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CRITICAL INTERRELATIONS BETWEEN ICT AND ELECTRICITY SYSTEM

Janusz W. Bialek

Institute for Energy Systems, School of Engineering

The University of Edinburgh, UK

Email: Janusz.Bialek@ed.ac.uk

Abstract

The widespread blackouts of 2003 have exposed the critical role of ICT systems in maintaining reliable operation of power systems. Fundamental errors in providing back-up and alarm function in the control room were one of the main contributing factors to the 2003 USA/Canada blackout. The lack of proper ICT infrastructure to enable proper communication and cooperation between System Operators in Italy and Switzerland led to delayed remedial actions and the consequent blackout of Italy in 2003. Improved ICT systems would enable a better real-time cooperation and coordination between utilities in an interconnected power system but the main challenge is political: overcoming resistance of individual utilities to give up partially their interdependence and operate within the paradigm of a distributed, but coordinated, control. Emergence of GPS-synchronised Wide Area Measurement Systems (WAMS) holds a great promise for improved monitoring and control of modern power systems and therefore avoiding future blackouts.

1 Introduction

Modern power systems are highly complicated, dynamic, non-linear, time-critical, and covering large geographic areas. In addition, reliable operation of the power grid is complex and demanding for two main reasons:

- As electricity flows at almost the speed of light and it cannot be stored economically at large quantities, its production must follow consumption on minute-by-minute basis. Any discrepancy between production and consumption will be absorbed by kinetic energy of all rotating generators resulting in their increased or reduced speed.

- The flow of electricity in a meshed network is governed by the laws of physics and cannot be directly controlled[1]. In order to avoid overloading of transmission lines, System Operators (SOs) must have ability to adjust output of generators (or consumption of loads) in certain locations.

All those reasons mean that monitoring and control of modern power systems requires advanced ICT systems. Any problems with ICT systems may have grave consequences for security of supply. This paper will discuss two aspects of critical interrelations between ICT and electricity systems. Firstly we will illustrate this criticality by discussing how inappropriate ICT systems contributed to widespread blackouts in USA/Canada and Italy in 2003. Then we will discuss the potential of GPS-synchronised Wide Area Measurement Systems (WAMS) in preventing power system blackouts.

2 ICT systems and blackouts

The critical dependence of electricity supply systems on ICT systems has been most vividly demonstrated during a number of blackouts that occurred in recent years. There were 6 blackouts within 6 weeks in the late summer of 2003 affecting about 112 million people in US, UK, Denmark, Sweden and Italy. They were all transmission-based, i.e. there were no problems at the time with the level of generation. The systems were not stressed before the blackouts occurred – in Italy the blackout even happened at night. Obviously the direct reasons for the blackouts were purely electrical (short-circuits) but one of the reasons the blackouts spread so widely was the inadequate provision of ICT systems. This point will be described in more detail using the example of the USA/Canada and Italia blackouts. The attention will be concentrated not on the blackouts themselves but rather on how inadequate provision of ICT system has exasperated the situation. Please refer to Appendix A for explanation how security of an interconnected power system is maintained and to [2] for more details on blackouts of 2003.

2.1 US blackout on 14 August 2003

The blackout was triggered by some initial innocuous-looking outages in northern Ohio, which spread to the North East of USA and parts of Canada. 62 GW were lost, about 50 million people were affected, full restoration took several

[1] Power flows can be controlled to some extent by so-called Flexible AC Transmission System (FACTS) devices but they are still too expensive for general use.

days. The blackout description below contains extended excerpts from the final report [1]

2.1.1 The course of events

Figure 1 shows the geographical area and the control areas in the area where the blackout started. It is important to note that the events involved directly 6 control areas, which shows the importance of proper communication and coordination between System Operators. The disturbances started in northern Ohio controlled by FirstEnergy (FE) – see Figure 1.

At 14:02 EDT, Dayton Power & Light's (DPL) Stuart-Atlanta 345-kV line (see Figure 1) tripped off-line due to a tree flashover[2]. This line had no direct electrical effect on FE's system—but it did affect Midwest Independent System Operator (MISO) performance as reliability coordinator, even though PJM is the reliability coordinator for the DPL line[3]. 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 EDT and 15:34 EDT, 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 EDT MISO could not determine that with an earlier trip of Eastlake 5 power station in Cleveland, other transmission lines would overload if FE lost a major transmission line, and could not issue appropriate warnings and operational instructions.

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[2] Flow of current causes transmission lines to heat and sag. If trees growing underneath are not cut in time, a flashover may occur.

[3] See Appendix A for explanations about reliability of interconnected power systems, state estimation, SCADA systems, etc.

