



**SIEMENS**

[www.siemens.com/energy](http://www.siemens.com/energy)

# Global Blackouts – Lessons Learned

**Presented at**  
**POWER-GEN Europe 2005, Milan, Italy**  
**June 28 – 30, 2005**

Updated Version, July 2011

**Authors:**  
Günther Beck, Dusan Povh,  
Dietmar Retzmann, Erwin Teltsch  
Siemens AG, Energy Sector,  
Power Transmission Division, Germany

**Answers for energy.**

# Table of Contents

<b>0. Overview</b>	<b>3</b>
<b>1. Trends in Power Systems</b>	<b>3</b>
<b>2. Large Blackouts 2003 – a Review on the Events and direct Causes</b>	<b>6</b>
2.1 Probability of Blackouts	6
2.2 The Events in North-America	7
2.3 The 2003 Events in Europe	14
2.4 Blackouts in other Countries	18
2.5 Costs and Consequences of System Outages	18
<b>3. Elimination of Bottlenecks in Transmission – Lessons learned</b>	<b>19</b>
3.1 How large can Synchronous System be?	19
3.2 Solutions for System Interconnection	20
3.3 Elimination of Transmission Bottlenecks with HVDC and FACTS	21
<b>4. Use of HVDC and FACTS for System Enhancement</b>	<b>23</b>
<b>5. Prospects of HVDC and FACTS Technologies</b>	<b>27</b>
<b>6. Conclusions</b>	<b>27</b>

## **0. Overview**

The growth and extension of AC systems and consequently the introduction of higher voltage levels have been driven by a fast growth of power demand over decades. Power systems have been extended by applying interconnections to the neighboring systems in order to achieve technical and economical advantages. Regional systems have been extended to national grids and later to interconnected systems with the neighboring countries. Large systems came into existence, covering parts of or even whole continents, to gain the well known advantages, e.g. the possibility to use larger and more economical power plants, reduction in reserve capacity in the systems, utilization of the most efficient energy resources, as well as to achieve an increase in system reliability. Global studies show that power consumption in the world follows the increase in population closely. In the next 20 years power demand in developing and emerging countries is expected to increase by more than 250%, in industrialized countries, however, only by 37% (Global Insight 2008, Siemens E ST MOP 10/2008).

In future, in the course of deregulation and privatization, the loading of existing power systems will strongly increase, leading to bottlenecks and reliability problems. System enhancement will be essential to balance the load flow and to get more power out of the existing grid in total. Large blackouts in America and Europe confirmed clearly that the favorable close electrical coupling of the neighboring systems might also include the risk of uncontrollable cascading effects in large and heavily loaded interconnected systems.

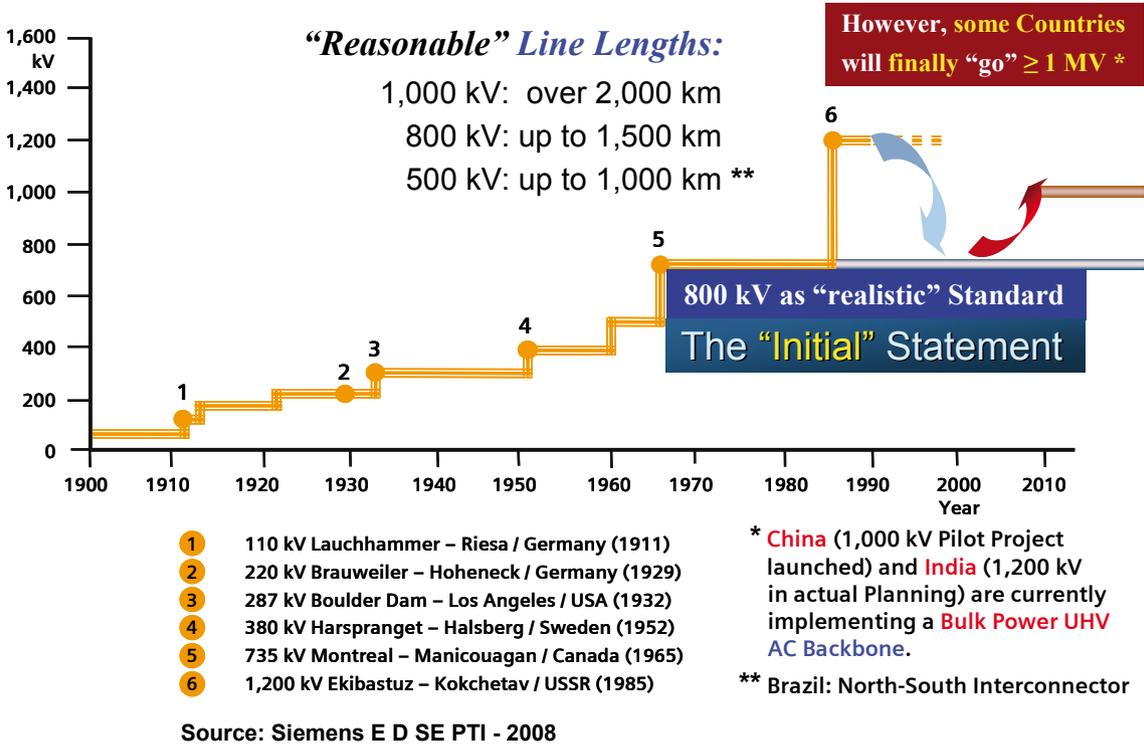
An overview of the sequence of blackout events in US/Canada and Europe is given and countermeasures for blackout prevention - "Lessons learned" - are discussed. Avoidance of loop flows, prevention of voltage collapse, elimination of stability problems in large power systems as well as the implementation of "firewalls" are presented. The benefits of HVDC (High Voltage Direct Current) and FACTS (Flexible AC Transmission Systems) for system enhancement are explained.

## **1. Trends in Power Systems**

The development of electric power supply began more than one hundred years ago. Residential areas and neighboring establishments were supplied first by DC via short lines. At the end of the 19th century, however, AC transmission has been introduced utilizing higher voltages to transmit power from "remote" power stations to the consumers.

Large systems came into existence, covering parts of or even whole continents, to gain the well known advantages, e.g. the possibility to use larger and more economical power plants, reduction in reserve capacity in the systems, utilization of the most efficient energy resources, as well as to achieve an increase in system reliability.

The developments in AC transmission voltages are depicted in Fig. 1.

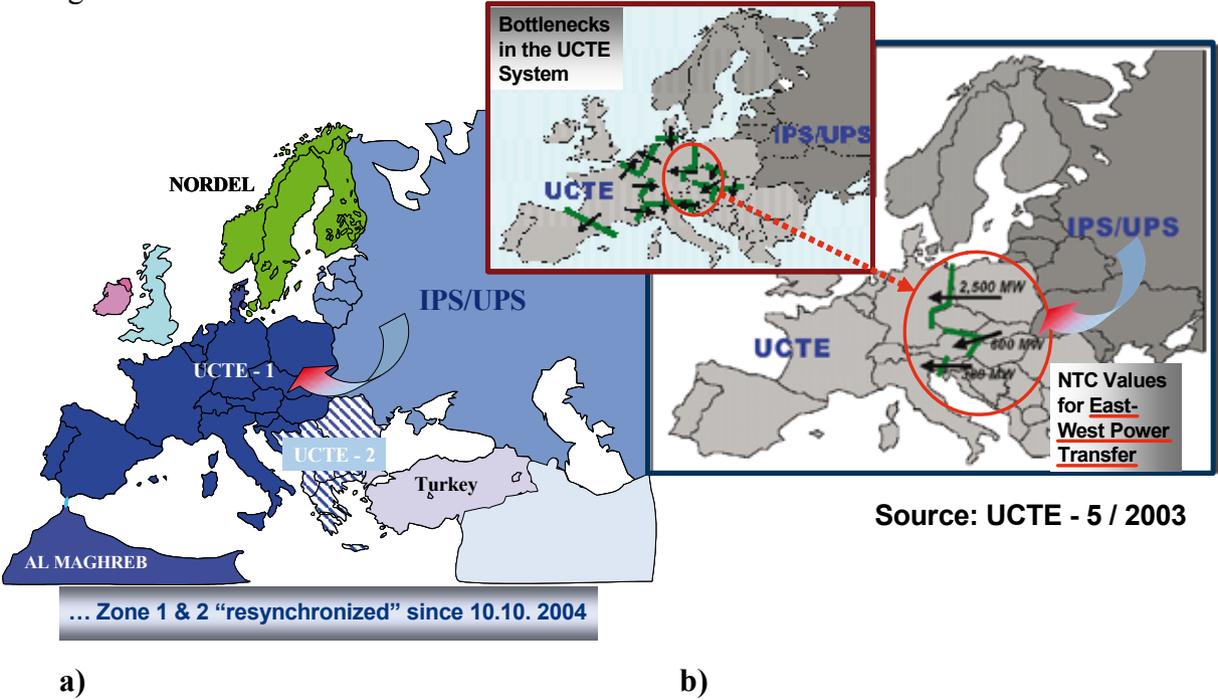


**Fig. 1: Development of AC Transmission**

In Western Europe 400 kV became the highest voltage level, in Far-East countries mostly 550 kV and in America 550 kV and 765 kV. The 1150 kV voltage level was anticipated in the past in some countries and also some test lines have already been built. China and India for example, are currently implementing a Bulk Power UHV AC Backbone at 1,000/1,200 kV with regard to very long transmission distances between generation and load centers. However, it is not expected in the near future that AC voltage levels above 800 kV will be utilized to a greater extent in other regions of the world.

The performance of power systems decrease with the size and complexity of the networks. This is related to problems with load flow, power oscillations and voltage quality. Should power be transmitted through the interconnected system over longer distances, transmission needs to be supported. This is, for example, the case in the Western European UCTE system (Fig. 2a), where the 400 kV voltage level is relatively low for large cross-border and inter-

area power exchange. Bottlenecks are already identified (NTC - Net Transfer Capacity, Fig. 2b), and for an increase in power transfer advanced solutions need to be applied. Such problems are even deepened by the deregulation of the electrical power markets, where contractual power flows no more follow the design criteria of the existing network configuration.



**Fig. 2: European Power Systems (2004)**  
 a) Overview of the Systems  
 b) Bottlenecks in UCTE (now CE)

Additional problems are expected when renewable energies, such as large wind farms, have to be integrated into the system, especially when the connecting AC links are weak and when there is no sufficient reserve capacity in the neighboring system available. Fig. 3 summarizes the prospects of power system developments.

<b>Globalisation/ Liberalisation</b>	<b>Deregulation - Privatization:</b> Opening of the markets, Independent Transmission Companies ITCs, Regional Transmission Organisations RTOs
<b>Bottlenecks in Transmission</b>	Problem of uncontrolled <b>Loop-Flows</b> <b>Overloading &amp; Excess of SCC Levels</b> System <b>Instabilities &amp; Outages</b>
<b>Investments in Power Systems</b>	<b>System Enhancement &amp; Interconnections:</b> <ul style="list-style-type: none"> <li>◆ Higher Voltage Levels</li> <li>◆ New Transmission Technologies</li> <li>◆ Renewable Energies</li> </ul>

**Fig. 3: Trends in High Voltage Transmission Systems**

Increasing part of the installed capacity will, however, be connected to the distribution levels (dispersed generation) in the future, which poses additional challenges to planning and safe operation of the systems, see Fig. 4.

