Analysing the Causes of the Italian and Swiss Blackout, 28th September 2003

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Abstract

On the 28th September 2003, a blackout affected more than 56 million people across Italy and areas of Switzerland. Estimates vary for the number of fatalities that were directly related to the loss of power. 30,000 people were trapped on trains. Several hundred passengers were stranded on underground transit systems. There were significant knock-on effects across other critical infrastructures. Many commercial and domestic users suffered disruption in their power supplies for up to 48 hours. The immediate trigger for the blackout stemmed from a fault in the Swiss transmission system. The consequences of the initial failure propagated across the border affecting the networks in France, Slovenia, and Austria. It also led to a domino effect that ultimately led to the separation of the Italian system from the rest of the European grid. The 2003 blackout, therefore, has immense importance for the future development of European energy policy. The immediate causes of the failure acted as a catalyst for longer term, technical vulnerabilities to do with the regulation and monitoring of energy transfers and the algorithms used to predict potential distribution problems. The 2003 power failure also had managerial and human factors causes; these arguably included an over-reliance on computer-based decision support systems. The following paper applies accident investigation techniques to represent and reason about the complex interactions between these causes. In particular, we use Violation and Vulnerability (V2) diagrams to map out the causal factor behind this engineering failure. This article is a companion paper to a previous study that applied the same analytical techniques to the US and Canadian blackout, 14th August 2003 (Johnson, 2006).

Keywords: Infrastructure security, power distribution.

1 Introduction

During the early morning of the 28th September 2003, a cascading series of line trips led to the isolation and eventual blackout of the Italian electricity distribution network. Although the most serious consequences were experienced South of the Alps, the immediate causes of the failure originated in the Swiss transmission system. A 380kV line between Mettlen and Lavorgo was loaded at 86% of its maximum capacity. The core temperature of the cable rose to a point where it began to sag close to nearby trees. This led to a flashover and subsequent attempts to close the line were unsuccessful. The failure of the Mettlen-Lavorgo line had the knock-on effect of increasing the loading on the 380kV Sils-Sosa line. As before, the high loading increased core temperatures. Attempts by the Swiss operators to reduce the loading on Sils-Sosa were insufficient to prevent a flashover with a tree causing a line trip after 24 minutes. Load then increased on the 220 kV Airolo Mettlen line, which was disconnected by automated protection devices.

These initial failures had a strong effect on the Italian power system, according to some estimates the national generation capacity was only able to support around 87% of its annual domestic demand (SFOE, 2003). The relatively high operating costs of domestic generation facilities also increased incentives for Italian suppliers to import electricity from other states during periods of relatively low demand. In consequence, the domino-effect created by the Swiss line failures led to a sudden loss of voltage. This created angle instability that placed the Italian network out of synchronization with the rest of its partners in the Union for the Co-ordination of Transmission of Electricity (UCTE). In consequence, automatic protection devices again intervened to separate all remaining lines between the Italian grid and the UCTE neighbours.

More than 56 million people lost power across Italy and areas of Switzerland. This was around 6 million more people than the blackout that affected the North-Eastern USA and areas of Canada during August of the same year (Johnson, 2006). The disruption lasted for more than 48 hours as crews struggled to reconnect areas across the Italian peninsula. Rolling blackouts were used to prevent demand from exceeding supply during this restoration phase. 30,000 people were trapped on trains. Several hundred passengers were stranded on underground transit systems. Although hospitals and other emergency centres were able to call upon reserve generators, there were significant knock-on effects across other critical infrastructures. The mobile phone system began to fail as transceivers lost power. Other areas of the networks became overloaded as customers tried to contact friends and family. The blackout also affected large areas of the Internet as UPS sources either failed or ran out of battery power (Cowie et al, 2004).

2 European Background

Traditionally, many European states relied upon a small number of companies to both produce power and transmit it to end-users. This led to local monopolies because potential competitors could not gain access to the transmission networks. The European Union, therefore, began a process of liberalization with a directive to open internal energy markets in 1996. This created deadlines by which consumers were supposed to have a choice of supplier. Member states were also required to set up an independent regulator, which would in part help to audit the unbundling process. A second directive was accepted in 2003 to counter a perceived lack of progress. Further European directives were also developed to ensure that the allocation of transmission capacity both within and between states must be transparent, ideally through the use of auctions. Many of these detailed regulations had to be revised following the Italian blackout (OECD, 2006).

France and Italy developed national legislation to meet the provisions of the EU directives. They took steps to unbundle Transmission System Operators (TSOs) from the generation companies. They also set up regulatory organizations, the Italian Autorità per l'energia elettrica e il gas, (AEEG) and the Fremch Commission de régulation de l'énergie (CRE). Although the Swiss Federation remains outside the European Union, their physical infrastructure and generating capacity continue to meet power needs across member states. They, therefore, participated in the European Union for the Co-ordination of Transmission of Electricity (UCTE). The UCTE is an association of transmission system operators across continental Europe. However, there is no widespread, independent means of verifying whether or not a state complies with UCTE requirements. UCTE regulations can, therefore, be interpreted in different ways in different countries. Early in 2000, 7 grid owners and operators from across Switzerland helped to create an independent company known as ETRANS. The intention was to ensure that Swiss interests were well represented, via UCTE, as European member states began to implement the liberalization embodied in successive EU directives.

3 Modelling Causes

Techniques from accident analysis can be extended to represent and reason about complex infrastructure failures. Figure 1 provides an overview of a V2 (violation and vulnerability) analysis. Dotted boxes represent events that lead towards a failure. In the following diagram, an event is used to denote that the Transmission System Operators (TSOs) exchanged their schedules for the following day at 18:30 on the 27th of September via the UCTE. Colour and shading are used to distinguish events that involve different countries and these are shown in the key of this diagram. In addition, the first parentheses of each event provide timing information and, where appropriate, the second parentheses denote country information. Hence an event that begins with the label (03:01:21)(Ch) refers to something that took place at just after 3am and principally affected the Swiss networks.