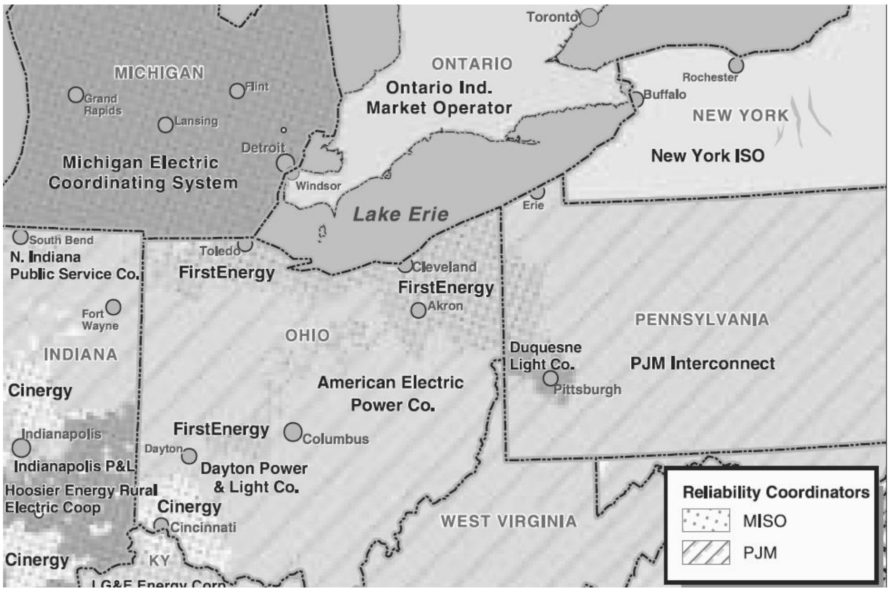


Figure 1 The area of blackout origination [1]

Starting around 14:14 EDT, 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) system 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 EDT. 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.

From 15:05:41 EDT to 15:41:35 EDT, three 345-kV lines tripped in Cleveland area at 43.5%, 87.5% and 93.2%, respectively, of their normal and emergency line rating. As each of the transmission lines failed, power flows shifted to other transmission paths increasing their loading and resulting in further trips. Additionally, voltages on the rest of FE's system degraded further.

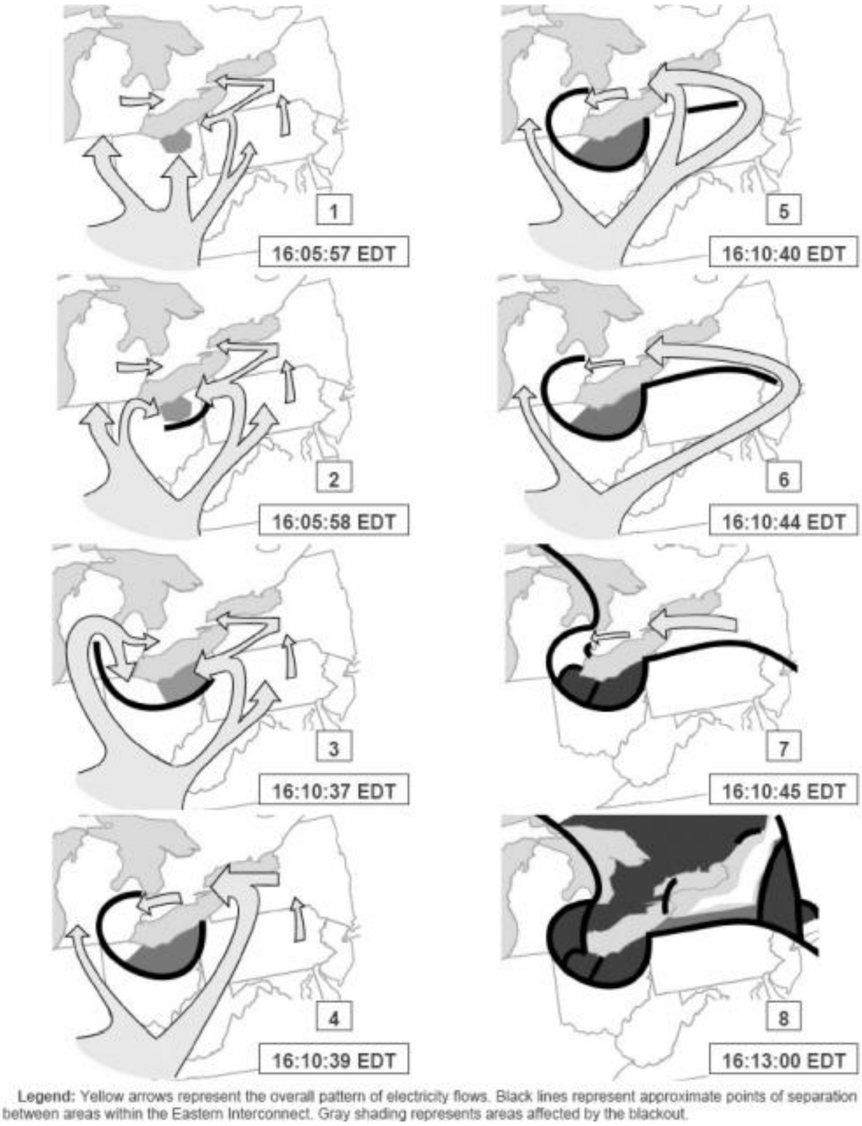


Figure 2 Overview of power flows during the blackout [1].