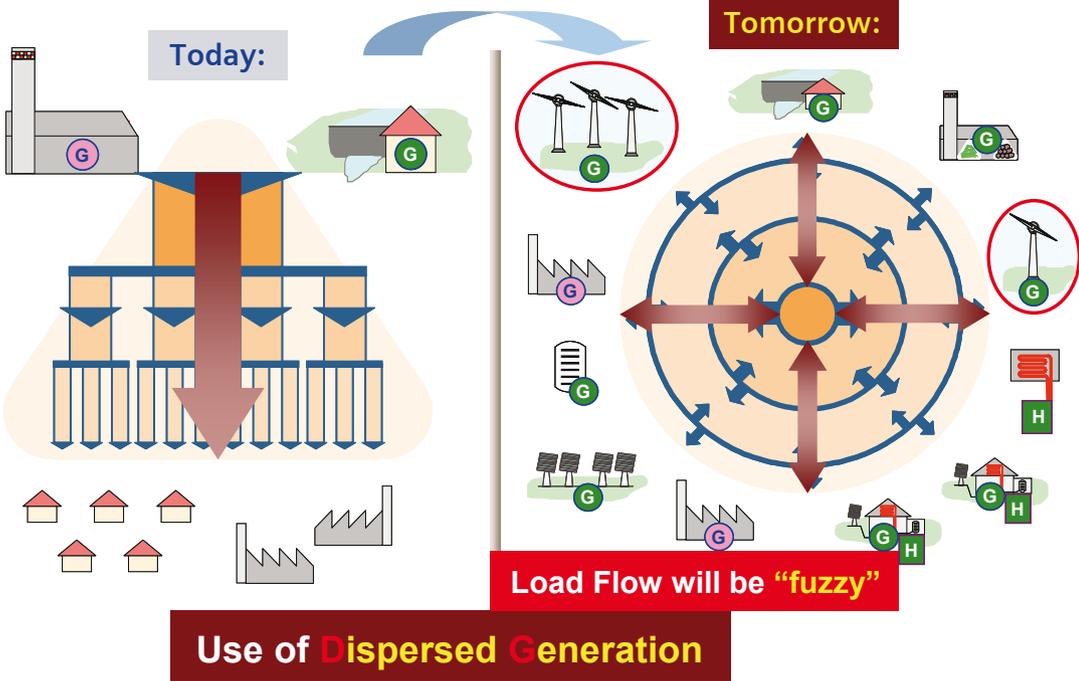


Fig. 4: Prospects of Network Developments

2. Large Blackouts 2003 – a Review on the Events and direct Causes

2.1 Probability of Blackouts

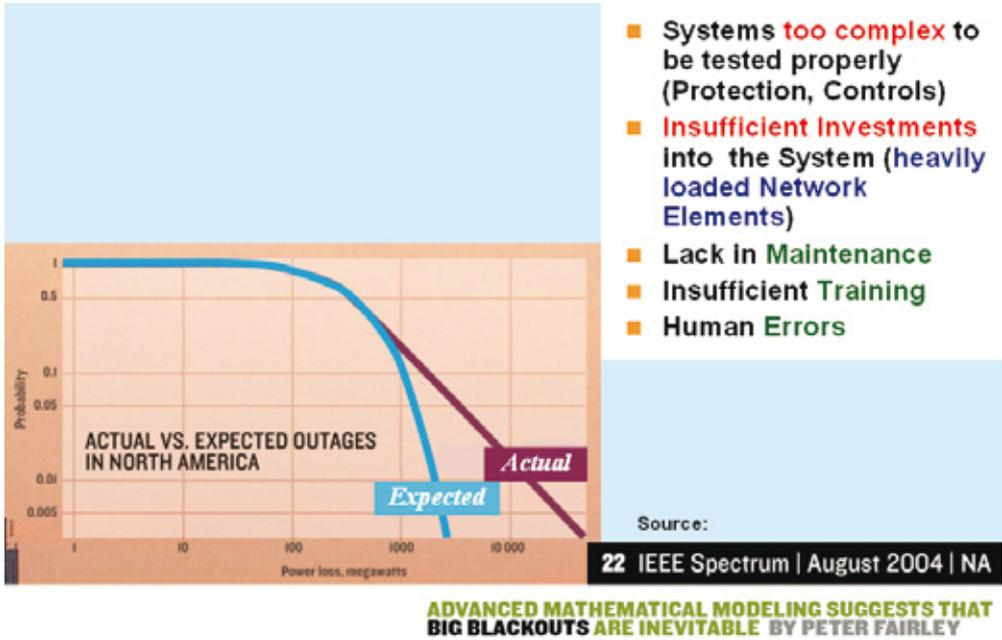
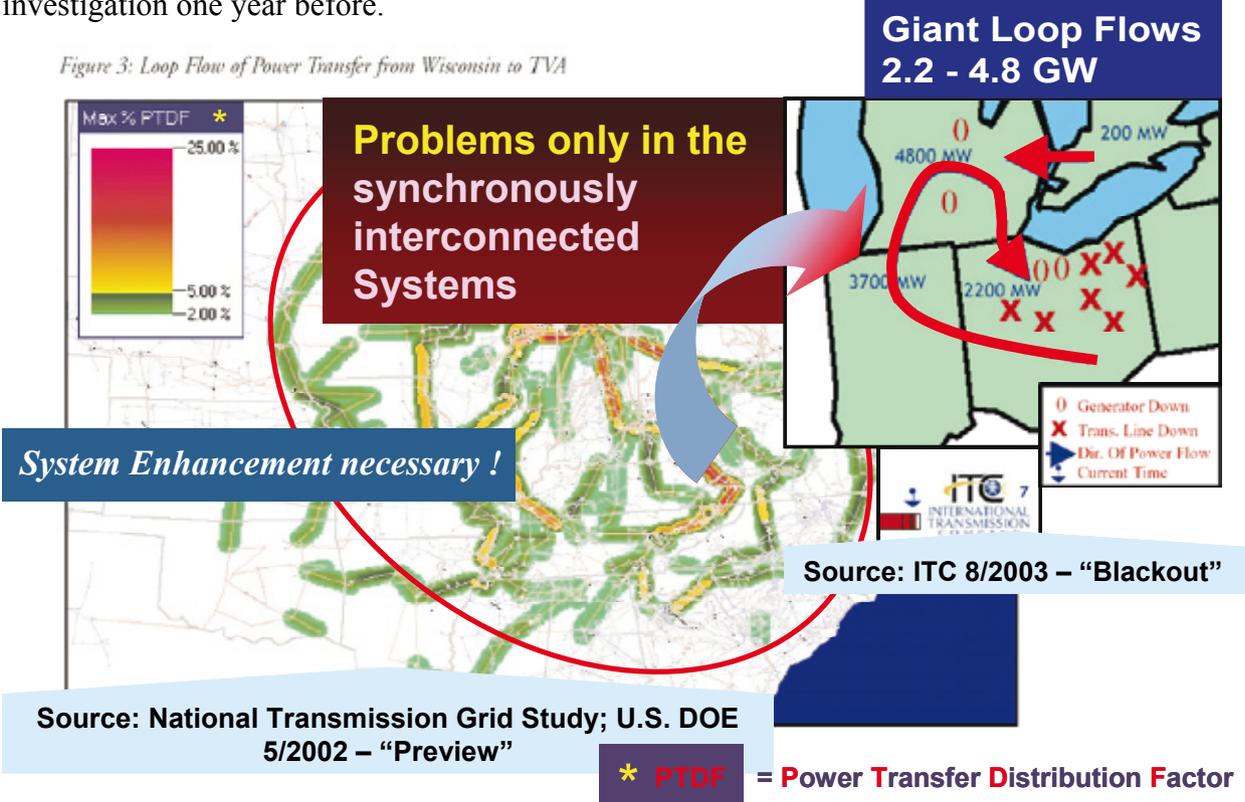


Fig. 5: Reasons for high Probability of Blackouts

Fig. 5 shows that the probability of large Blackouts is much higher than calculated by mathematical modeling, especially when the related amount of power outage is very large. The reasons for this result are indicated in the figure. This means that, when once the cascading sequence is started, it is mostly difficult or even impossible to stop it, unless the direct causes are eliminated by means of investments into the grid and by an enhanced training of the system operators for better handling of emergency situations.

**2.2 The Events in North-America**

The Blackout sequence started on August 14, 2003, around noon. Reactive power and voltage problems have been reported, but not major ones. Fig. 6 shows the results of a study on the related transmission systems, which was published in May, one year earlier. It can be seen, that load flow in the system is not well matching the design criteria, ref. to the “hot lines”, shown in red color. On the upper right-hand side of the figure, one of the later Blackout events with “giant” loop flows is attached, which happened just in the same area under investigation one year before.



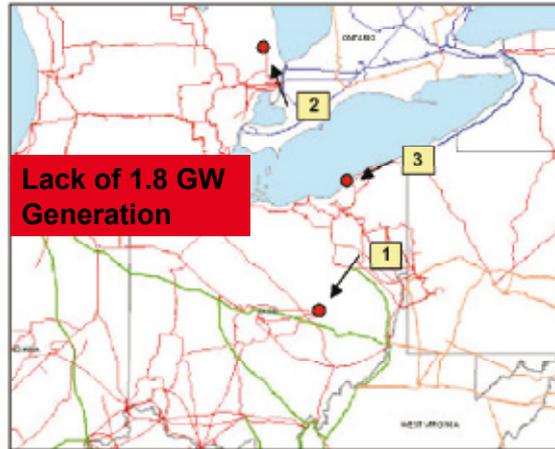
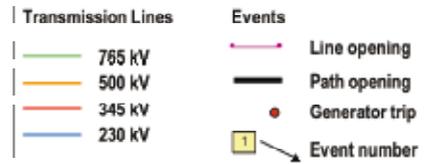
**Fig. 6: Comparison of Study Results 2002 with the real Blackout 2003 Scenario**

In the following, a summary of the events is given and the key-findings are discussed.

Fig. 7 shows that there was in fact plenty of time (1.5 hours) for remedial actions, before the power outage reached a larger amount (1.8 GW).

12:05:44 – 1:31:34 PM – Generator trips

1. 12:05:44 – Conesville Unit 5 (rating 375 MW)
2. 1:14:04 – Greenwood Unit 1 (rating 785 MW)
3. 1:31:34 – Eastlake Unit 5 (rating: 597 MW)



Source: Blackout Summary, U.S./Canada Power Outage Task Force 9-12-2003

**Fig. 7: The US Blackout – Events 1-3**

It was reported in the “Blackout Summary of the Power Outage Task Force”, that a lack of communication and exchange of information among the operators was a major cause of the cascade of events. A server computer outage, as indicated in Fig. 8, was contributing to that. It led to a significant un-awareness of the upcoming risk in the system, although there was sufficient time for actions, such as splitting the system and trip of selected loads.

2:02 PM – Transmission line disconnects in southwestern Ohio

4. Stuart – Atlanta 345 kV

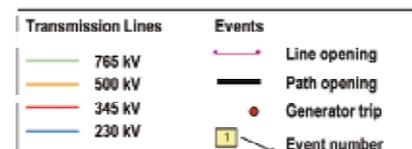
**Reported Reasons:**

Brush-Fire under the Line

(Source: U.S. DOE Timeline 09-12-2003)

Starting around 2:14, FirstEnergy lost a number of **EMS functions** along with **Primary & Backup Server Computer**

(Source: EURELECTRIC 06-2004)



**Fig. 8: Event 4 – plus major Computer Failures at 2:14**

Around 3 to 4 hours after the first event (ref. to Fig. 7) the situation became in fact critical, as indicated in Fig. 9.

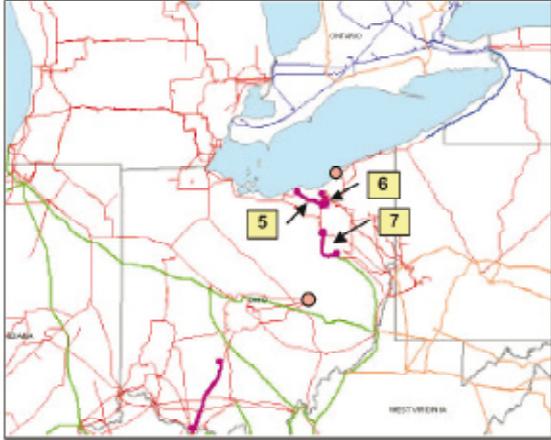
3:05:41 – 3:41:33 PM – Transmission lines disconnect between eastern Ohio and northern Ohio

- 5. 3:05:41 – Harding-Chamberlain 345 kV
- 6. 3:32:03 – Hanna-Juniper 345 kV
- 7. 3:41:33 – Star-South Canton 345 kV

Outage of Line (5) was **not reported** to the Dispatching Center

Line (6) **contacted a tree\*** and tripped

*\*Source: NERC-Technical Analysis 07-2004*



**Fig. 9: Events 5-7 – From now on a critical Situation**

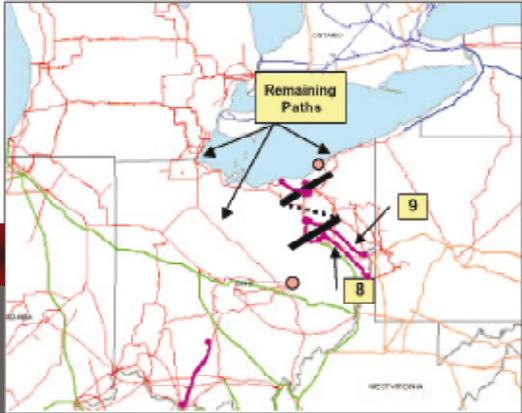
At 4:06, a wrong relay operation (Sammis-Star Line, Fig. 10) initiated the final cascade, and shortly after, at 4:14, the “point of no return” was reached, as shown in Fig. 11. This event initiated huge loop flows across several states and the beginning of voltage collapse. Fig. 12 depicts such a situation with a huge loop of 2.8 GW. This led to further disconnections of lines and large amounts of generation capacity, with significant voltage and frequency fluctuations, up and down. Voltage collapse and the final Blackout were the consequence.