Events that contravene operating norms and procedures are shown as violations. These can be inadvertent. For instance, operators may not know about applicable rules and regulations. Violations can also be deliberate and may, in some cases, be justified. This happens when, for instance, rules and procedures fail to take into account particular environmental conditions that would further jeopardize safety if operators were to follow them. For example, Figure 1 shows that the Swiss authorities believed that ETRANS companies were in compliance with 'rights of way maintenance' regulations that were intended to ensure that vegetation was kept at an acceptable distance from transmission lines. This V2 diagram might, however, be amended to include a violation symbol if there was evidence to show that these rules had not been complied with.

Dotted ellipses represent conditions. For example, Figure 1 records the observation that the TSOs had to cooperate with ETRANS to ensure N-1 compliance. This is a short hand because events could be used to represent the need for coordination at 03:00, 03:01, 03:02 etc. Under UCTE requirements, transmission systems must be operated so that any single incident will not jeopardize the security of any service. In other words the loss of any 1 node from the N that are currently available will not interrupt supply. UCTE requirements also state that following any component failure, service operators must take actions to ensure that the system returns to N-1 security as soon as possible.

Solid ellipses represent vulnerabilities that threaten complex systems. Figure 1 shows that the Swiss authorities took steps to revise their maintenance and inspection procedures in the aftermath of the blackout. Figure 1 also uses a vulnerability node to show that there was no explicit agreement between the Swiss company ETRANS and the Italian network operators GRTN to shut down Italian storage pumps during any line overloading. These pumps helped store power by transferring water to high reservoirs when overnight electricity prices were low. The water could then be released using gravity to generate electricity as demand rose during the day. These pumps were close to the Swiss-Italian exchange points and hence had an important impact on loading. The pumping accounted for approximately 3500MW of demand.

Figure 1 also shows how the initial fault on the Mettlen-Lavorgo triggered attempts to reconnect the service. These automated responses failed. The right hand sequence of events illustrates further attempts by the Swiss ETRANS operators to coordinate load-shedding through their Austrian colleagues. However, the lack of any explicit agreement to coordinate the shut down of the Italian pumping stations created vulnerabilities that affected subsequent events.

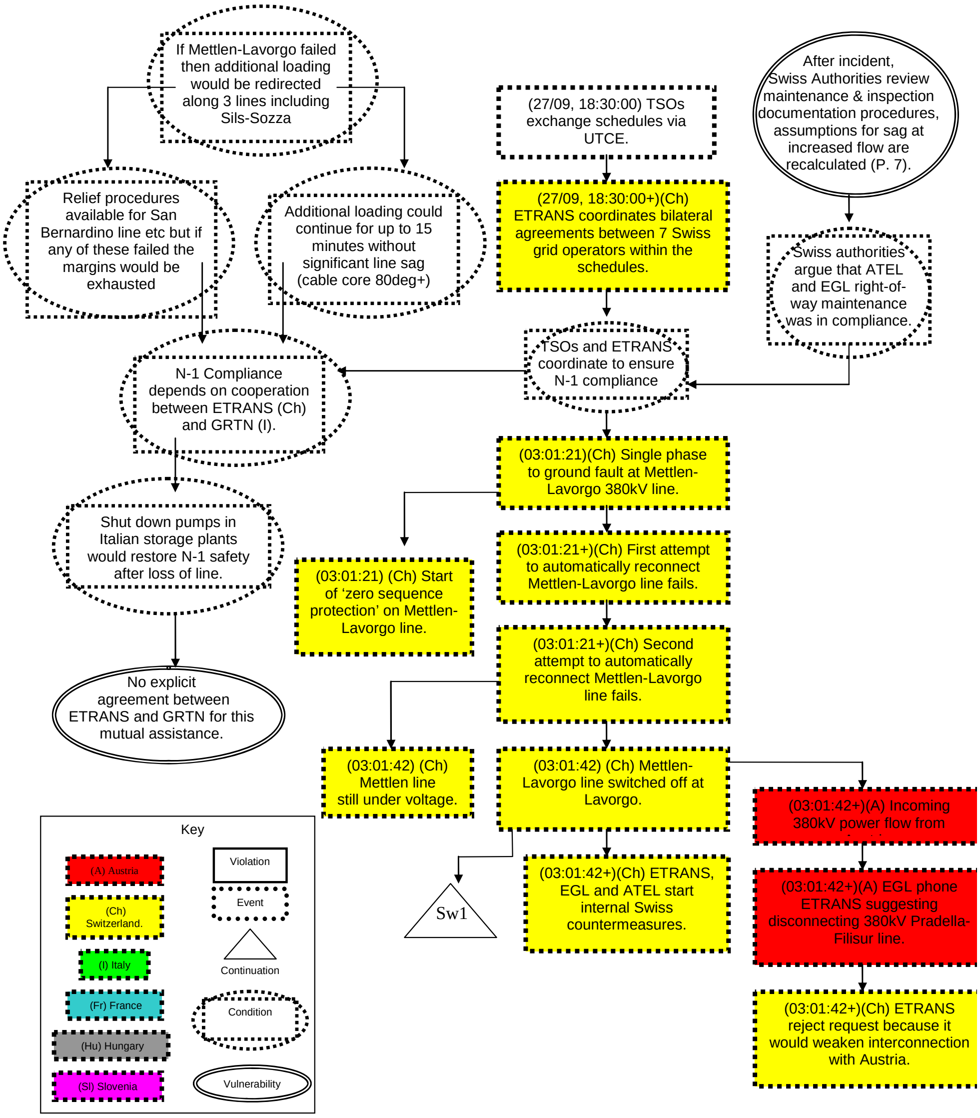

Figure 1: Initial Events Leading to the Italian and Swiss Blackout

The triangle labelled Sw1 is a continuation symbol denoting that the diagram continues in Figure 2. The failure of Mettlen-Lavorgo increased the load on the Mettlen-Airolo line. This led to a loading alarm at the Lavorgo transformer but staff failed to close the line after 03:08:23. Attempts were then made to coordinate the actions of the Swiss company ETRANS and the two immediate line operating companies EGL and ATEL Netz AG. The primary concern was to reduce the load on the Sils-Soazza 380kV line. ATEL altered the transformer tap at Lavorgo and EGL switched off another 380/220 transformer. However, this did little to reduce the overload on Sils-Soazza and eroded the 15 minute 'safety margin' for increased loading on this area of the network. During the early hours of the morning, when the blackout occurred, there was only a single ETRANS operator monitoring the systems. They were unaware that there was any maximum recommended time limit for increased load and this may have contributed to a lack of urgency over the Sils-Soazza 380kV line. Eventually at 03:10:45, ETRANS asked the Italian operator GRTN to reduce imports by 300MW. This request was made informally over the telephone. Regulations had been drafted to ensure that any requests should be made using faxes following a power failure in September 2000. ETRANS do not seem to have made any fax transmissions before the blackout and no phone call was received by the French company, RTE. Further disagreements have arisen over whether or not the ETRANS operator mentioned the Mettlen-Lavorgo line when they did contact their Italian counterparts at GRTN.