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 EDT, the first of an eventual sixteen 138-kV lines began to fail. As these lines failed, the resulting 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 tripped out, they blacked out customers in Akron and the areas west and south of the city, ultimately dropping about 600 MW of load.

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 – see Figure 2.1. This pathway in northeastern Ohio became unavailable with the collapse of FE's transmission system. The electricity then took alternative paths to the load centres located along the shore of Lake Erie – see Figure 2.2. 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.

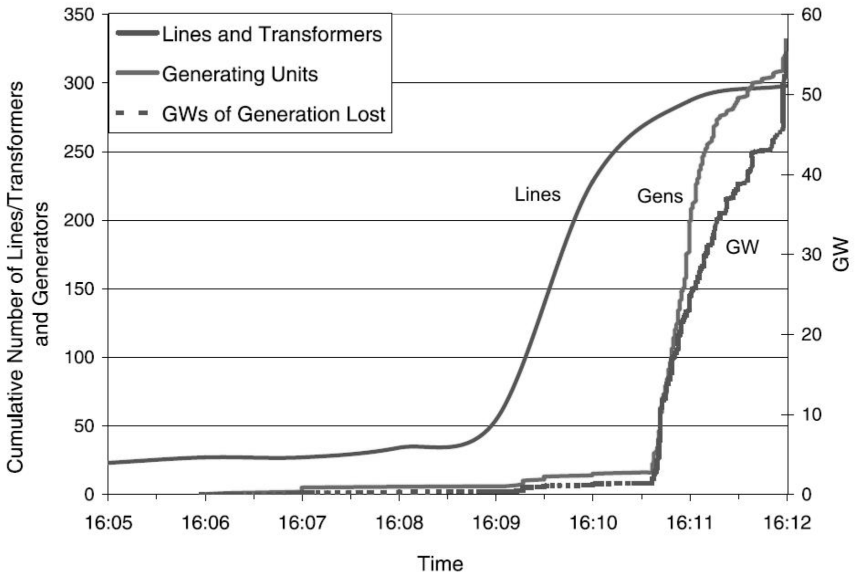
The northeast then separated from the rest of the Eastern Interconnection due to these additional power surges. The power surges resulting from the FE system failures caused lines in neighbouring areas to see overloads that caused impedance relays to operate[4]. The result was a wave of line trips through western Ohio that separated AEP from FE - - Figure 2.3. Then the line trips progressed northward into Michigan separating western and eastern Michigan - - Figure 2.4. 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 - - Figure 2.4. Power flow from Ontario into Detroit suddenly changed direction and a period of sustained oscillations ensued indicating system instability. The impedance relays on the lines between PJM and New York saw the massive power surge as faults and tripped those lines. Lines in western Ontario also became overloaded and tripped - - Figure 2.5 and Figure 2.6. The entire northeastern United States and the province of Ontario then became a large electrical island separated from the rest of the Eastern Interconnection -- Figure 2.7. 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.

2.1.2 Criticality of ICT systems for the USA/Canada blackout

The most critical issue from the point of view of ICT systems was that during the crucial hour when transmission lines started to trip, the operators at FE control room were unaware of what was going on in their systems. Not only there were unaware of the situation but that did not know that they were unaware. It is quite

[4] Impedance relay trips a transmission line when its load exceeds a pre-set value.

likely that had they known, they could have taken actions to avert the fast-spreading blackout. It is important to emphasise that time-criticality is essential for preventing blackouts. This is illustrated in Figure 3 which shows the number of system elements that tripped during the blackout. Once a cascade starts, it is next to impossible to stop it.



F**igure 3** Speed of blackout spreading [1]

The report [1] identified a number of causes of the blackout and they were also reviewed in [2]. Below we quote the causes [1] that directly relate to ICT systems :

- 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.
- 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 se-

curity 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.

2.2 Italian blackout on 28 September 2003.

The blackout happened at 3 am when Italy was importing 6651 MW from France, Switzerland, Austria and Slovenia [3]. The import constituted about 24% of total demand and was about 300 MW above the agreed import level. The pattern of flows into Italy through the tie-lines depends on the overall generation pattern in surrounding countries. At the time, the Swiss transmission grid was highly stressed operating close to (N-1) security criterion however the Italian System Operator (SO) was not aware of it. The high usage of Swiss grid by imports to Italy was difficult to control by the Swiss operator by its own means.

2.2.1 The course of events

At 3.01 am a tree flashover tripped an overhead 380 kV Mettlen-Lavorgo line in Switzerland – see Figure 4. At the time the loading on the line was about 86% of its maximum capacity and the flashover was probably caused by insufficient distance of the tree from the conductors. An attempt was made to reclose the line but it was unsuccessful due to a too high phase angle difference (42^o) resulting from a high power flow to Italy. The load carried by the tripped line was taken over by other parallel lines and resulted in overloading by 10% of another 380 kV line Sils-Soazza – see Figure 4. According to operating standards the line load should have been relieved within 15 minutes to prevent automatic disconnection.