In Fig. 13 a view on the affected area is given (part a) and the satellite photos show the situation before and after the events (part b). The figure indicates that the Québec system in Canada was not affected due to its DC interconnection to US, whereas Ontario (synchronous interconnection) was fully “joining” the cascade.

3:45:33 – 4:08:58 PM – Remaining transmission lines disconnect from eastern into northern Ohio

- 8. 3:45:33 Canton Central-Tidd 345 kV
- 9. 4:06:03 Sammis-Star 345 kV

**Wrong Operation of a Protection Relay**  
**This was the main “Trigger” of the final Blackout Sequence**  
*(Source: EURELECTRIC 06-2004)*

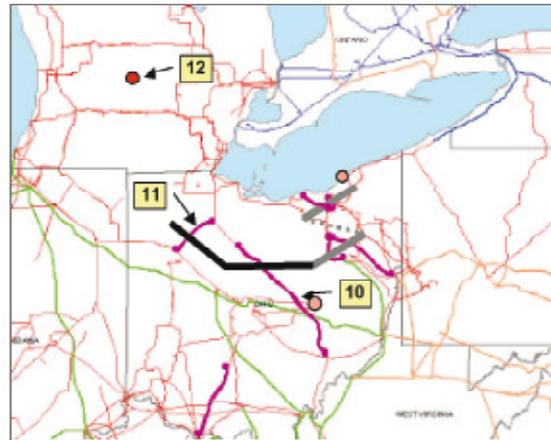


**Fig. 10: Event 8 and the decisive Event 9**

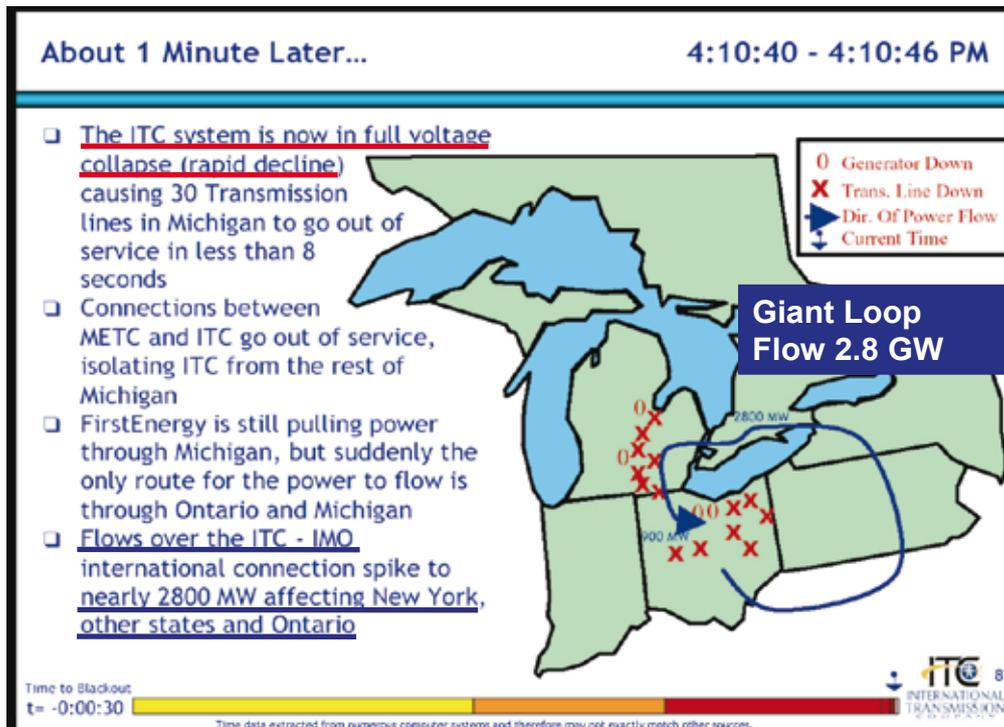
4:08:58 – 4:10:27 PM – Transmission lines into northwestern Ohio disconnect, and generation trips in central Michigan

- 10. 4:08:58 Galion-Ohio Central-Muskingum 345 kV
- 11. 4:09:06 – East Lima-Fostoria Central 345 kV
- 12. 4:09:23-4:10:27 Kinder Morean (rating: 500 MW; loaded to 200 MW)

**4:09 PM - “Point of no Return”**  
*(Source: ITC 08-2003 – “Blackout”)*



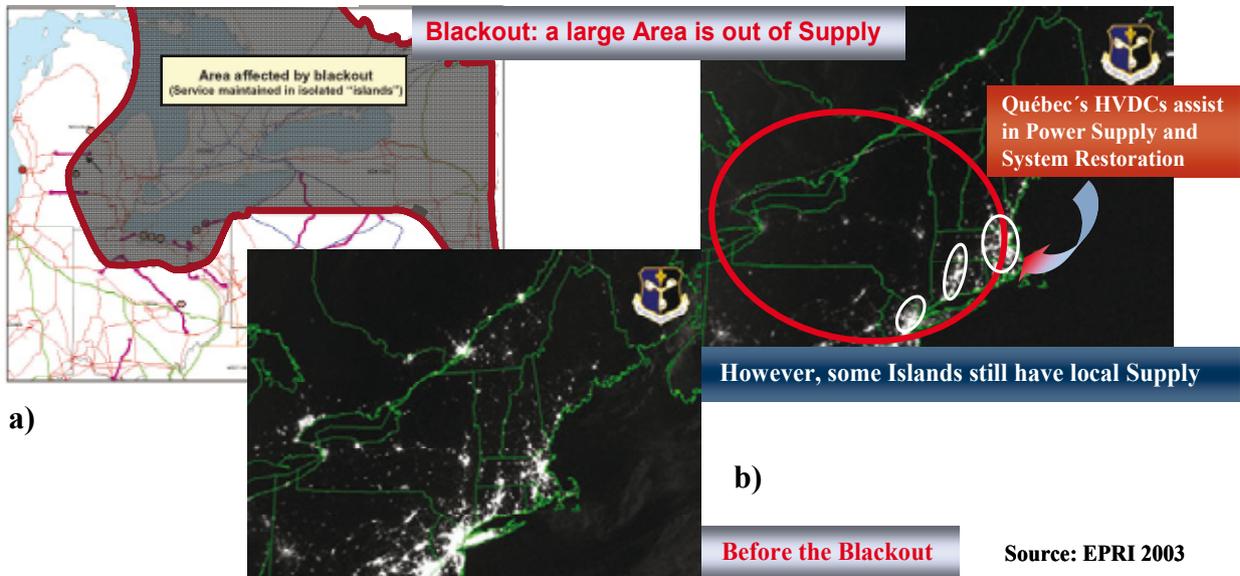
**Fig. 11: Events 10-12 – Begin of Voltage Decline**



**Fig. 12: Event 18 – 30 s to Blackout**

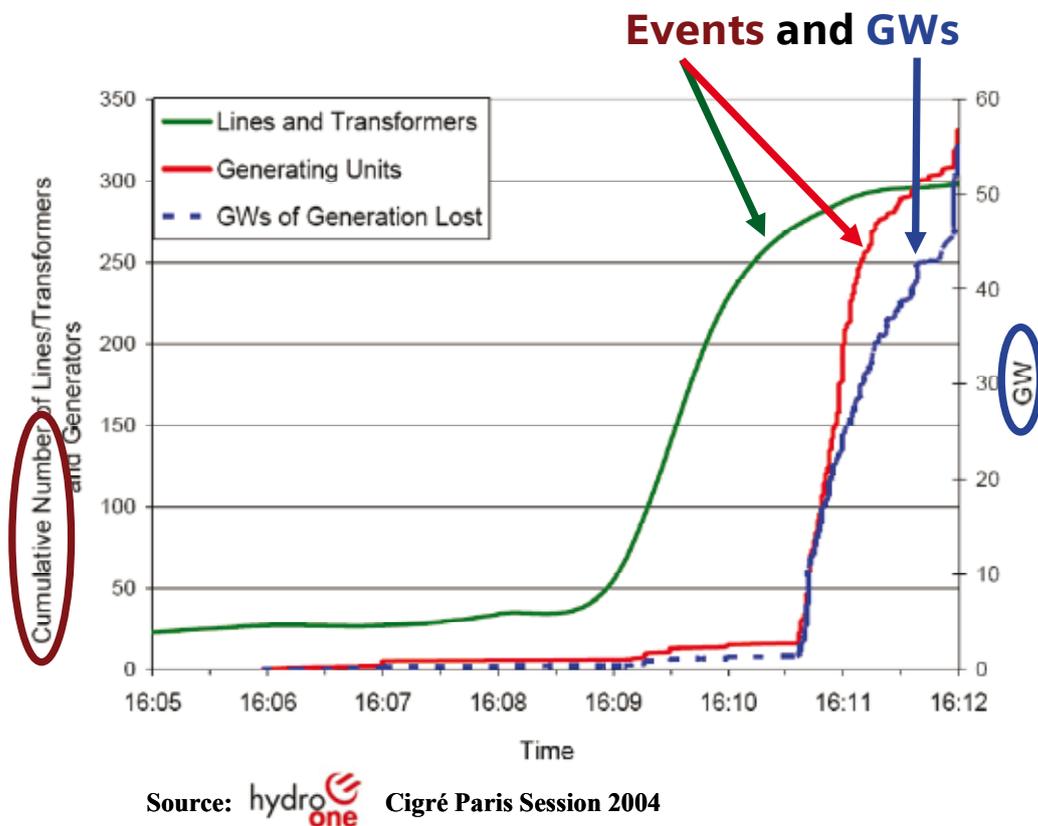
The reasons why Québec “survived” the cascade are very clear:

- Québec’s major Interconnections to the affected Areas are **DC-Links**
- These **DC-Links** are like a **Firewall against Cascading Events**
- They **split the System** at the right Point on the right Time, whenever required
- Therefore, Québec was **“saved”**
- Furthermore, the **DCs assisted** the US-System Restoration by means of **“Power Injection”**

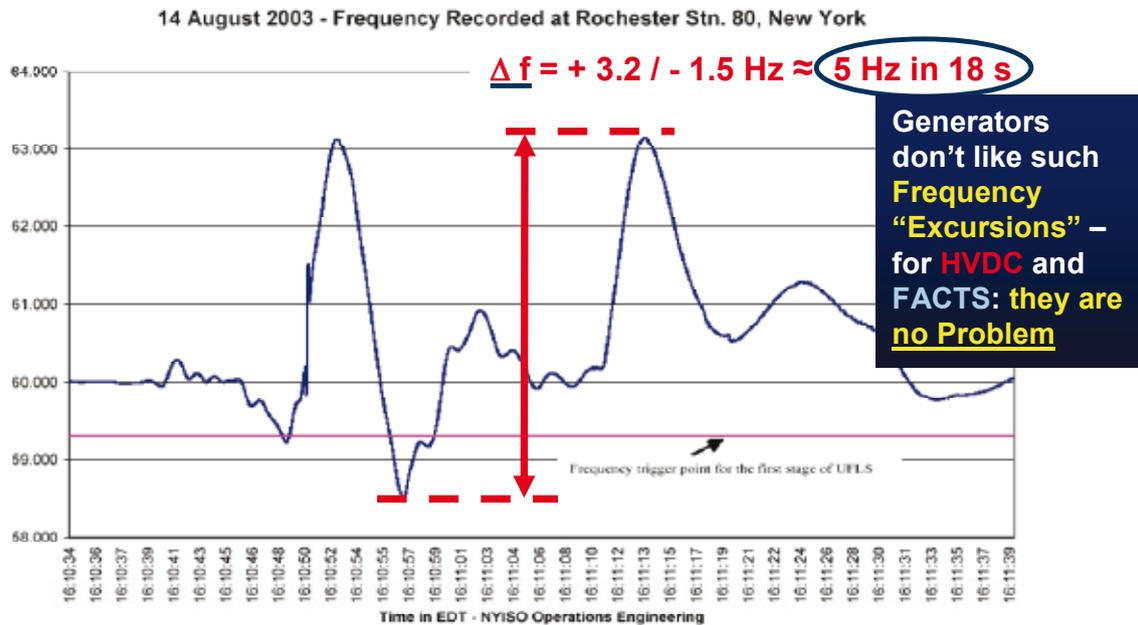


**Fig. 13: The Blackout Area a) and a Satellite View b), before and after the Outage**

Fig. 14 and Fig. 15 depict a view of the systems dynamics during the cascade. It can be seen that the number of disconnections and fluctuations in power and frequency were in fact huge. In total, an amount of about 62 GW customer loads were lost, and about 50 million people in seven states were out of supply. However, 50 GW loads were reconnected within 16 hours.