The requested 300MW reduction was only sufficient to alleviate the overloading on the Sils-Soazza line under ideal conditions. These included assumptions about the wind speed necessary to partially cool the cables. There is some disagreement over whether or not these and other assumptions were met, especially concerning the distance between the heated cables and nearby vegetation. However, it seems clear that the immediate 300MW reduction was only sufficient to provide temporary relief to the overloaded Sils-Soazza line. This may have been caused by poor situation awareness stemming from the lack of joint training between Swiss and Italian dispatchers. Another reason for the lack of situation awareness was the limited flow of information between the Swiss company ETRANS and the Italian operator

GRTN. The southern company did not have access to the same real-time data flows that were available to the Swiss operators. This is understandable; much of this ETRANS data would not be of immediate use to GRTN operators. A key insight from blackout is that an integrated European energy market requires greater access to and exchange of real-time operational information in order to meet reliability requirements. The bottom nodes in Figure 2 represent the failure of the Sils Soazza 380kV line. This triggered automatic protection devices for the 220kV Mettlen-Airolo line.

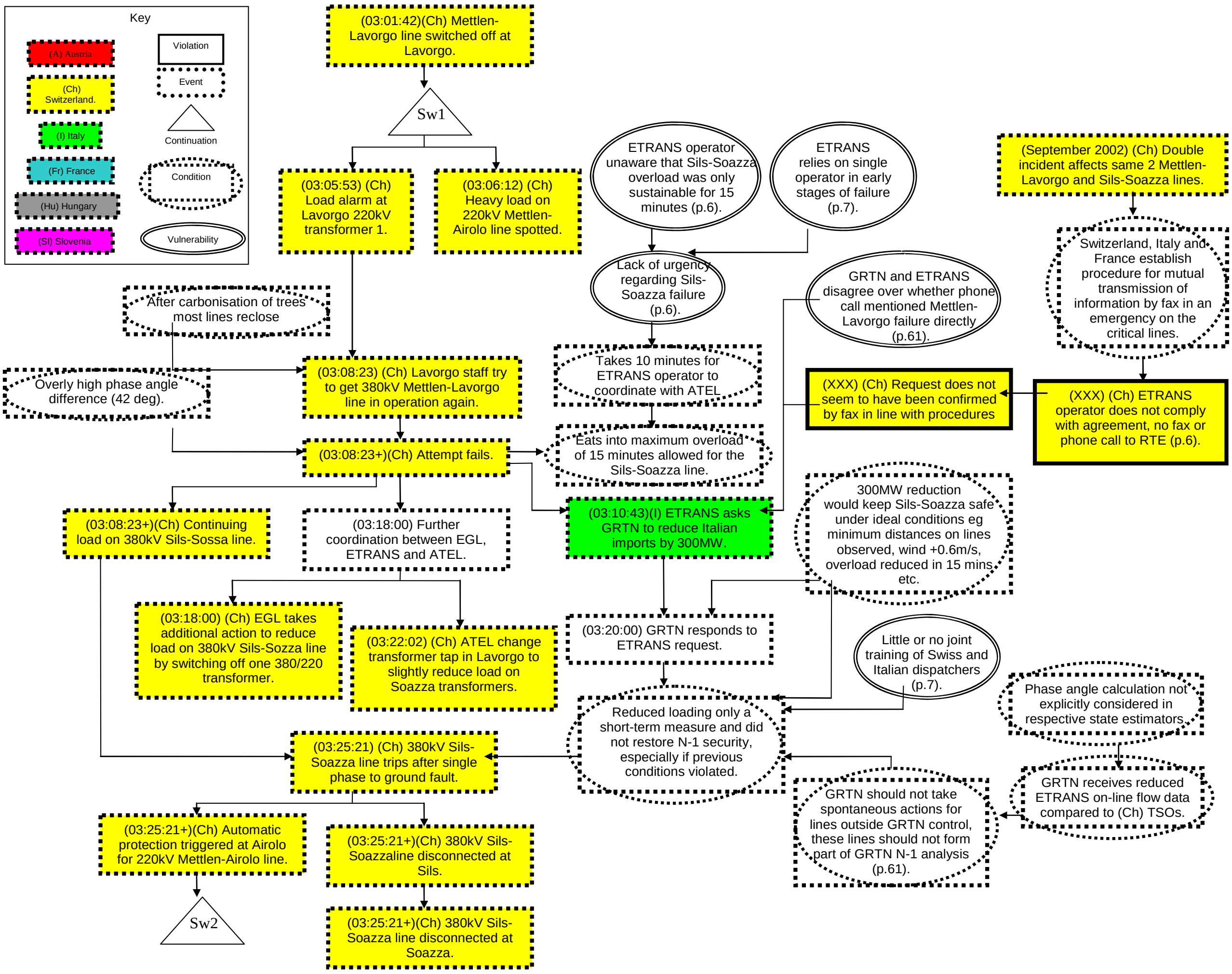

Figure 2: Initial Responses to the Failure at Mettlen-Lavorgo and the Loss of Sils-Soazza

Figure 3 presents the immediate consequences of Sils-Soazza failure. The automatic protection device on the 220kV Mettlen-Airolo line functioned as intended. However, it left many substations under increasingly heavy voltage levels as the available power found the route of least resistance across the remaining network. 'Over voltage' alarms began to propagate across UTCE zone 1. This is an area of synchronous supply including Austria, Belgium, France, Germany, Hungary and Slovenia. As can be seen from Figure 3, Hungary responded by switching on 350Mvar shunts. Austria took similar action. These shunts can be thought of as conductors that have low resistance and function in parallel with the rest of the network. Several of the zone 1 nations began to operate units at their 'under excitation' limit.