The Swiss operator, ETRANS, telephoned the Italian operator GRTN at 3.11 am and requested reduction of imports by 300 MW to the previously agreed levels. According to ETRANS, they have also informed GRTN about the line outage but this claim is disputed by GRTN. GRTN reduced import at 3.21 am by shutting down pumps at pumped-storage plants but this, together with some internal countermeasures undertaken within the Swiss system, was not sufficient and at 3.25 am, i.e. 24 minutes after the first line tripped, the overloaded Sils-Soazza line sagged and tripped after a tree flashover. From this moment on, a severe system failure was inevitable. Loss of the second import line resulted in a severe overload of other import lines and the third line (Airolo-Mettlen) tripped after 4 seconds.

Additionally, Italy lost synchronism with the rest of UCTE (loss of angle stability) and the remaining import lines tripped almost instantaneously isolating Italy from the rest of Europe at 3.25 am. Quite importantly, the dynamic interaction between the Italy and rest of UCTE main grid during the last seconds before separation led to a fast voltage collapse in Italy. Following islanding of Italy, the internal generation deficit was about 6.4 GW and frequency started to fall. Although about 10 GW of load was shed by automatic under-frequency load shedding, it proved ineffective as 21 out of 50 thermal plants were tripped due to low voltage even before frequency reached 47.5 Hz. Consequently the whole Italy, apart from Sardinia, was blacked out 2 minutes and 30 seconds after separation.

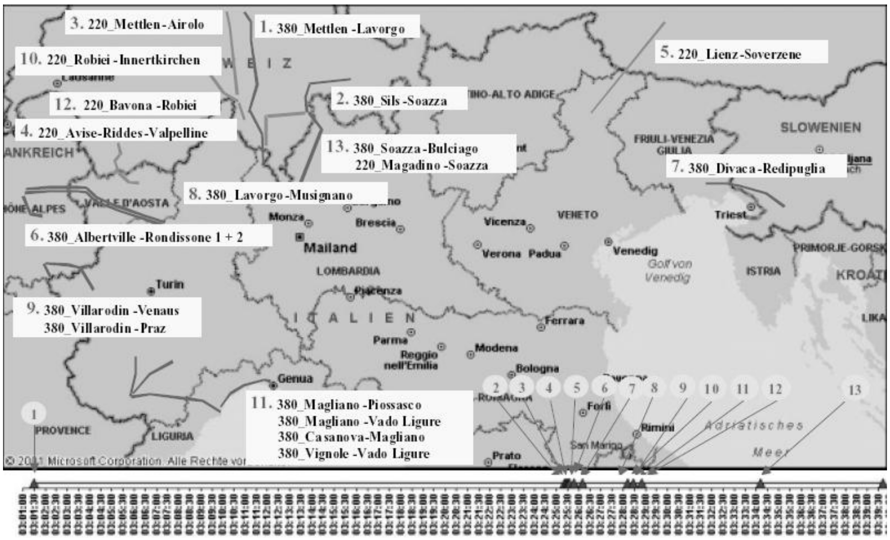


Figure 4. Italian blackout and its timeline [3].

Following separation of Italy, the rest of UCTE network was also in a dangerous position. Frequency quickly increased to 50.25 Hz, significant power fluctuations were recorded and the European power flows took an unpredicted pattern. Some generating units were tripped by over-frequency or under-voltage relays. Loading of lines from France to Germany and Belgium increased significantly. However the system operators took various emergency actions so that further spreading of blackouts was avoided.

2.2.2 Criticality of ICT systems for the Italian blackout

Similarly as it was the case with the US blackout, the real underlying reason for such a widespread blackout was insufficient coordination of real-time security assessment and control between the Swiss and Italian System Operators. Additionally Italian system operator was unaware of the overall load flow situation in Europe and the resulting consequences for Italy. Proper ICT systems would have made exchange of real-time information possible and could have prevented the blackout.

The report [3] also concluded that in Europe, where the network is highly meshed and stability problems never appeared to be so critical, power system stability must be thoroughly analysed - even in the case of N-2 contingencies. This will require deeper stability analyses, in order to identify possible conditions leading to stability problems and to define suitable countermeasures if necessary. Such system-wide stability analyses would require a continent-wide comprehensive ICT system.

2.3 Need for coordination of operation in interconnected power systems

One of the main problems with cross-border trades in an interconnected power system is that trades do not travel according to "contract paths" agreed between the seller and the buyer but rather they flow over many transmission lines, as determined by Kirchhoff's and Ohm's laws. This is referred to as a parallel, or loop-flow, effect. Consequently utilities find their networks loaded with power transfers they have little idea about. Figure 5 shows different routes through which an assumed 1000 MW trade between Northern France and Italy would flow [4]. Only 38% of power would flow directly from France to Italy; the remaining 62% would flow through different parallel routes loading the transit networks. Note that 15% of power would even flow in a round way via Belgium and Netherlands.