**Fig. 14: Recordings from HydroOne – from 16:05 to 16:12**



**Fig. 15: Frequency Recordings from New York – 16:10:34 to 16:11:39**

Fig. 15 shows that such large frequency deviations must in fact lead to generator tripping. On the other hand, if more power would be fed in by HVDC from surrounding parts of the grid, such a cascade could have been avoided, because HVDC and in general power electronics (e.g. FACTS for voltage support) can withstand a wide range of frequency variations, e.g. even +/-5 Hz are usually no problem for such controllers.

The primary root causes of the US-Canada events can be summarized as follows:

***A brief Summary of the “primary” Root Causes:***

- **Lack of Investments** into the Grids (high Cost-Pressure for the Asset-Owners due to Deregulation), leading to **Bottlenecks in Transmission**
- **Lack of Communication** among the Operators
- **Need for more Regulatory Works** (Rules, Grid Code etc.) for the Operation of Transmission Systems and Power Plants in **Case of Cascading Events**
- **Weak Points in System Protection, Energy and Demand Side Management - EMS, DSM**

The conclusions of the Outage Task Force final report are depicted in Fig. 16. Fig. 17 shows, how the relay tripping at Sammis-Star Line could have been avoided by means of modern numerical protection relays, and Fig. 18 gives an example for avoiding voltage collapse by use of reactive (FACTS) and active power injection (HVDC).

- ◆ Failure to maintain adequate reactive power support
- ◆ Failure to ensure operation within secure limits
- ◆ Inadequate vegetation management
- ◆ Inadequate operator training
- ◆ Failure to identify emergency conditions and communicate that status to neighboring systems
- ◆ Inadequate regional-scale visibility over the bulk power system.

Source: US-Canada Blackout Final Report April 2004

### 3T: Trees - Tools - Training

- Conductors contacting trees
- Ineffective visualization of power system conditions and lack of situational awareness
- Ineffective communications
- Lack of training in recognizing and responding to emergencies

### System Enhancement & Elimination of Bottlenecks

- Insufficient static and dynamic reactive power supply
- Need to improve relay protection schemes and coordination
- On-Line Monitoring and Real-Time Security Assessment
- Increase of Reserve Capacity

Fig. 16: Conclusions of the US-Canada Blackout Final Report April 2004

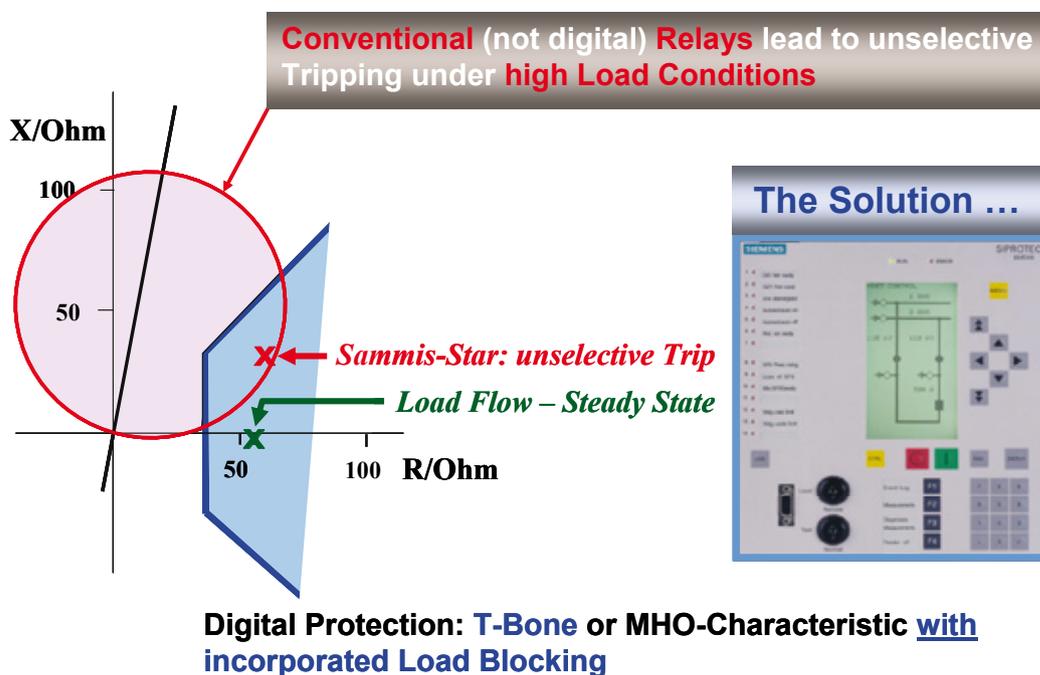
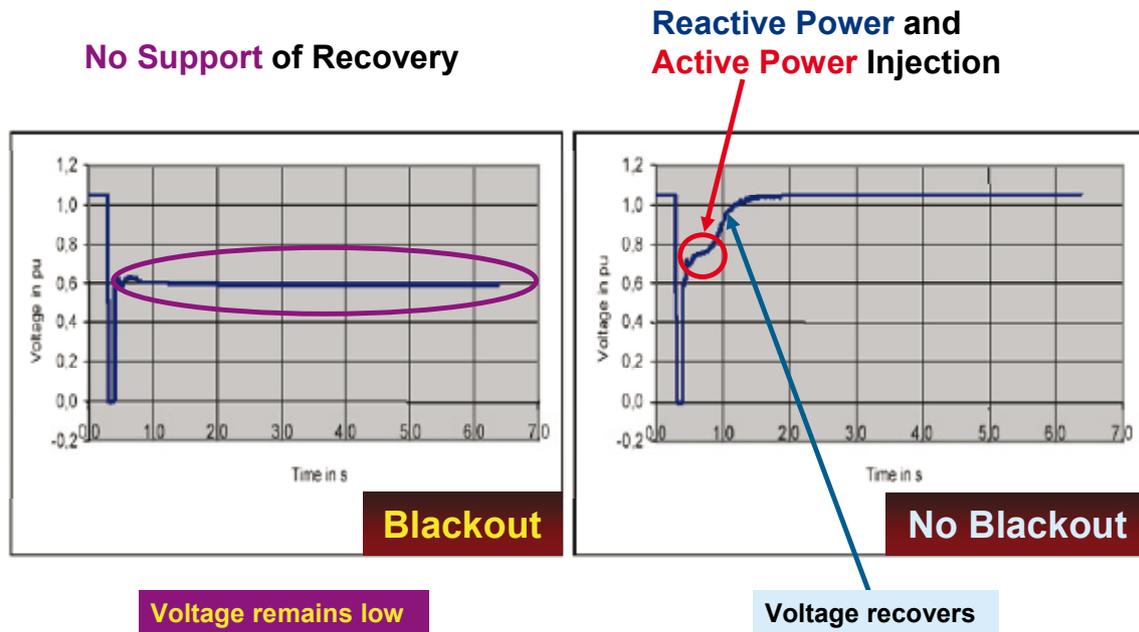


Fig. 17: Avoidance of Outages through Investments in new Technologies – Example of System Protection



**Fig. 18: Avoidance of Voltage Collapse by means of Power Electronics with fast Reactive and Active Power Injection**

### 2.3 The 2003 Events in Europe

These events can be summarized as follows:

#### **Great Britain (August 28):**

- 1 Transformer out of service due to Buchholz Alarm and a wrong Protection Relay Setting. However, only a limited Area (South London) was affected

#### **Denmark-Sweden (September 23):**

- A large Collapse in the Synchronous Area due to Power Station Outages in Combination with a double Busbar Fault (storms and wrong “construction”)

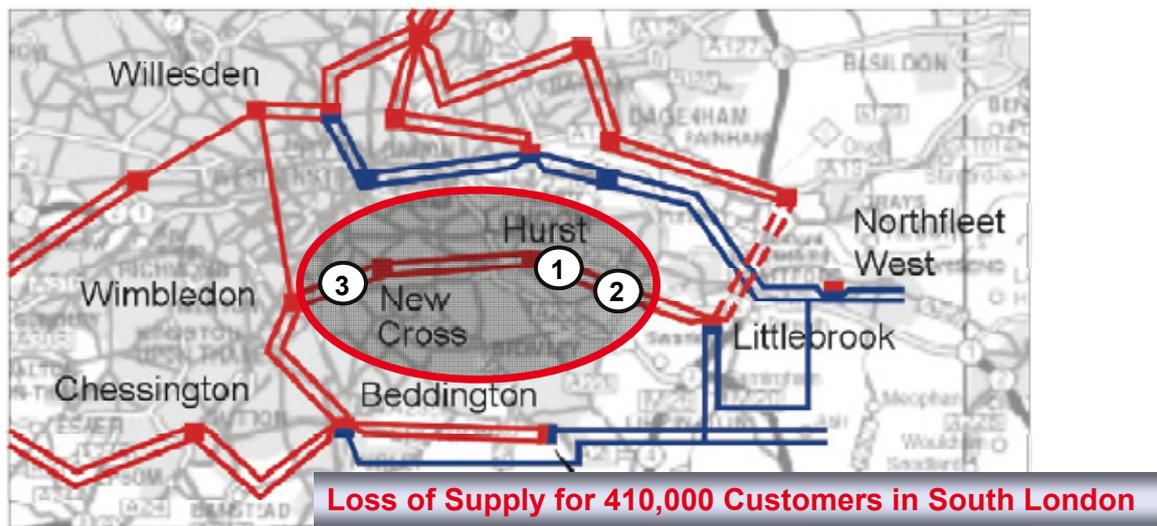
#### **Italy (September 28):**

- Outage of 2 major Transmission Lines; Overload on the remaining Lines – Full Blackout – very similar to the US-Canada Event

In Great Britain, shortly after the US-Canadian events, a transformer was taken out of service due to a wrong Buchholz alarm in a transformer located in the City of London. During this operation, an adjacent cable section was tripped due to a wrong protection relay setting, which led to power outage on a limited area (Fig. 19), see the shaded region.

About one month later a Blackout occurred in the synchronous area of Denmark-Sweden too, due to a power station outage and a double busbar fault (wrong construction plus strong winds), which is really a very seldom event in power systems, and this was followed by an

other power plant outage. A large part of the synchronous area lost its supply for half a day (see Fig. 20), and even the parliament in Copenhagen was blacked-out.