The Austrian network incorporated a range of protection devices that were intended to safeguard their infrastructure during overload conditions. Following the increasing voltage across the UCTE states, these devices began to separate the Austrian network from its Italian interconnections. In contrast to these areas of high voltage, Figure 3 also shows that some areas of France, including the Albertville 380kV line, and Austria suffered from 'under voltage' following the Swiss line failures. Figure 3 shows how an internal failure to a single line within Switzerland quickly propagated across international borders.

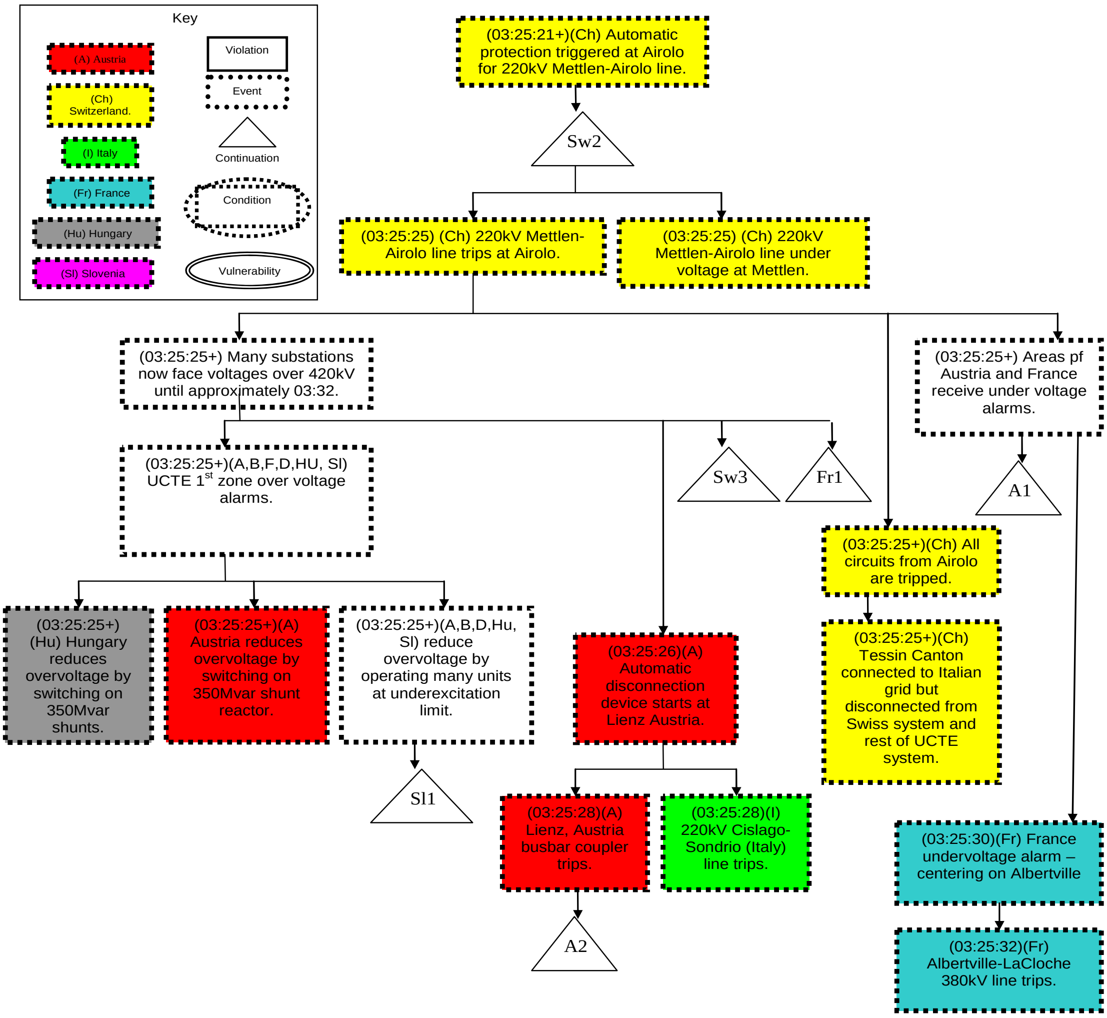

Figure 3: The Failure of Sils-Soazza Propagates Trips in Austria, Switzerland, France and Italy

