead lines tripped prematurely, which increased the deterioration of the system further. The lack of appropriate mitigating actions, manual and automatic, led to further overload, cascaded tripping and eventually blackout.

Whether the inadequate vegetation management should be considered a root cause or a contributing cause of the event is unclear, since it is questionable that, if corrected, it would prevent similar events from occurring in the future.

Thus, recognised root causes to this event are:

- Inadequate understanding of the power system
- Lack of situational awareness

3.2.3 *Potential remedial solutions*

Many recommendations on how to improve the reliability of the power system in order to prevent future events are given in (TaskForce 2004) and (NERC 2004). Implemented actions and future challenges are further described in (NRCA-DOE 2004).

Here follows a general overview of given recommendations:

- Improve, clarify, and enforce reliability standards
- Enhance operator performance through improved: training, coordination, communication procedures, emergency procedures, system monitoring and management tools, system models,
- Strengthen the system security through: enhanced system protections, improved reactive power and voltage support criteria and practices, standardise ratings of transmission lines, identification of critical equipment
- Improve IT security
- Establish standards for vegetation management
- Invest in further research in reliability related fields

This event had a quite long initial period, with the initial failure occurring several hours before the blackout. The reason for the length of this event is that the operators were unaware of what was happening in the system. The importance of availability and reliability of monitoring and control systems, including appropriate backup facilities, is clearly shown by this event.

Improved system separation and controlled islanding schemes could have further limited the consequences of this event.

3.3 *Event: Italy, September 28 2003*

This event is reported in (UCTE 2004), describing the sequence of events and an analysis of the root causes. The report also includes an overview of short-term actions taken to improve the system security and recommendations for further work in the UCTE.

3.3.1 *Identified sequence of events*

This event started with the trip of one of the major transmission lines into Italy, and ended with the blackout of the Italian power system. At the beginning of the event, the Italian system was in a high, though considered secure, import state.

The sequence of event can be described as:

1. The event started with the trip of a transmission line. The line tripped due to inadequate vegetation management, and an excessive phase angle difference across the breaker prohibited auto-reclosing.
2. This failure moved the system to an insecure operating state.
3. A lack of system understanding, situation awareness, and communication issues, resulted in inadequate countermeasures.
4. Leading to overload of parallel lines, which also tripped prematurely due to inadequate vegetation management.
5. This triggered a fast cascaded tripping of the rest of the interconnecting lines to Italy.
6. Leaving the Italian system isolated from the rest of the continental European power system.
7. The Italian system suffered from imbalance between load and production, due to the former

high import, unwanted tripping of generation and insufficient load shedding.

8 Resulting in a full blackout of Italy

3.3.2 *Identified causes*

In (UCTE 2004), four main causes of the blackout are identified:

- Excessive phase angle difference
- Inadequate countermeasures due to lack of sense of urgency
- Angle instability and voltage collapse
- Inadequate vegetation management

The reason for the high phase angle over the first tripped breaker was the large power transfer together with the topology of the network. At a lower phase angle, it is likely that the auto-reclosing would function. Similar events could be prevented by including a maximum angle difference level into planning and online analysis tools, and using this level as a criterion in defining power transfer limits. Hence, insufficient system planning and operating criteria is considered a root cause of the event.

If adequate countermeasures had been taken directly after the trip of the first overhead line, the remaining lines would most likely not have been disconnected and the event would have been avoided. With a time period of around 25 minutes between the triggering event and cascaded tripping predefined manual emergency actions should have been able to be implemented. However, since it took 20 minutes before the first load reduction of 300 MW took place; the time left was too short for further manual intervention. Hence, a lack of situational awareness is considered a root cause of the event.

An efficient and adequate island operation scheme could have prevented the Italian power system from collapse, and would then have limited the consequences of the event to shedding of load. It would, however, not prevent the Italian system from entering island operation. Inadequate controlled islanding scheme is considered a root cause of the event.

It could be argued that the insufficient vegetation management should be considered a root cause of the event, since it is the cause of the trip of several of the overhead lines. It is, however, the insecure operating state which prohibits the reconnection of the first line, hence, causing the disturbance.

Thus, recognised root causes to this event are:

- Inadequate system planning and operating criteria
- Lack of situational awareness
- Inadequate controlled islanding schemes

3.3.3 *Potential remedial solutions*

Several recommendations are given in (UCTE 2004), here follows a summary:

- Improve emergency procedures between TSOs
- Improve and harmonise the N-1 reliability criterion
- Improve long term system planning
- Improve real-time data exchange between TSOs
- Harmonise / define minimum requirements on generation units
- Improve defence and restoration plans
- Improve frequency control
- Accelerate ongoing implementation of a wide area monitoring system for improvements in dynamic analysis and monitoring purposes

Improved operator awareness and automatic emergency actions, as well as an improvement of the controlled islanding schemes, could play important parts in order to prevent similar events in the future.

4 SUMMARY, CONCLUSIONS AND FURTHER WORK

There are many correlating factors between the general sequence of event shown in Figure 1 and the events analysed in the case study, supporting the proposed generalisation of extraordinary events in Part I. Two particularities noticed in the case study are:

- Adequate control actions and controlled islanding schemes limited the consequences and prevented a blackout of the continental European power system on November 4, 2006
- A very long period of increased deterioration of the power system characterises the initial part of the blackout occurring in the Eastern Interconnection on August 14, 2003. The main reason for this was the unavailability of monitoring systems, limiting the situational awareness of the operators

The recognised root causes to the events analysed in the case study are:

- Lack of situational awareness
- Inadequate controlled islanding schemes
- Inadequate understanding of the power system
- Inadequate operating, emergency, and communication procedures
- Inadequate system planning and operating criteria

Lack of situational awareness is a common root cause for the three studied events. The importance of the situational awareness can also be identified when analysing the time available for remedial actions (between the triggering event and cascaded tripping or instability). The events described in this case study all had at least 25 minutes available for the implementation of remedial actions, which cannot be considered too short for the use of manual emergency actions according to the operating practices. One of the reasons why the described events could occur is the operators' unawareness of the vulnerability of the situation. Hence, through enhancement of monitoring systems enabling improved situational awareness, essential contributions could be made to decrease the vulnerability to extraordinary events in the power system. Similar conclusions can be drawn from (Kirschen 2009), where an extended power system security analysis framework is suggested in order to point out the importance of identifying the *"informationally insecure"* state.

Controlled islanding has also played a major role in the studied events. In the first case, controlled islanding operation prevented Europe from a major blackout. In the other two cases, the system separation resulted in blackout of separated islands. Improvements of system sectioning and controlled islanding schemes therefore seem as promising areas to limit the disturbance propagation and consequences of extraordinary events. Such improvements could make the difference between total system blackout and controlled load shedding.

The proposed generalised description of extraordinary events in electric power systems will be developed further providing input to the development of countermeasures to reduce the risk of extraordinary events, in terms of enhanced monitoring, protection and control systems. The further work will emphasise special protection schemes and wide area monitoring systems for improved situational awareness and to decrease the vulnerability to extraordinary events in the power system.

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