- ① Transformer Buchholz Alarm
  - ② Disconnection of the first 275 kV Cable Section to isolate the Transformer
  - ③ Wrong Protection Setting → Disconnection of the 2<sup>nd</sup> Cable Section
- Source: NGC Investigation Report 10-10-2003

Fig. 19: Causes and Events of the Outage in Great Britain, August 2003

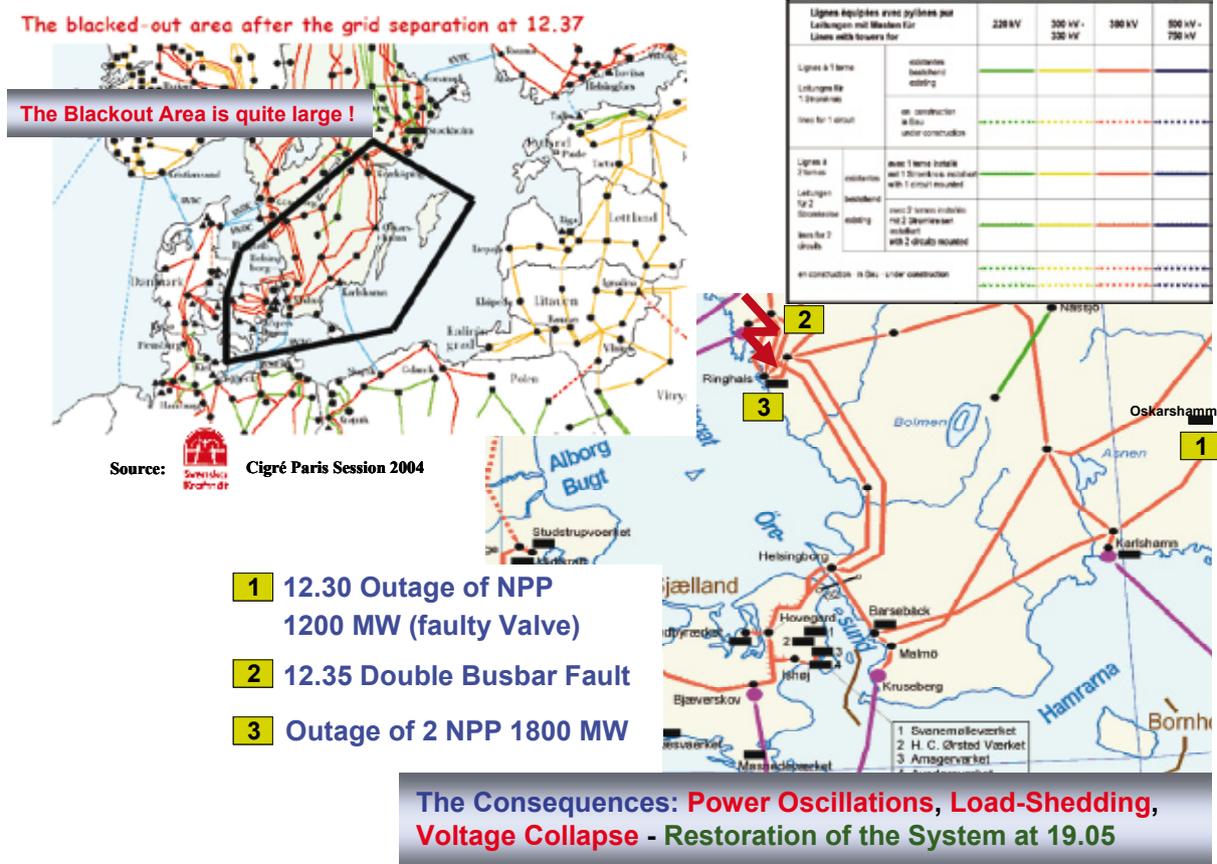
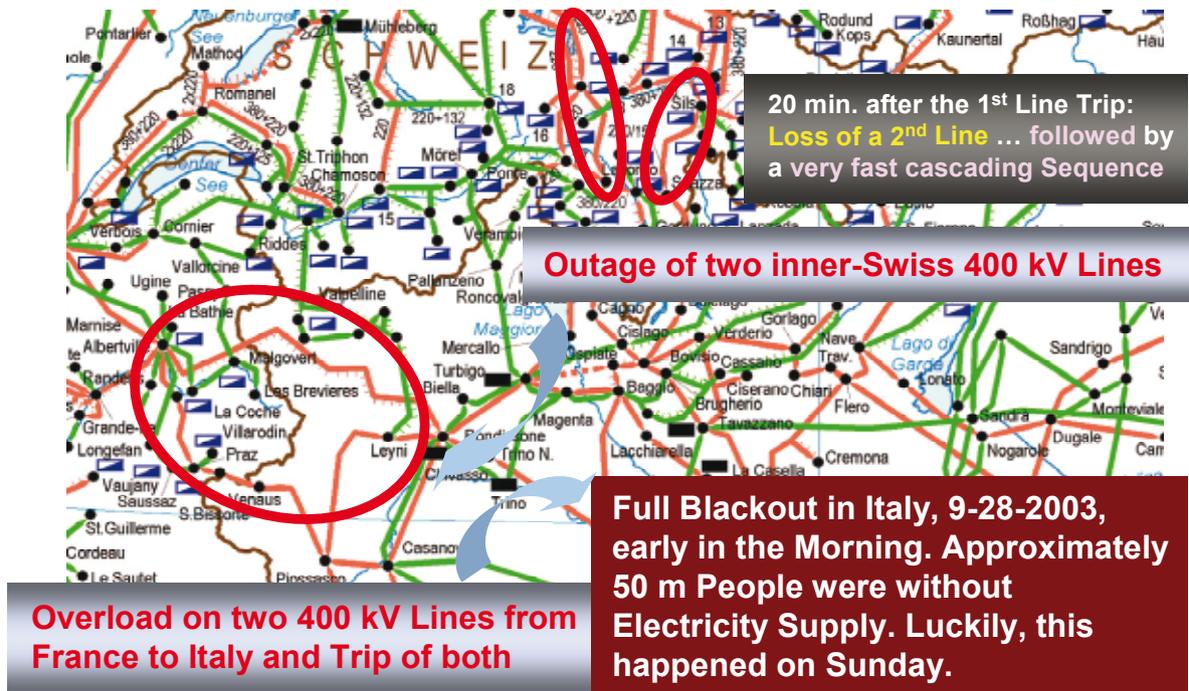


Fig. 20: The Blackout in Denmark-Sweden, Sept. 2003

The “follow-up” was then done by Italy, shortly after Denmark-Sweden, only 5 days later. This event was in fact a huge Blackout, similar to the events in US-Canada, ref. to Fig. 21.



**Fig. 21: Large Blackout in Italy, very similar to the US-Canada event**

The Italian Blackout was initiated by a line trip in Switzerland. Reconnection of the line after the fault was not possible due to a too large phase angle difference (about 60 degrees, leading to blocking of the Synchro-Check device). 20 min later a second line tripped, followed by a fast trip-sequence of all interconnecting lines to Italy due to overload (Fig. 21). During the sequence the frequency in Italy ramped down for 2.5 Hz within 2.5 min, and the whole country blacked-out. Several reasons were reported: wrong actions of the operators in Italy (insufficient load rejection) and a too high power import from the neighboring countries in general. In deed, during the night from Saturday to Sunday, the scheduled power import was 6.4 GW, this is 24 % of the total consumption at that time (27 GW; EURELECTRIC Task Force Final Report 06-2004). In addition, the real power import was still higher (6.7 GW; possibly due to country-wide celebration of what is known as “White Night”).

In Fig. 22 the sequence of events is depicted and Table 1 summarizes the reasons for the Italian Blackout and the countermeasures to be taken. It is one of the key-consequences of deregulation that the power transfer across the systems is nowadays much more wide-spread and fluctuating than initially designed by the system planners. The system elements are going to be loaded up to their limits with risk for losing the n-1 reliability criteria. System enhancement will be essential in the future, in Europe too.



Fig. 22: The Sequence of Events in Italy – UCTE Final Italian Blackout Press Release and Interim Report 10-27-2003

**Lessons Learned:** Power Systems have not been designed for “Wide-Area” Energy Trading with load patterns varying daily

Identified root cause	Impact on events	Origin of root cause	Action
1 <u>Unsuccessful re-closing of the Lukmanier line because of a too high phase angle difference.</u>	Decisive	Large phase angle due to power flows and network topology	Study settings of concerned protection devices. Reassess possible consequences for NTC to Italy. Coordination of emergency procedures.
2 <u>Lacking a sense of urgency regarding the San Bernardino line overload and call for inadequate countermeasures in Italy</u>	Decisive	Human factor	Operator training for emergency procedures. Reassess acceptable overload margins. Study real-time monitoring of transmission line capacities
3 <u>Angle instability and voltage collapse in Italy</u>	Not the cause to the origin of the events but was the cause that successful island operation Italy after its disconnection did not succeed.	General tendency towards grid use close to its limits	Further studies necessary on how to integrate stability issues in UCTE security & reliability policy.
4 <u>Right-of-way maintenance practices</u>	Possible	Operational practices	Perform technical audit if necessary. Improve tree cutting practices

**A Key-Issue in many Power Systems today:**  
**The Grids are “close to their Limits”**

Table 1: Summary of Root Causes for the Italian Blackout and Action Plan UCTE Interim Report 10-27-2003

## 2.4 Blackouts in other Countries

In addition to the outages mentioned above, some other Blackouts have been reported:

*EURELECTRIC Task Force Report 6-2004:*

- **Spain, 12-17-2001: extremely cold weather conditions (high loads)**
  - ✓ **2 hours of emergency conditions** in the Spanish Grid – saved by 500 MW load shedding
- **Denmark, 12-28-2002: loss of supply for 1 million customers**
  - ✓ **Reasons: 2 independent protection relay errors.** Supply fully recovered in 3 hours
- **Austria, 8-27-2003: outage of Krsko Nuclear Power Plant in Slovenia, during tests,**
  - ✓ followed by transmission line trip Hungary Croatia (welded relay contact)
  - ✓ **Automatic disconnection device in Austria triggered, followed by severe cross-boarder load changes.** Full system restoration within 2 hours, **no loss of supply**

*... and some more (Cigré 2004 - 2008, Paris Sessions)*

**Various Reasons: e.g. load-flow problems; breaker explosion (Iran); tornados, ice and snow storms (Europe, China), double-circuit line outage (Germany)**

The reasons for these events are similar to the previously mentioned cases: overloads, mal-operation of protection and equipment as well as human errors. The examples underline the necessity of investments into the grids.

## 2.5 Costs and Consequences of System Outages

The electric power supply is essential for life of a society, like the blood in the body. Without power supply there are devastating consequences for daily life: breakdown of public transportation systems, traffic jams, computer outages as well as still-stand in factories, shopping malls, hospitals etc.

***The Costs depend on the Type of “Loads”:***

- **Short Outages for Industrial Customers: 1,000 €/kWh**  
→ **very high Costs**
- **Very long Outages (more than 24 hours) for residential Consumers: 5 €/kWh**
- **Outages less than 24 hours for residential Consumers: 1 €/kWh**

*Note: “Typical” Long-Distance Transmission Costs are ≈ 1-2 € Cents/kWh !*

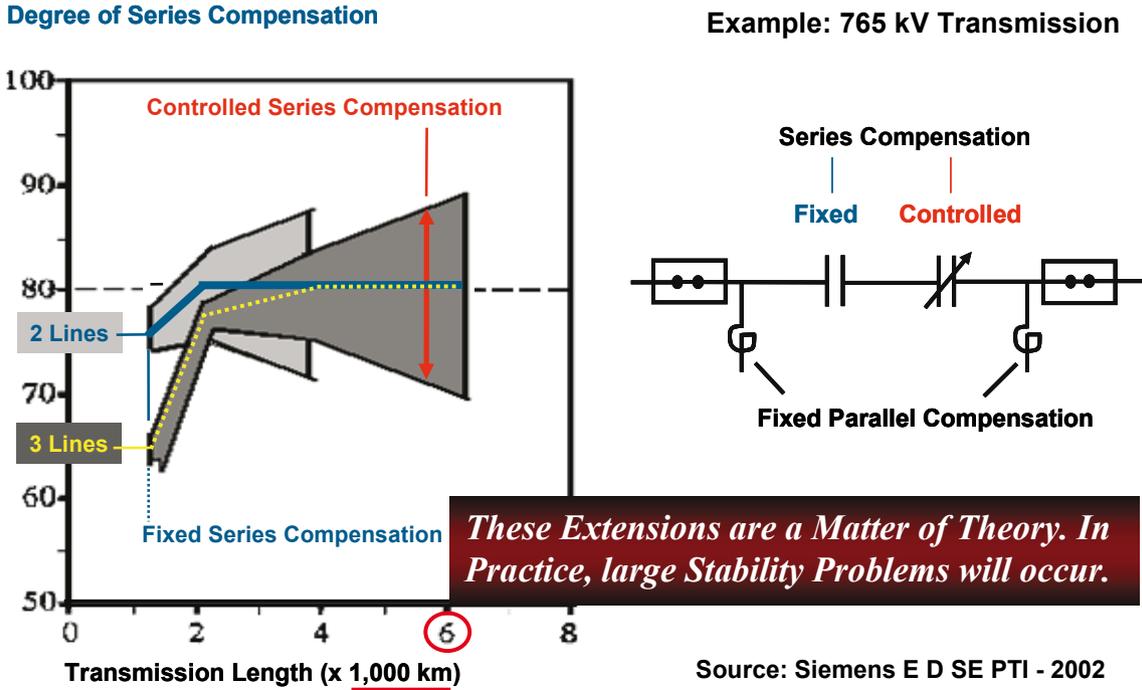
**Table 2: Costs of Blackouts are very high (Source: EURELECTRIC Task Force Final Report 06-2004)**

UPS (Uninterruptible Power Supplies) are available only for very few specific applications for cost reasons. As a result, the consequences of large Blackouts can be dramatic: very high economic losses and very high costs, depending on duration of the outage and kind of loads, ref. to Table 2.