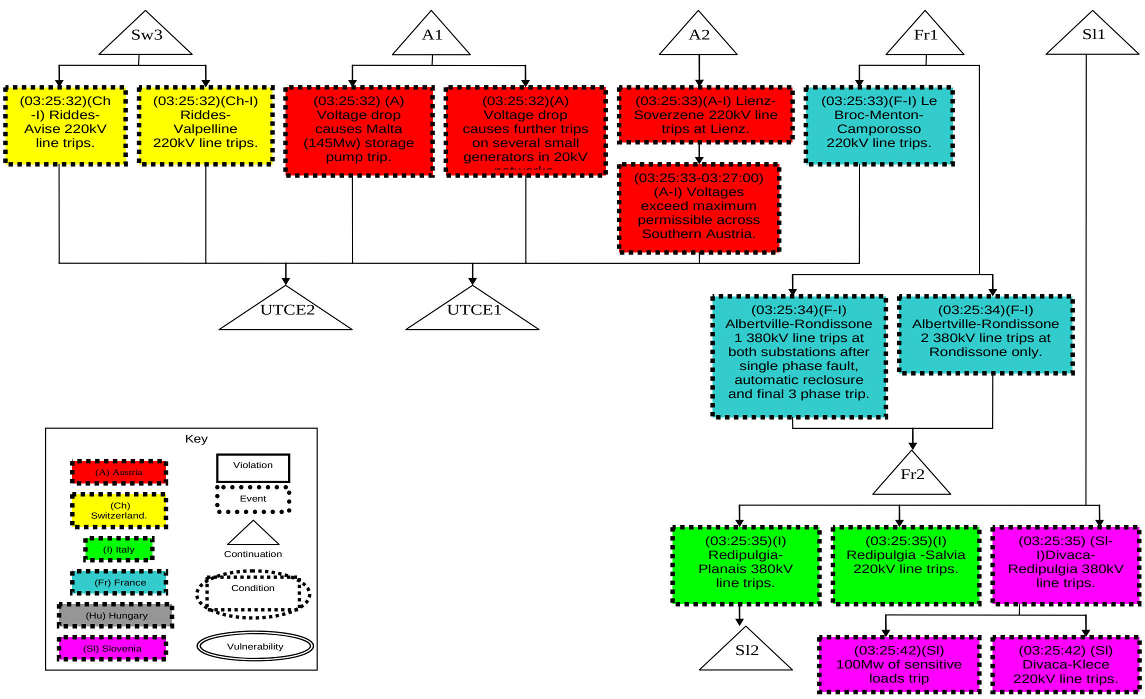

Figure 4: Knock-on Effects Propagating Across UTCE Zones 1 and 2

Figure 4 represents knock-on effects across several of the UCTE member states. These are denoted using parentheses showing both countries. For example, (Ch-I) is used to indicate an event that affected both the Swiss and Italian infrastructures. As can be seen, the over voltage caused by the loss of the Mettlen-Airolo line led to the loss of the Riddes-Avises 220kV and the Riddes-Valpelline 220kV lines on the Italian and Swiss borders. There were also effects on the connections between Austria and Italy. The trip by the Lienz busbar coupler shown in Figure 3 is linked to Figure 4 by the continuation symbol A2. The loss of the busbar led on to a trip on the Lienz-Soverzene 220kV line and to voltages that exceeded the maximum permissible levels across Southern Austria.

The loss of the Swiss lines also had an impact on Slovenian networks. In Figure 4, over-voltage conditions led to the loss of the Divaca- Redipulgia 380kV line on the Italian border. This had further consequences inside Slovenia as the Divaca-Klece 220kV line tripped. Approximately 100Mw of sensitive loads were also lost when protection devices activated. These effects on the Slovenian network began to propagate into the Italian system with the further loss of the Redipulgia-Salvia 220kV line and the Redipulgia-Planais 380kV line. Meanwhile, secondary effects were also creating problems for the French and Italian distribution networks. The Albertville-Rondissone-1 380kV line tripped at both substations after a single phase fault. The attempted automatic re-closure failed. The Albertville-Rondissone-2 380kV line also tripped at Rondissone.