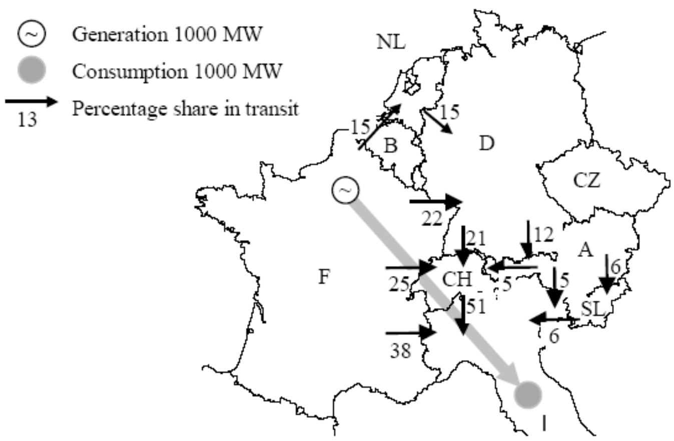


Figure 5. Percentage shares through different transit routes for a trade from northern France to Italy [4].

Parallel flows did not cause major problems pre 1990, as inter-area exchanges were usually agreed well in advance by the system operators and were relatively small. Post 1990, inter-area trades have not only increased significantly in volume, but they also started to be arranged by independent agents, rather than system operators. The result is illustrated in Figure 6 which shows that a large proportion of flows on the Belgian grid in 1999 was unexpected by the Belgian system operator. That situation led to a few nearly avoided blackouts in Belgium in 1990s.

A similar parallel flow effect was one of the main factors contributing to US and Italian blackouts. In the case of US, as the existing transmission corridors were increasingly blocked by lines tripping off, power to supply northern Ohio and Ontario had to find alternative ways and did so through neighbouring utilities (Michigan, PJM and New York) – see Figure 2. The relevant system operators suddenly saw huge increases in power transfers through their territories but they did not know what caused them and could do little about them.

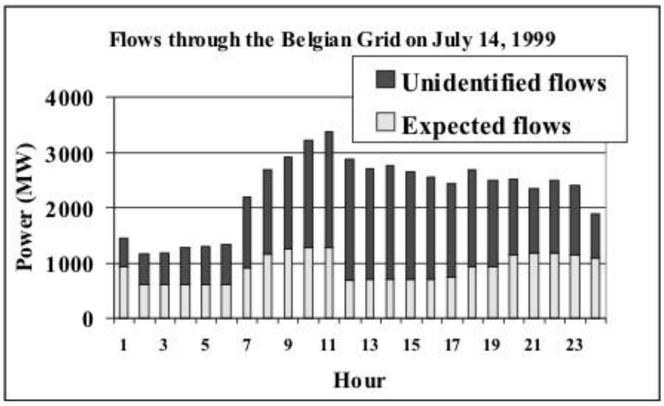


Figure 6. Expected and unidentified flows through Belgian grid [5].

In the case of Italian blackout, transfers through Switzerland to Italy depended on the overall pattern of generation in surrounding countries. Although some of Swiss lines were operating close to their limits, Swiss operators could do little to relieve them.

Proper accounting for parallel flows is difficult enough in operational planning stages. In emergencies, when power system topology may be different to the assumed one and some power stations may be lost, proper accounting for parallel flows would require real-time security monitoring and automatic exchange of information between SOs, rather than telephone-based coordination.

Proper coordination between System Operators in an interconnected power system would require a overcoming a number of technical, political and organisation challenges [6]. The best way forward would be to change the paradigm of operation from the existing decentralised to the coordinated one in which each SO would still look after its own area in day-to-day operation and planning but necessary coordination would be required for system-wide security assessment and control purposes. To do that information would have to be exchanged to assess the impact of planned trades and outages on all the areas involved or, in other words, to assess accurately all the parallel flows in both operational planning and real-time operation stages. Furthermore, real-time coordinated security assessment would be needed to assess the impact of any contingencies on the whole interconnected network. Obviously this would require advanced ICT systems. The next step would be coordinated reaction to contingencies. When each SO defends itself against a contingency without taking into account the big picture, the results may be detrimental for the system as the whole. The next important problem is determination of who, and how much, should pay for the reliability-connected actions.