**3. Elimination of Bottlenecks in Transmission – Lessons learned**

**3.1 How large can Synchronous System be?**

In theory, by using controlled and fixed series compensation, a transmission system can be extremely large, e.g. 6,000 km, ref. to Fig. 23. However, at such lengths, there will be major stability constraints, even when using a high transmission voltage and active damping features on the transmission line.



**Fig. 23: Limits of Long Distance AC Transmission**

In Fig. 24 the basic limitations of such very large power systems are depicted, for both AC long distance transmission and for interconnected power systems. The two tables shows the basic constraints and problems of very large systems, and the right hand figure compares efforts (=costs) for system adaptation versus the benefits (e.g. wide-area power trading, sharing of reserve capacity), depending on the system size.

It can be seen, that the best solution is a “medium” sized grid with optimal cost-to-performance ratio.

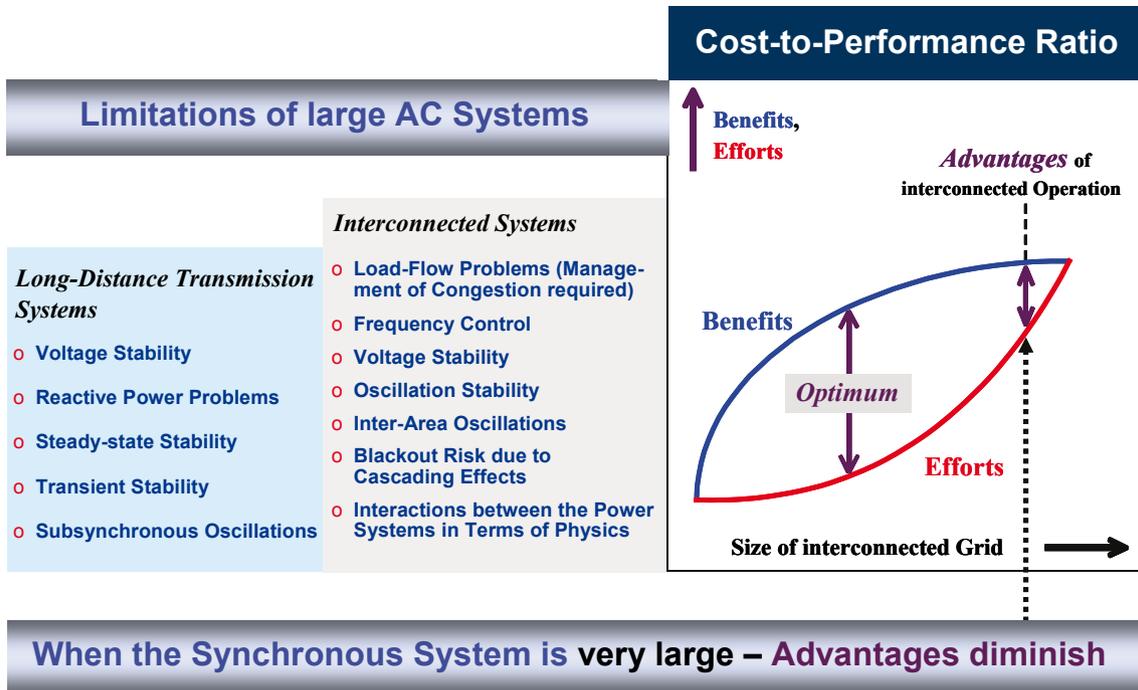


Fig. 24: How large can a synchronous System be ?

### 3.2 Solutions for System Interconnection

There are basically three possibilities to interconnect power systems, ref. to Fig. 25:

- synchronous interconnection (AC Solution)
- asynchronous interconnection using HVDC (DC Solution)
  - HVDC Back-to-Back (without DC-Line)
  - HVDC Long-Distance Transmission with DC Line
- hybrid synchronous interconnection (Hybrid Solution)

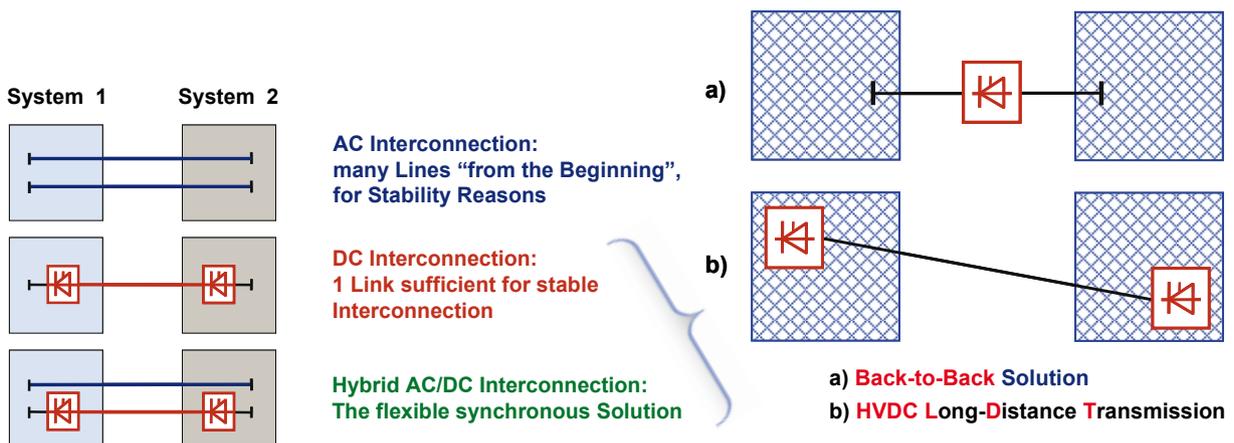
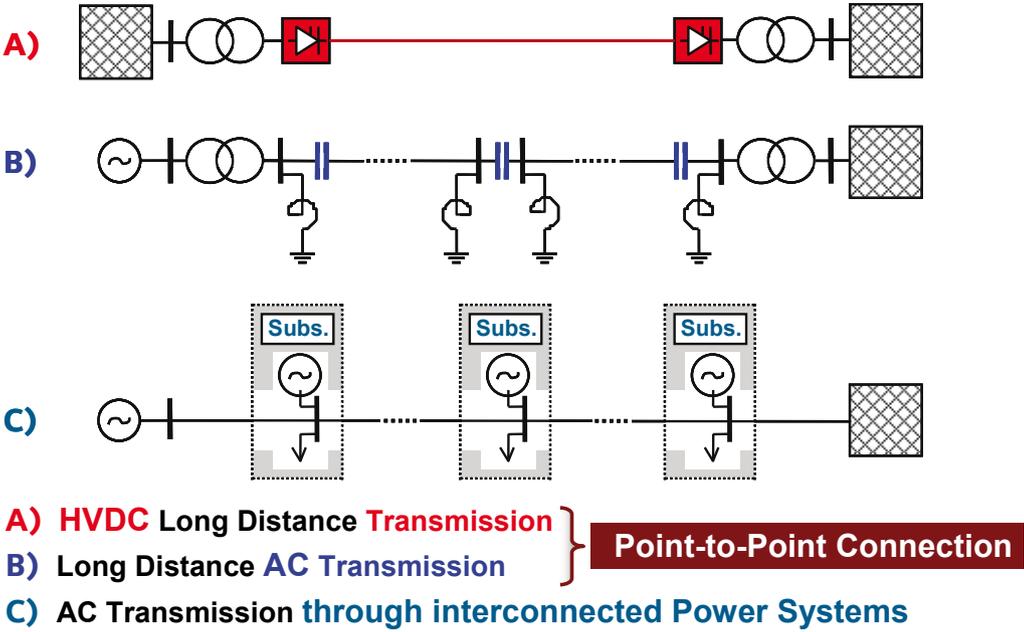


Fig. 25: Alternatives of Power System Interconnections

By using DC for interconnection of power systems, many benefits can be achieved: with DC, an easy staging is possible (one link is already stable), whereas an AC-Interconnection must

be strong from the beginning on for stability reasons (many lines in parallel), even if the demand on power exchange were significantly smaller than the sum of the transmission lines capacity. The Hybrid Solution is the preferred solution in countries with strongly growing networks due to high energy demand: e.g. in Brazil (from Itaipu to Sao Paulo) and in China. The Hybrid Solution offers specific control functions to stabilize parallel AC links: power oscillation damping for inter-area oscillations and voltage control.

Fig. 26 shows long distance point-to-point interconnection with DC and AC in comparison with AC transmission through interconnected synchronous subsystems, which is the today's solution in UCTE. In Fig. 26 B), series compensation is used to increase the transmission capacity of the long AC line.



**Fig. 26: Network Configurations for Long Distance Transmission**

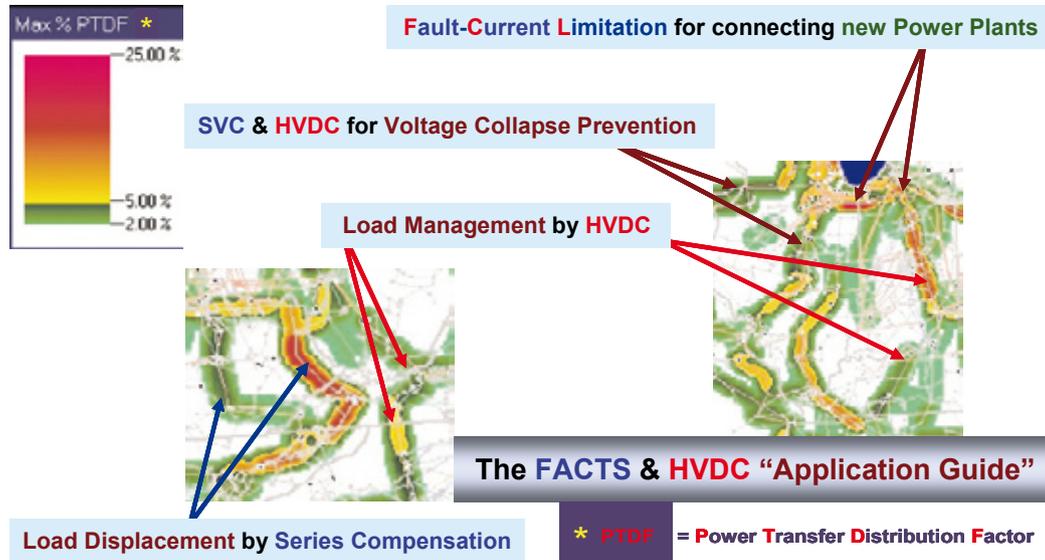
In case of long distance AC transmission by means of controlled series compensation (mostly in combination with some fixed series compensation) an active stability function can be achieved, similar to the DC or Hybrid Solution. Examples are presented in the next section.