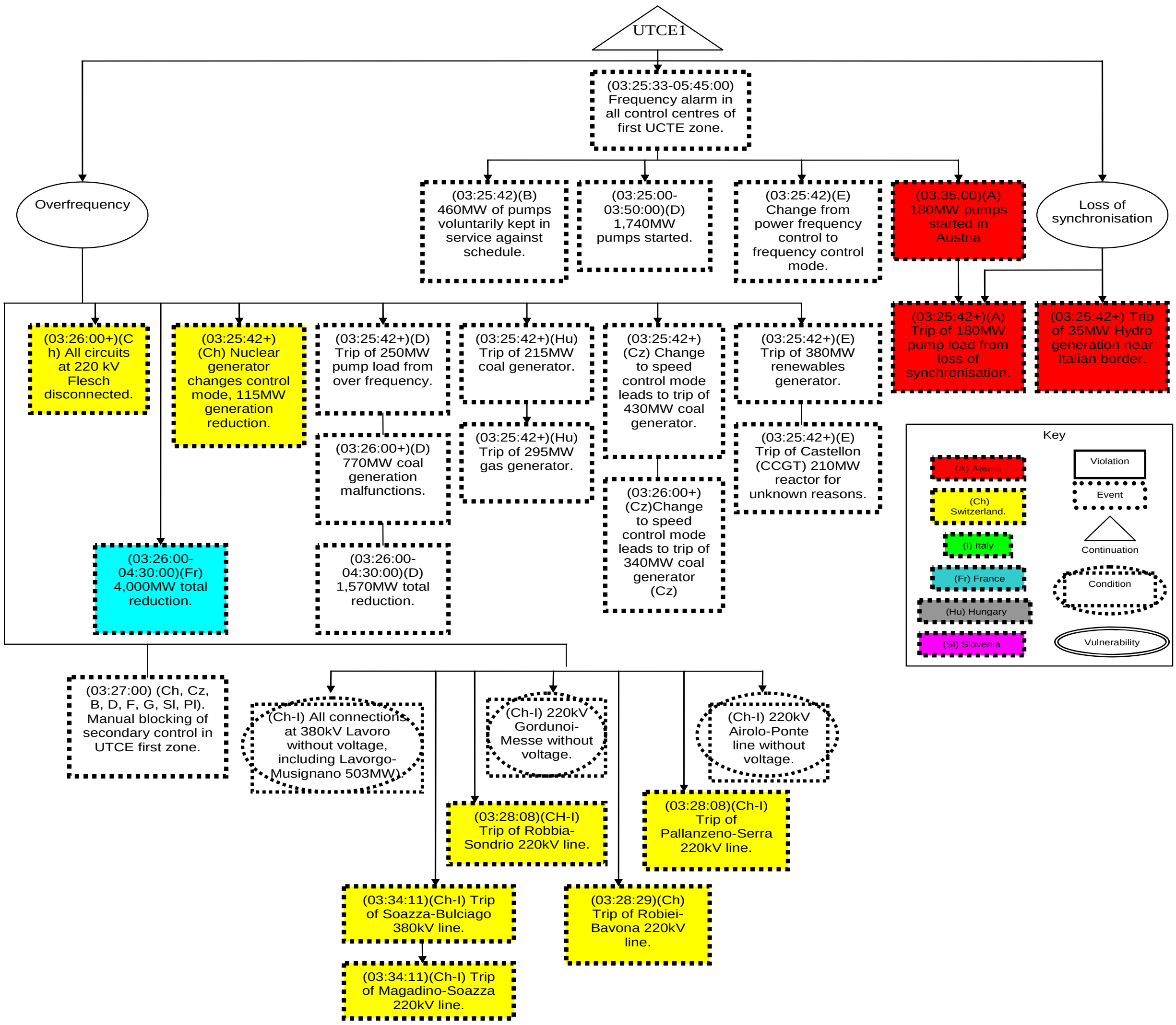

Figure 5: Knock-on Effects of the Initial Faults across UTCE Zone 1

Figure 5 focuses on the impact that the 'over voltage' conditions had upon UCTE zone 1. The impact of the initial failures led to changes in the generation and transmission schedules in Belgium as 460MW of pumps were kept in service for longer than had been planned. In Germany, 1,740MW of pumps were started to reduce the loading on other areas of the network. The Austrian companies started 180MW of pumps. However, these and other measures failed to prevent a loss of synchronization across the networks. In general terms, a loss of synchronization will affect power quality and may damage or disrupt a range of devices. Ideally electric power would be supplied as a sine wave with amplitude and frequency given by national standards. Loss of synchronization affects supply characteristics. In Austria, the loss of synchronization led to a 180MW pumps being tripped and to the loss of 36MW of hydo-generation capacity on the Italian border. As far away as Spain, the network operators had to intervene in order to ensure the stability of their system.

In other areas of UTCE zone 1, the initial failures across the Swiss network led to 'over frequency' problems. It is important to understand this phenomenon because it illustrates how line failures had knock-on effects beyond the intended destinations for energy transfers. These line trips also affected countries that were directly and indirectly involved in the supply of power to the Italian networks. As the Italian infrastructure was gradually isolated from the UCTE grid there was no destination for the power that should have been transferred to them. In broad terms, an excess of generating capacity over demand can lead to 'over frequency' problems. Generators will often be equipped with governing devices that respond to such frequency rises by cutting output. In Figure 5 this can be seen in the way that France reduced output by some 4,000MW between 03:26 and 04:30. In Germany, a pump system trip removed 250MW. In addition, 770MW of coal fired generators were tripped as a result of 'over frequency' detection. Swiss nuclear generating capacity fell by 115MW. In Hungary, 215MW of coal and 295MW of gas generating capacity tripped. In the Czech Republic, the over frequency problems led to a change in control mode and to the loss of a 430MW of coal generator and then a 340MW plant. The Spanish network lost a 380MW renewables generator. The Swiss 220kV Flesch circuits also disconnected.

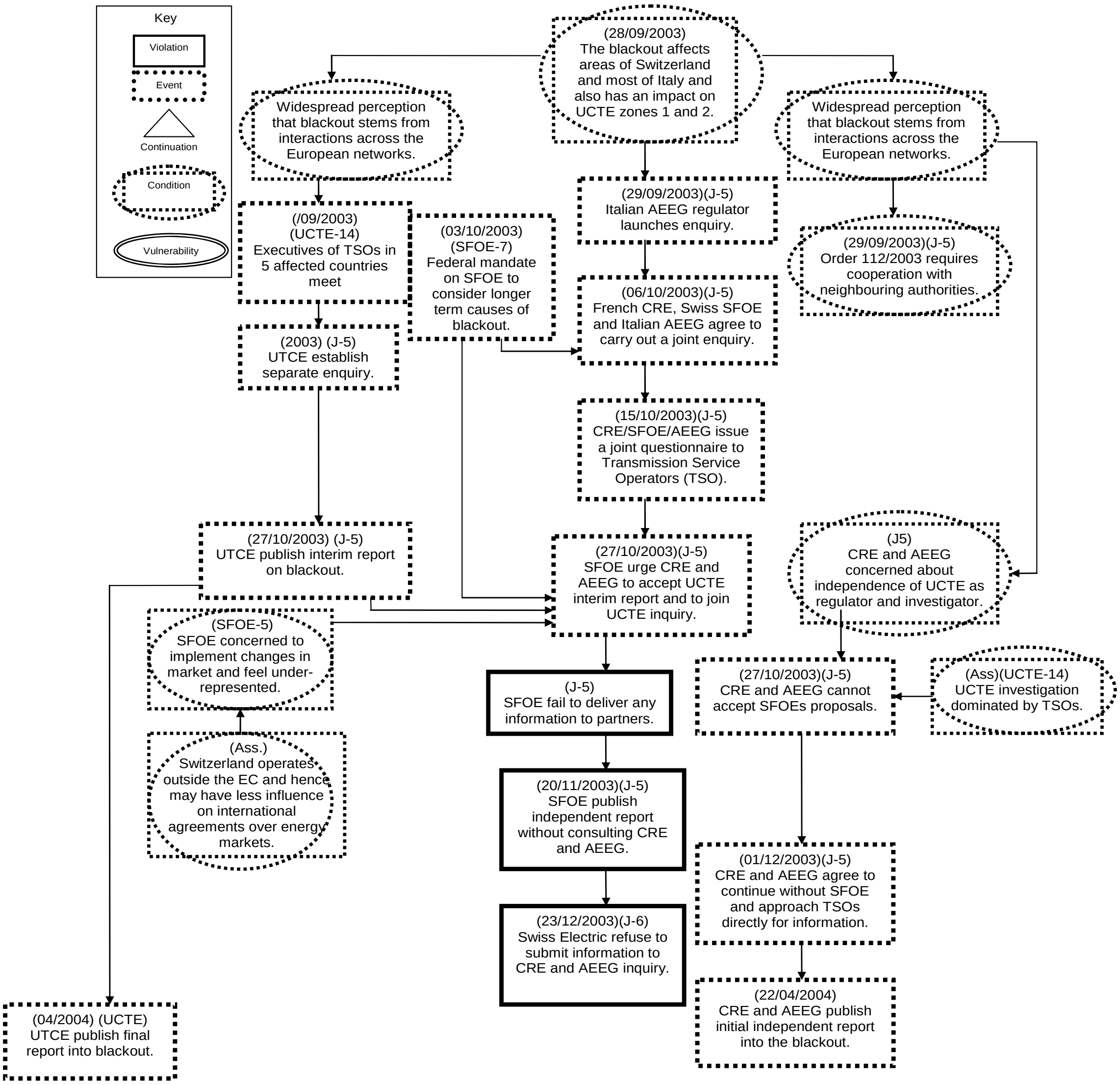

Figure 6: Tensions Leading to Schisms over the Investigation of the Blackout

Figure 6 continues the French effects from the continuation symbol labelled Fr2 in Figure 4. Increased loading exceeded the capacity set on protection devices. Overload limiters began to isolate the 400kV line between Hernani in Spain and Argia in France. A 380kV line between Villarodin and Praz as well as the 712kV Villarodin-Venaus line tripped. Figure 6 also denoted the consequences of 'over voltage' for Slovenia through the continuation symbol labelled Sl2. The initial loss of the Swiss lines caused the Redipulgia-Planais 380kV line to trip. Partly in consequence, a weak 132kV link between Italy and Slovenia also failed. This together with the loss of the 220kV Padriciano-Divacia line led to the final separation of the Italian network on the Slovenian border.