Development of ICT system to support such a mode of operation is a technical challenge but one which can be relatively easily overcome as the underlying technology is readily available. The main challenge is political: overcoming resistance of individual utilities to give up partially their interdependence and operate within the paradigm of a distributed, but coordinated, control. One of the other main problems with increased coordination is the necessity to exchange operational information about each control area. Such information could be deemed to be commercially sensitive so the SOs would be reluctant to share it. Traditional load-flow or stability programs require detailed information about generation and demand profiles at each node but for proposed coordinated operation and control exchange of full individual nodal profiles is not needed. The important thing is to asses the system-wide impact of situation in each control area. Further research is needed to establish what type of information is necessary to be exchanged, and in what way, in order to perform system-wide security assessment and control whilst which information can be deemed to be left as private to individual SOs. Following that, appropriate organisational structures would have to be established. There may be a need to establish a single body charged with maintaining real-time security of the whole interconnected system.

The need for improved coordination between utilities has been clearly recognised by the industry. The situation has improved over the last few years with establishment of Electric Reliability Organisation in the USA in 2005 and a number of initiatives undertaken by UCTE. However there is still a long way to achieve a proper real-time cooperation between utilities.

3 Preventing blackouts: Wide Area Measurement Systems (WAMS)

Utilities rely on SCADA systems for operational monitoring of their systems – see Appendix – but SCADA systems have some serious shortcomings. Firstly SCADA relies on the state estimator to obtain an estimate of the exact system topology, power flows and voltages. However all known state estimation algorithms have shortcomings especially with regard to bad data identification and robustness

[7]. Bad measurements, especially incorrect switch statues, may result in large errors in the estimation results. The periods of measurements in a SCADA scan are not synchronous causing significant time skew errors. All those errors may seriously affect power system security evaluation by SO.

The wave of power system blackouts in 2003 has provided an impetus to development of monitoring systems based on GPS-synchronised measurement technology referred to as Wide Area Measurement Systems – see Appendix B for technological details. Time-synchronised Phasor Measurement Units (PMUs) introduce the possibility of directly measuring the system state (i.e. voltage magnitudes and their angles) rather than estimating it based on system models and telemetry data. As measurements are tracked 20 to 60 times per second, PMUs can track system dynamics in real time. WAMS systems have a wide area of applications in monitoring and control [8] but here we will concentrate on the applications regarding prevention of blackouts.

Due to their accuracy and wide area coverage, WAMS may enable early warning systems to detect conditions that lead to catastrophic events, help, with restoration and improve the quality of data for event analysis. It is worth noting here that it took several months to gather information from different measurement stations following the 2003 USA/Canada blackout and perform analyses to recreate the course of events [1]. On the other hand synchronised frequency traces from different parts of Europe were available almost immediately following the UCTE disturbance in 2006 due to availability of PMUs [9].

WAMS may prevent blackouts due to their ability to provide system monitoring and tracking of power system dynamics in real time. Onset of unstable oscillations usually precedes a blackout and this can be detected quickly [10]. WAMS-based wide area protection and control systems offer a chance to see "the big picture", stop power system degradation, restore the system to a normal state and minimise the effect of disturbance [11]. WAMS could also provide a crucial building block for the concept of "smart grids" through their wide-area communication infrastructure and ability to monitor power operation in real time.

Although WAMS systems have been implemented in a number of places in USA, Brazil, China and various places in Europe, their more widespread adoption is still yet to be achieved. Probably the main factor preventing a wider use of WAMS systems is a lack of application algorithms which would provide a significant additional value in everyday power system operation. Also a business case for adoption of WAMS is not entirely clear as the main advantage of using them lies in improved system security which is a "common good" benefiting everyone. All European countries have adopted, or are adopting, a liberalised model of organisation of electricity supply industry in which distribution, supply, generation and transmission sectors are separated (so-called unbundling). In such a business model costs of WAMS, and resulting benefits, cannot always be easily associated with one particular player. This makes it difficult to justify and finance any widespread installations.

4 Conclusions

The widespread blackouts of 2003 have exposed the critical role of ICT systems in maintaining reliable operation of power systems. Fundamental errors in providing back-up and alarm function in the control room were one of the main contributing factors to the 2003 USA/Canada blackout. The lack of proper ICT infrastructure to enable efficient communication and cooperation between System Operators in Italy and Switzerland led to delayed remedial actions and the consequent blackout of Italy in 2003. Improved ICT systems would enable a better real-time cooperation and coordination between utilities in an interconnected power system but the main challenge is political: overcoming resistance of individual utilities to give up partially their interdependence and operate within the paradigm of a distributed, but coordinated, control.

Emergence of GPS-synchronised Wide Area Measurement Systems holds a great promise for improved monitoring and control of modern power systems and therefore avoiding future blackouts. Despite some initial successes with WAMS deployment, their wider adoption is still to be achieved due to a lack of application algorithms which would make WAMS systems more relevant to everyday power system operation. Another obstacle may lay in the unbundled industry organisation which makes it difficult to associate costs and benefits of WAMS with one particular industry player.