**3.3 Elimination of Transmission Bottlenecks with HVDC and FACTS**

Fig. 27 depicts the basic ideas of transmission enhancement by means of HVDC and FACTS (ref. to the system in Fig. 6). Depending on the grid structure, there are four basic cases:

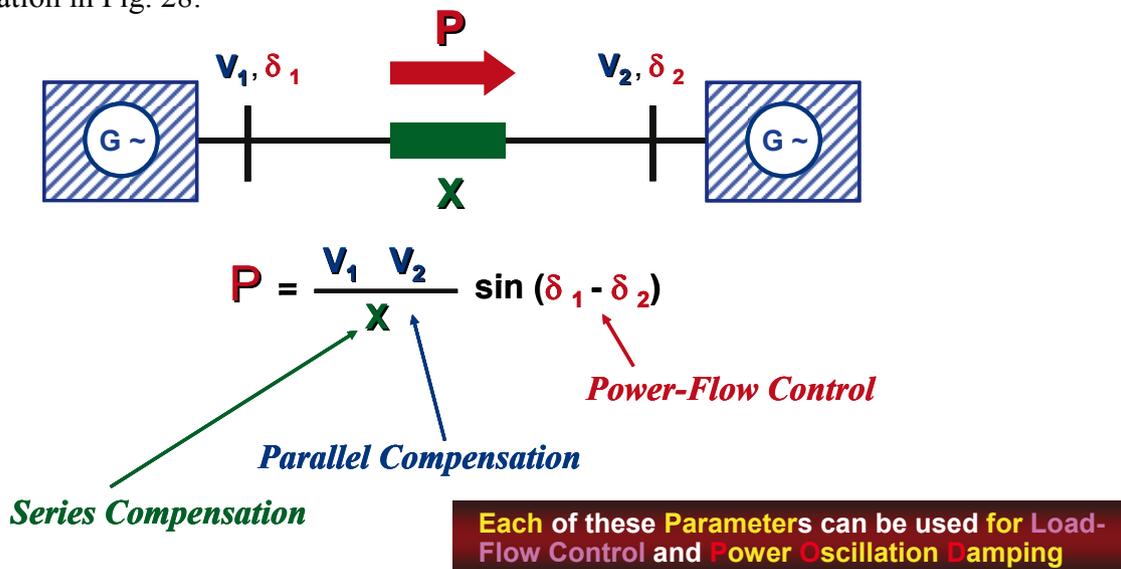
- load displacement by means of impedance variation (series compensation, FACTS)
- load-flow control with HVDC (or FACTS with a combination of series and shunt controllers)

- voltage collapse: reactive/active power injection (with HVDC/FACTS, ref. to Fig. 18)
- excess of allowed short-circuit level due to new power plants: short-circuit current limitation (FACTS/HVDC)



**Fig. 27: Elimination of Bottlenecks in Transmission - Prevention of Overloads and Outages**

The approach of system enhancement, as shown in Fig. 27, is based on the transmission equation in Fig. 28:

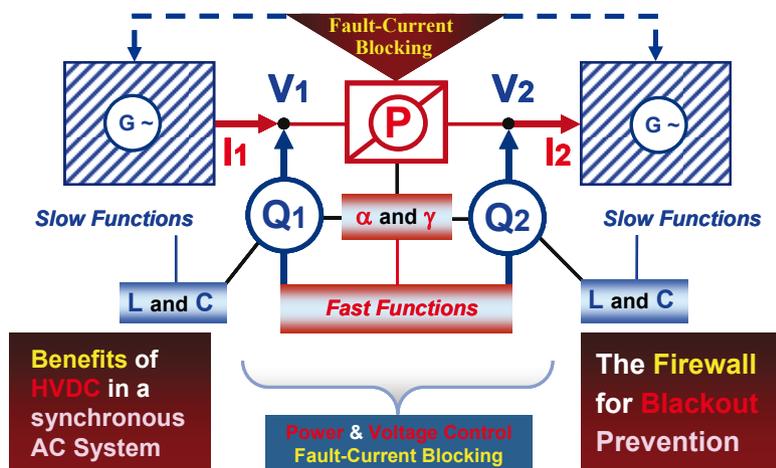
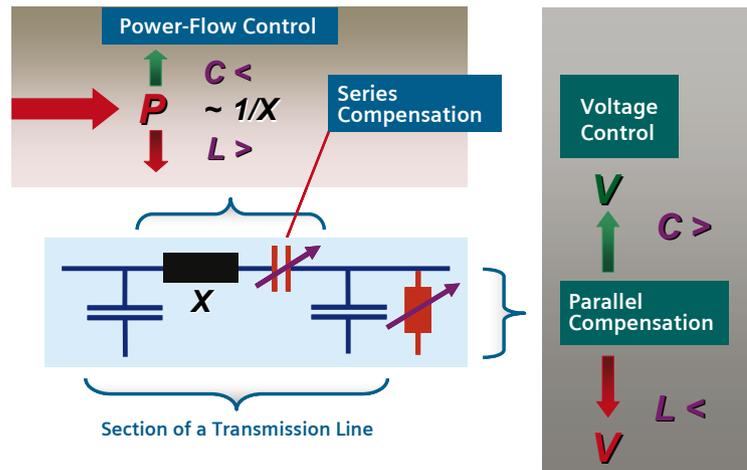


**Fig. 28: Power Transmission - The basic Equation**

Using FACTS for reactive power compensation the impedances and voltages of the system can be influenced: By adding a series capacitor (fixed or controlled) into the line its impedance X can be reduced or modulated (for power oscillation damping, ref. to the equation) and with FACTS parallel compensation the voltage can be stabilized (at constant values, or modulated for damping of oscillations). The transmission angle can be influenced

by a power-flow controller, e.g. HVDC Back-to-Back. These methods are explained in more details in Fig. 29 and 30.

**Fig. 29: FACTS for Reactive Power Compensation**



**Fig. 30: Benefits of HVDC - it makes Power flow**

Fig. 30 shows, that HVDC is well suitable also for short-circuit current limitation (fault current blocking). In addition to this, it acts like an “automatic” Firewall in case of cascading events by fast decoupling the systems during faults and immediate restart of power flow after the fault (AC links need time consuming re-synchronization, which can take many hours in case of large system interconnections). Alongside its main function of power-flow control, the HVDC incorporates also voltage control (by reactive power injection) for both sides of the system. It decouples the transmission equation by forcing the power to flow in a similar way, as the well known phase-shifting transformer, however, much faster and independent from the frequencies and angles of the two coupled systems.

#### 4. Use of HVDC and FACTS for System Enhancement

Fig. 31 gives an example of a project in Virginia Smith, USA with HVDC control, including power oscillation damping features. The left part of Fig. 31 shows the network in the area around the HVDC converter station, which is coupling two asynchronous operated grids. For the given fault, a critical stability situation arises in which one of the generators falls out of

step, see the left section of the recordings. By means of the HVDC control facilities the power flow can be modulated very effectively to stabilize the system, consequently avoiding generator tripping. Simulations and site tests have confirmed these results.

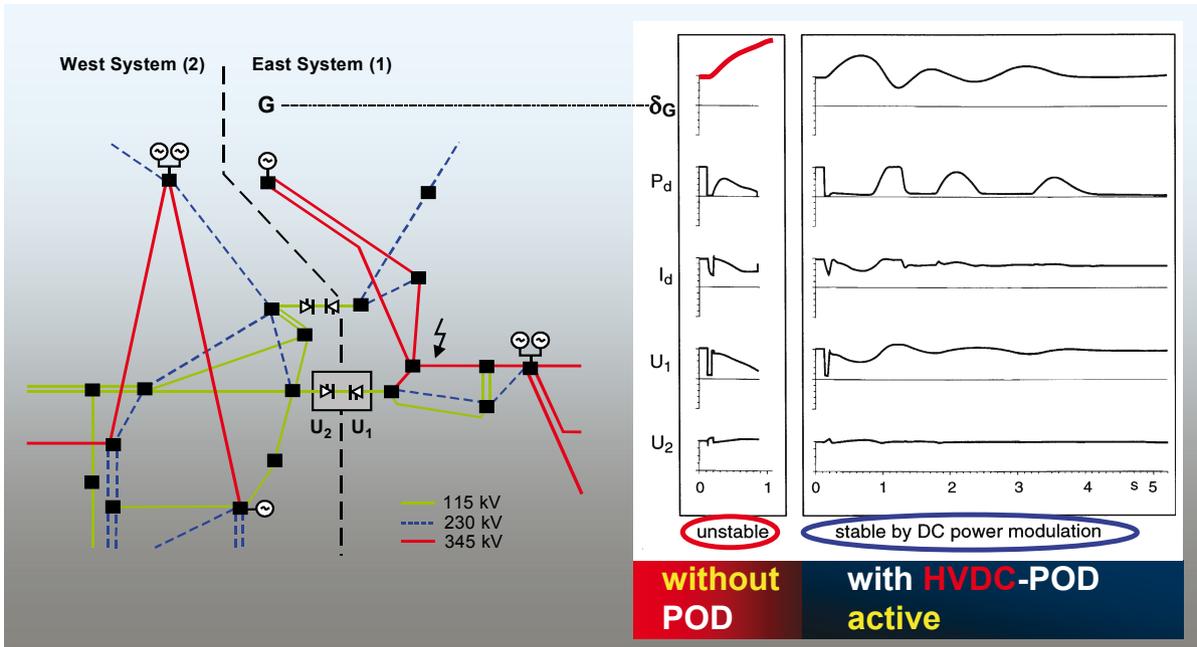


Fig. 31: Interconnection of Separated Grids in USA, Voltage Control and Damping of Power Oscillations - HVDC B2B - Virginia Smith Converter Station