4 Mapping Alternate Perspectives

Figure 6 shows how V2 diagrams can be extended to represent different phases in the investigation of the blackout. We have annotated some of the nodes to explicitly represent the sources that support those observations. For instance, (SFOE-5) refers to information that was presented on page 5 of the SFOE report (2003). Similarly, (J-6) refers to evidence presented on page 6 of the joint report published by the French, CRE, and Italian, AEEG (2004), regulators. (UTCE-14) cites information from page 14 of the UTCE (2004) report. These references are important when there are significant differences over the causes of the blackout.

In the immediate aftermath of the blackout, the Italian regulatory authority for electricity and gas (AEEG), the French CRE and the Swiss Federal Office for Energy (SFOE) developed a joint questionnaire that was sent to Transmission System Operators to gather evidence. The questionnaire was also intended to identify any exchange of reliability information between TSOs and the Swiss utilities. This initial collaboration led to disagreement. Technical, commercial and political differences emerged over the longer term causes. In particular, there were disagreements over the role of the Union for the Co-ordination of Transmission of Electricity (UCTE). In addition to the investigations launched by the national regulators, the UCTE began to coordinate a joint investigation to determine whether the blackout offered insights for the future regulation of energy transmission. The Swiss SFOE urged the other two regulators to accept the findings presented in the UCTE interim report. They also suggested that all three of the national bodies should coordinate their investigations with the joint European investigation led by the UCTE. This led to considerable disagreement. The Italian AEEG and the French CRE were concerned that the UCTE were both investigating the failure and were also responsible for setting standards for power transmission (page 5, AEEG, 2004).

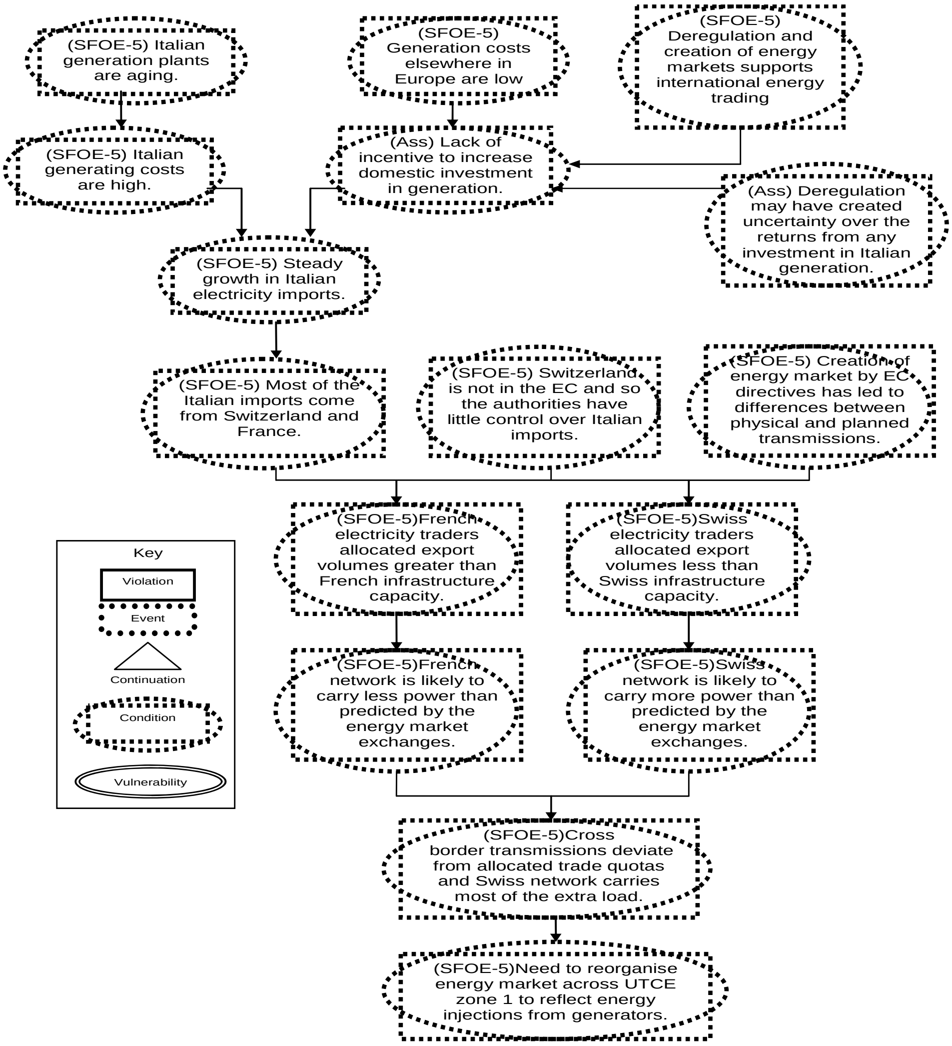

Figure 7: High-Level Overview of the SFOE Analysis of the Italian Blackout

Figure 6 identifies additional political and organizational factors that may have influenced the course of subsequent investigations. The UTCE enquiry was established by a group of Transmission Service Operators; national regulators may have been concerned that these companies would have undue influence over the course of an investigation. Additional evidence is required to support such as assertion, hence it is not annotated with any reference to particular reports but is labelled (Ass). Similarly, it can be argued that the SFOE supported the UTCE investigation because this body provided them with direct means of influencing the regulation and practice of cross-border energy transmissions. Figure 6 uses a condition node to emphasis that such channels of influence were particularly important given the Swiss operated outside frameworks available to EC members.