5 References

1. US-Canada Power System Outage Task Force "Interim Report: Causes of the August 14th Blackout in the United States and Canada" November 2003.
2. J. W. Bialek: "*Recent Blackouts in US and Continental Europe: Is Liberalisation to Blame*?", The Cambridge –MIT Institute, Working Paper EP34, Cambridge, 2004
3. UCTE: "Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy".
4. H.-J. Haubrich, W. Fritz: "Study on Cross-Border Electricity Transmission Tariffs by order of the European Commission, DG XVII/C1" Aachen, April 1999.
5. P. Bonnard: "Power System Collapse: European Utility Experience" 2003 IEEE Trans. Distr. Conf.
6. J.W. Bialek; *"Why has it happened again? Comparison between the 2006 UCTE blackout and the blackouts of 2003"*, IEEE PowerTech Conference, Lausanne, 2007
7. M. Shahidehpour, W. F. Tinney, Y Fu: "Impact of security on power system operation" Proc. of IEEE, Vol. 93, No. 11, Nov. 2005.
8. D. Novosel, V. Madani, B. Bhargava, K. Vu, J. Cole: "Dawn of the Grid Synchronization" IEEE Power and Energy Magazine, Jan/Feb. 2008
9. UCTE: "Final Report. System Disturbance on 4 November 2006"

10. D. Wilson, J. W. Bialek, K Hay, P. McNabb, J. Trehern: “Identifying Sources of Damping Problems in Power Systems”, 16th Power Systems Computation Conference, Glasgow, 2008.
11. M. Begovic, D. Novosel, D. Karlsson, C. Henville, G. Michel: “Wide area protection and emergency control”, Proc. IEEE, Vol. 93, No. 5, May 2005.

Appendix A: Maintaining reliability of an interconnected power system

A *control area* is a geographic area within a large interconnected network in which a System Operator (SO) balances generation and loads in real time to maintain reliable operation. Control areas are linked with each other through transmission interconnection tie lines. Close cooperation between System Operators is required to support the reliability of their interconnection. There are approximately 140 control areas in North America while in Europe a control area usually means a single country although larger countries may be divided into more control areas (as e.g. Germany). In the US, *reliability coordinators* are responsible for coordination between a number of SOs controlling different control areas.

ICT system are fundamental for maintaining power system reliability. System Operators look at potential problems that could arise on their systems by using contingency analyses, driven from state estimation, that are fed by data collected by the SCADA system.

SCADA: System operators use **S**ystem **C**ontrol **a**nd **D**ata **A**cquisition systems to acquire power system data and control power system equipment. SCADA systems have three types of elements: field remote terminal units (RTUs), communication to and between the RTUs, and one or more Master Stations. Field RTUs, installed at generation plants and substations, are combination data gathering and device control units. They gather and provide information of interest to system operators, such as the status of a breaker (switch), the voltage on a line or the amount of real and reactive power being produced by a generator, and execute control operations such as opening or closing a breaker. Telecommunications facilities, such as telephone lines or microwave radio channels, are provided for the field RTUs so they can communicate with one or more SCADA Master Stations or, less commonly, with each other. Master stations are the pieces of the SCADA system that initiate a cycle of data gathering from the field RTUs over the communications facilities, with time cycles ranging from every few seconds to as long as several minutes. In many power systems, Master Stations are fully integrated into the control room, serving as the direct interface to the Energy Management System (EMS), receiving incoming data from the field RTUs and relaying control operations commands to the field devices for execution.

State Estimation: System Operators must have visibility (condition information) over their own transmission facilities, and recognize the impact on their own systems of events and facilities in neighbouring systems. To accomplish this, system state estimators use real-time data measurements (real and reactive power flows, the state of switches) available on a number, but not all, of transmission lines, substation and other plants. This information is fed to a mathematical model of the power system to estimate voltages and real and reactive power flows throughout the system.

Contingency Analysis: A power system must be able to withstand on its own, i.e. without intervention of the System Operator, impact of probable events (such as tripping of lines or generators) that are referred to as contingencies. The most common criterion used is “N-1” contingency which means that a trip of a single element should not result in overloading of power system elements, loss of stability or voltage violation. This gives SO time to adjust operation should a contingency happen. Contingency analysis is run regularly by SO based on the current system operating conditions as identified by the state estimator.

Appendix B: Wide Area Measurement Systems (WAMS)

Wide area measurement system (WAMS) is a measurement system based on transmission of analogue and/or digital information using telecommunication systems and allowing a synchronisation (time stamping) of the measurements using a common time reference. Measuring devices used by WAMS have their own clocks synchronised with the common time reference using satellite GPS (global positioning system).

WAMS and WAMPAC based on GPS signal

The satellite GPS system is the result of many years of research undertaken by US civil and military institutions aiming to develop a very accurate navigation system. The system has been made available for civil users around the world.

The accuracy of the GPS reference time of about 1 μs is good enough to measure the AC phasors with frequency 50 Hz or 60 Hz. For a 50 Hz system, the period time corresponding to a full rotation corresponding to 360^0 is 20 ms = 20 x 10^3 μs. The time error of 1μs corresponds to the angle error of $360^0/(20 \text{ x } 10^3)$ = 0.018^0 .i.e. 0.005%. Such an error is small enough from the point of view of phasor measurements.

The possibility of measuring directly voltage and current phasors in a power system has created new control possibilities:

- Monitoring of operation of a large power system from the point of view of voltage angles and magnitudes and frequency. This is referred to as *wide area monitoring* (WAM).
- Application of special power system protections based on measuring phasors in large parts of a power system. Such protection is referred to as *wide area protection* (WAP).
- Application of control systems based on measuring phasors in large parts of a power system. Such control is referred to as *wide area control* (WAC).

Wide area measurement system WAMS integrated with wide area monitoring WAM and wide area protection WAP and wide area control WAC is referred to as *wide area measurement, protection, and control* (WAMPAC).

Recent years have seen a dynamic expansion of WAMPAC systems. Measurement techniques and telecommunication techniques have made a fast progress but the main barrier for the expansion of WAMPAC system is a lack of WAP and WAC control algorithms based on the use of phasors. There has been a lot of research devoted to that problem but the state of knowledge cannot be regarded as satisfactory.

Structures of WAMS and WAMPAC

WAMS, and constructed on their basis WAMPAC, may have different structures depending on telecommunication media used. With point-to-point connections, the structure may be multi-layer when PMU data are sent to phasor data concentrators PDC. One concentrator may service 20-30 PMUs. Data from concentrators is then sent to computers executing SCADA/EMS functions or WAP/WAC phasor-based functions. An example of a three-layer structure is shown in Figure 7.

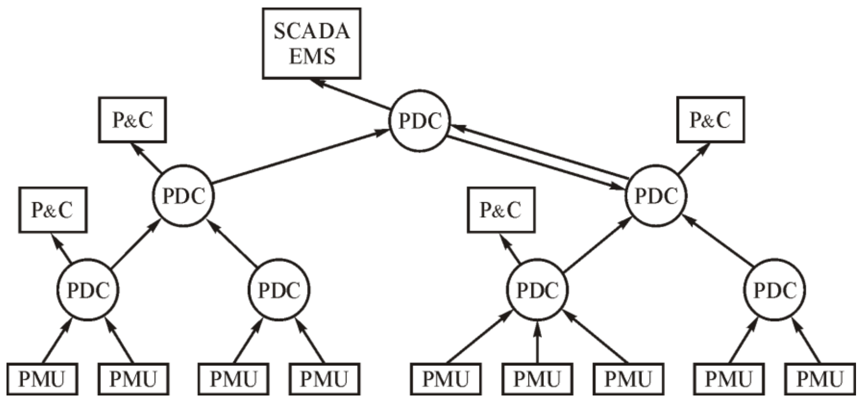


Figure 7 An example of a three-layer structure of WAMPAC. PMU – phasor measurement unit, PDC – phasor data concentrator, P&C –protection and control based on phasors

In each stage of data transmission, delays are incurred. Concentrators in the lowest layer service PMUs. As the delays are the smallest at that stage, the concentrators may supply data not only for monitoring (WAM) but also for protection (WAP) and control (WAC).

The middle-layer concentrators combine data from individual areas of a power system. The data may be used for monitoring and for some WAP or WAC functions.

The top, central, concentrator services the area concentrators. As at that stage the delays are the longest, the central layer may be used mainly for monitoring and for those SCADA/EMS functions that do not require a high speed of data transmission.

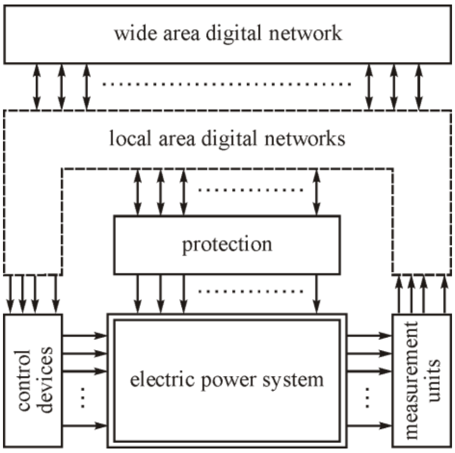


Figure 8 WAMPAC structure based on a flexible communication platform

The main advantage of the layered structure is the lack of direct connections between area concentrators. Such connections may make it difficult, or even impossible, to execute those WAP or WAC functions that require data from a number of areas. The only way to get access to data from another area is via the central concentrator which incurs additional delays. That problem may be solved by adding additional communication between area concentrators. That leads to more complicated communication structures as more links are introduced.

Computer networks consisting of many local digital area networks LAN and one wide area digital network WAN offer best possibilities of further WAMPAC development and application. Such a structure is illustrated in Figure 8. LAN network services all measurement units and protection and control devices in individual substation. The connecting digital wide area network (WAN) creates a flexible communication platform. Individual devices can communicate with each other directly. Such a flexible platform may be used to create special protection and control systems locally, for each area, and centrally. The platform could also be used to provide data for local and central SCADA/EMS systems.