Relations between national regulators were further strained when the Swiss SFOE issued an independent report on the blackout without consulting their Italian or French counterparts. Figure 6 denotes this as a violation of the previous joint agreement based on information from the AEEG and CRE report. This is a subjective decision, as mentioned in previous sections, and the classification could be amended to show this as a more 'neutral' event. However, the publication of the independent report helped to persuade the AEEG and CRE to continue their investigation without the SFOE. The integrated Swiss electricity companies then argued that all necessary information had been provided to the UCTE, SFOE and Italian Government investigations. This deprived the AEEG and CRE of direct access to some evidence about the course of the blackout.

The UCTE plays a central role in ensuring the future growth and stability of European infrastructures. If the Italian and French regulators are correct in their criticisms then this would support a strong case for the creation of a new, independent agency for the investigation of cross-border infrastructure failures. These differences led to the publication of independent reports by the UCTE, by the Italian (AEEG) and French (CRE) regulators and by the Swiss Federal Office of Energy (SFOE). This list is not exhaustive as many different companies and regulatory agencies were affected by the blackout. For example, Nordel, the Scandinavian industry body, was also asked to carry out an independent study by CRE, SFOE and AEEG.

The analysis provided by the SFOE argued that the immediate causes stemmed from the ground fault on the Mettlen-Lavorgo line. The Swiss regulator also identified problems in the actions to restore the line. In particular, there were inadequate communications between the Swiss transmission company, ETRANS, and the Italian network operator GRTN. They also pointed to inherent instabilities in the Italian network. They were, however, careful to stress that these were not the underlying causes. SFOE argued the main problems stemmed from "unresolved conflicts" between the trading interests of particular countries and the physical capacity of the networks through which those trades might be realized. Figure 7, therefore, extends our analysis to focus on the causal arguments presented in the SFOE report. As can be seen, the Swiss regulators focused on the impact of market deregulation and structure on the longer terms causes of the blackout. Elements of the Italian generating infrastructure were relatively old. The Italian industry also suffered from relatively high costs. In contrast, the deregulation of supply and the promotion of EC energy markets together with the relatively low costs of generation in other European countries provided disincentives for future investment in Italian domestic generation. These various factors combined to fuel a steady growth in energy imports.

The rising demand necessarily had an impact on the Swiss networks, either directly through exports from Swiss generating companies or indirectly as a transmission route for other generators. However, the SFOE argued that Switzerland had little influence on the regulatory and political decisions that had helped to create this situation because they were not an EC member state. Successive steps towards the creation of a deregulated energy market had created an environment in which the loading on cross-border networks often deviated from agreed trading quotas. In particular, the SFOE argued that French electricity traders had been allocated export volumes that exceeded the physical transmission capacity between France and Italy. This situation was contrasted with the position of Swiss electricity traders who operated within the limits imposed by the physical transmission capacity between Italy and Switzerland. The report of the Swiss regulator SFOE, therefore, argued that the longer term causes of the blackout stemmed from the differences that existed between the trades that were allowed across European energy markets and the physical capacity of the transmission networks to support these transactions. The report implicitly criticizes the trading practices that took place under the Italian and French national regulators, AEEG and CRE. It also agues for greater European coordination in order to ensure that market forces do not undermine the reliability of UCTE services.

The French and Italian agencies argued that the Swiss operators took 'inappropriate measures' and made 'operational mistakes' that led to the loss of the Sils-Soazza line after the initial fault on Mettlen-Lavorgo. They also argued that the events of the 28th September revealed a need for greater coordination between TSOs in planning for the real-time control of interconnected transmission networks. There were further differences between the SFOE and the joint AEEG/CRE reports. The AEEG and CRE looked less at the relationship between market movements and physical transmission capacity. Instead, they focused on the actions of the Swiss operators to anticipate and then respond to any potential problems. They argued that the Swiss companies did not comply with UCTE operating rules on the night of the blackout. A further conclusion was, therefore, that compliance should be legally binding and that companies should be subject to independent verification. They went on to argue that the Swiss government should construct a legal and regulatory framework that is consistent with EU legislation in order to ensure the security of the European grid.

5 Conclusions

On the 28th September 2003, a blackout affected more than 56 million people across Italy and areas of Switzerland. The immediate trigger was a fault in the Swiss transmission system. The consequences propagated across international borders affecting the networks in France, Slovenia, and Austria. It also led to a domino effect that ultimately led to the separation of the Italian system from the rest of the European grid.

This paper has traced the causes of this failure to technical vulnerabilities that, in turn, stemmed from changes in the regulation and monitoring of energy transfers across Europe. It has also identified had managerial and human factors causes; these arguably included an over-reliance on computer-based decision support systems. We have extended the application of accident analysis techniques to support these arguments. In particular, we have used Violation and Vulnerability (V2) diagrams to map out the causal factor behind the blackout. By focussing on longer term vulnerabilities and the more immediate violations, it is possible to identify interactions between technical, managerial and regulatory factors across several European states. It is also possible to contrast a number of alternate accounts of the causes of the Italian blackout, reflecting different attitudes between the Swiss, Italian and French authorities. This is important because, as we have seen, radically different solutions have been proposed by the various stakeholders that issued independent reports in the aftermath of this failure.

This article is a companion paper to a previous study that applied the same analytical techniques to the US and Canadian blackouts that occurred on the 14th August 2003 (Johnson, 2006). It is clear that there were similar technical, managerial and regulator issues in both incidents. Both have been described as 'litmus tests' that reveal attitudes towards deregulation in the energy sector. Similarly, Cowie et al (2004) have provided important insights into the resilience of the Internet under these two major power failures. Their work is significant because increasing areas of our infrastructure depend on this technology to support communication under contingency situations. Further work is urgently required to determine the knock-on effects that might be anticipated for future blackouts as society increasingly relies upon computational infrastructures that are susceptible to major power failures.

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