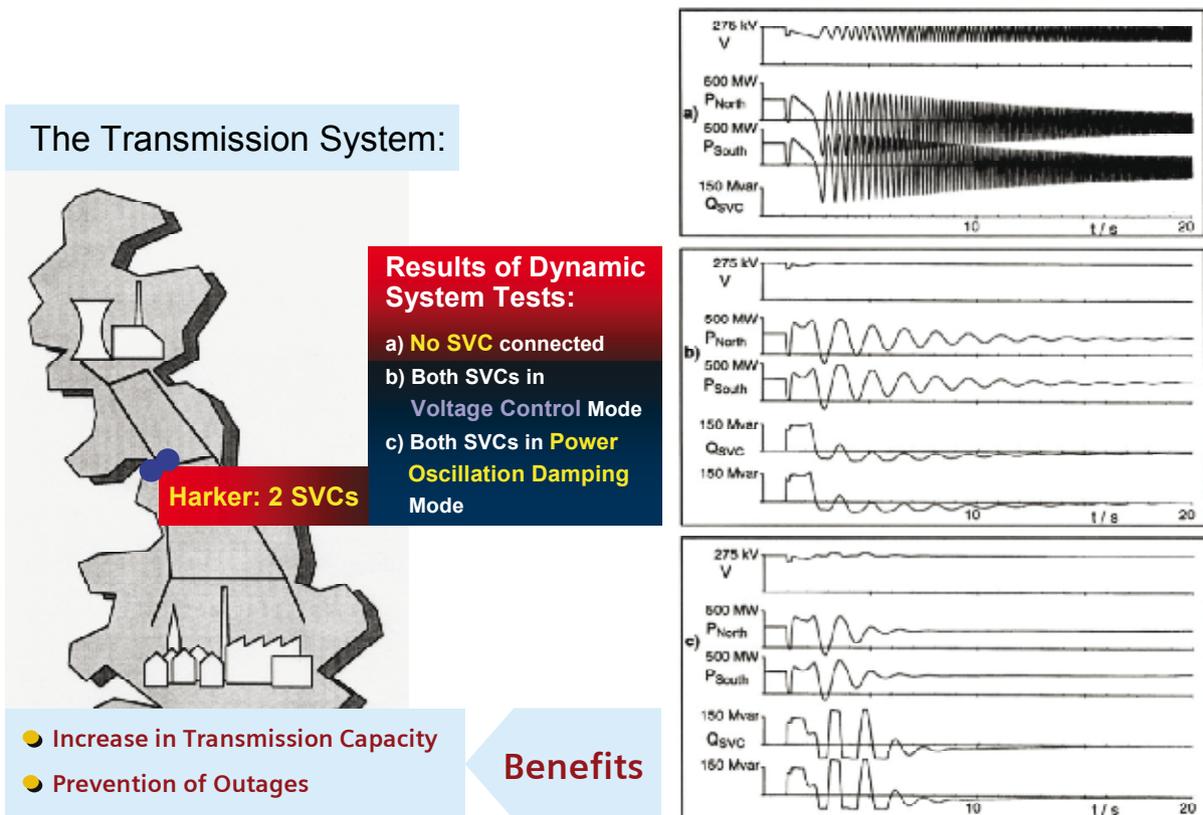
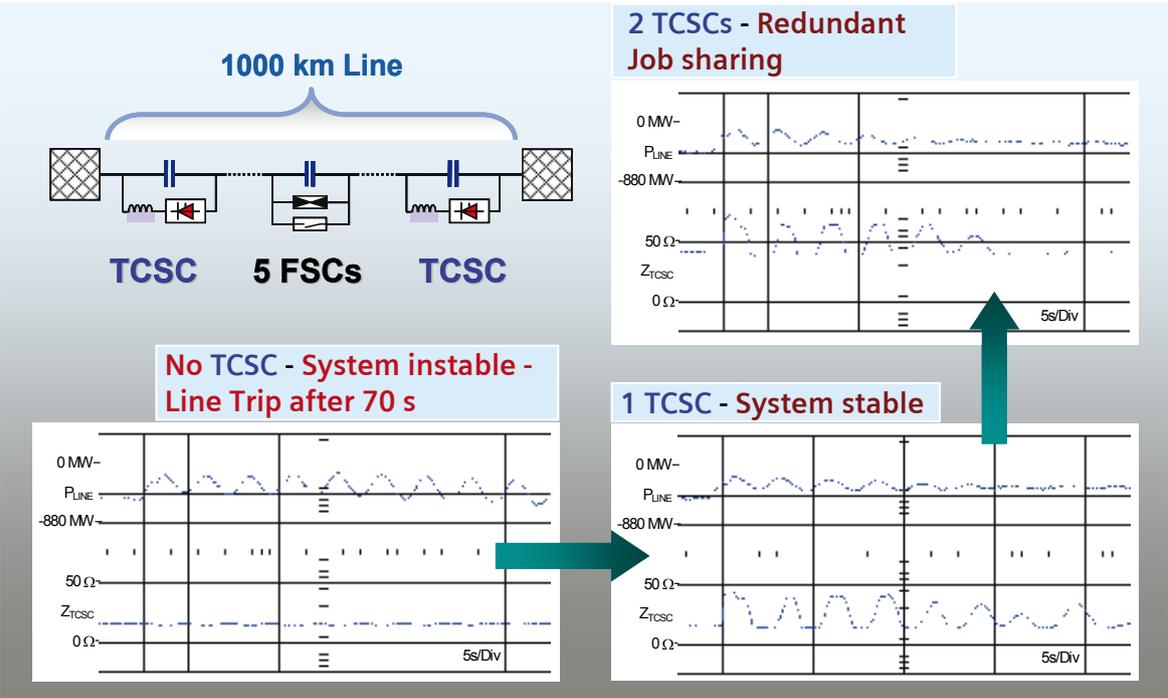


Fig. 32: Europe, UK goes ahead with FACTS - 27 SVCs in the Grid  
Example Harker Substation - 2 parallel SVCs

In Great Britain, in the course of deregulation, new power stations were installed in the north of the country, remote from the southern load centers, and some of the existing power stations in the south were shut down due to environmental constraints and for economic reasons, see Fig. 32, left side. To strengthen the transmission system, a total number of 27 SVC have been installed, because there was no right of way for new lines or higher transmission voltage levels. Fig. 32 c) shows the very effective power oscillation damping (main control function) with two of these SVCs, installed in Harker Substation in a parallel configuration.



**Fig. 33: 500 kV TCSC Furnas/Brazil – Essential for Transmission**

In Fig. 33 it is shown, how problems with large inter-area oscillations have been solved in the Brazilian System. In the Brazilian grid, the situation is critical because of a very long transmission distance between the interconnected systems: a 1,000 km 500 kV AC interconnection between North and South systems has been implemented. In the interconnection two TCSC devices were installed at both ends of the line which damp the inherent oscillations that occur between the systems. Additionally, 5 FSCs were necessary to reduce the transmission angle. The recordings from on-site tests show that the interconnection is unstable without the damping function of TCSC. If only one TCSC is in operation, the interconnection becomes already stable, and with both devices acting the inter-area oscillations are quite well damped, and redundancy is provided. From site experience it has been reported that under increased load conditions, the TCSC damping function is activated

up to several hundred times per day, thus saving power transmission and keeping the return on investments constantly “running”.

Fig. 34 a) shows an example of the Western European system: 500 MW should be transported from Hungary to Slovenia. It can be seen that the power flow is spread widely through the neighboring systems. Only a limited amount of power is flowing directly to the target location. Using a power electronic device for power-flow control, e.g. HVDC Back-to-Back as “GPFC” (Grid Power Flow Controller), the power exchange between the two countries can be improved significantly.

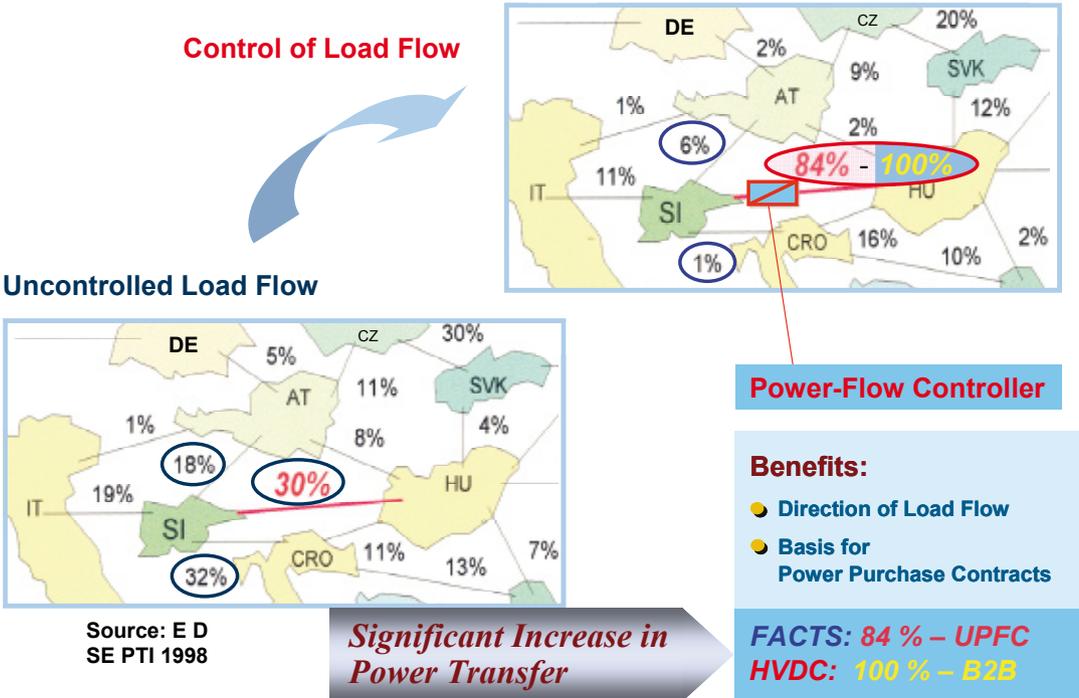


Fig. 34 a): Load-Flow Improvement with Power-Flow Controller

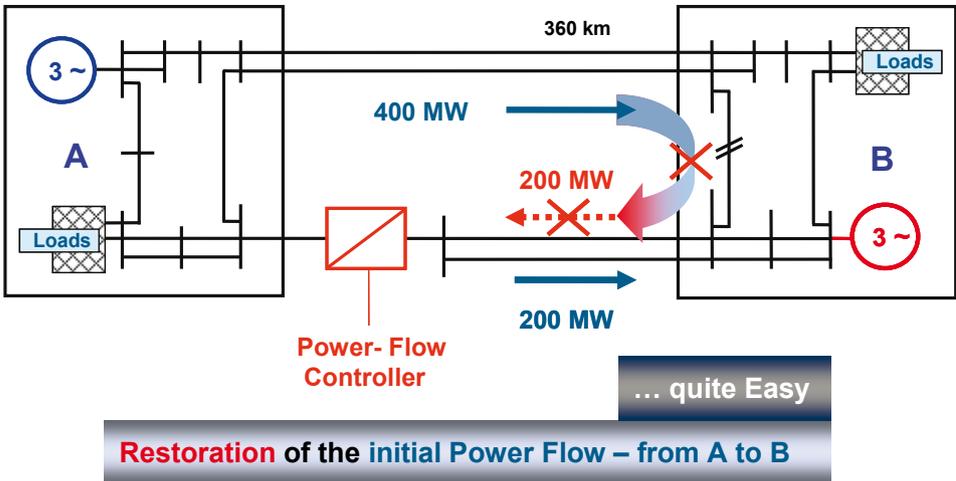


Fig. 34 b): Elimination of Loop Flows by means of Power-Flow Controller

In a similar way, as shown in Fig. 34 b), power loop flows (ref. to Fig. 6 and 12) across the interconnections between two systems, caused by the installation of a new power station (shown in red color) in grid B, can be eliminated by means of a Power Flow Controller.

## **5. Prospects of HVDC and FACTS Technologies**

Since the 60s of the last century, HVDC and FACTS have been developed to a viable technology with high power ratings. From the first small DC and AC "mini networks", at the end of the 19th century, there are now systems available, which can transmit 3 – 7,2 GW over large distances with only one bipolar DC transmission: 1,000 - 3,000 km or more are feasible with overhead lines. With submarine cables, transmission levels of up to 600 – 1,000 MW and distances of nearly 600 km have already been attained, and projects with cable transmission lengths of up to 1,000 km are in the stage of feasibility studies. As a Multiterminal System, HVDC can also be connected at several points with the surrounding three-phase AC network.

FACTS, based on power electronics, have been developed to improve the performance of weak AC Systems and for long distance AC transmission. FACTS can, however, contribute to solve also technical problems in the interconnected power systems. Excellent operating experiences are available worldwide and the technology became mature and reliable. Rating of SVCs can go up to 800 MVar; the world's biggest FACTS project with series compensation (TCSC/FSC) is at Purnea and Gorakhpur in India at a total rating of 1.7 GVar.

Recent developments are HVDC PLUS and SVC PLUS, which use innovative Modular Multilevel Converter technology (MMC) for highly efficient power transmission and reactive power compensation.

## **6. Conclusions**

Deregulation in Power Industry will be generally accepted worldwide. Priorities in future developments will be given to low costs at still adequate technical quality and reliability. Environmental constraints will also play an important role. The loading of existing power systems will further increase, leading to bottlenecks and reliability problems. As a consequence of "lessons learned" from the large Blackouts in 2003, FACTS and HVDC will play an important role for the system developments, leading to hybrid AC/DC systems with better controllability of the power flows and to assist in prevention of cascading disturbances.

Published by and copyright © 2011:  
Siemens AG  
Energy Sector  
Freyeslebenstrasse 1  
91058 Erlangen, Germany

Siemens AG  
Energy Sector  
Power Transmission Division  
Power Transmission Solutions  
Freyeslebenstrasse 1  
91058 Erlangen, Germany  
[www.siemens.com/energy/hvdc](http://www.siemens.com/energy/hvdc)

For more information, please contact  
our Customer Support Center.  
Phone: +49 180/524 70 00  
Fax: +49 180/524 24 71  
(Charges depending on provider)  
E-mail: [support.energy@siemens.com](mailto:support.energy@siemens.com)

Power Transmission Division  
Order No. E50001-G610-A128-X-4A00 | Printed in Germany |  
Dispo 30003 | c4bs No. 7805 |  
TH 150-110812 | BR | 472543 | SD | 08112.0

Printed on elementary chlorine-free bleached paper.

All rights reserved.  
Trademarks mentioned in this document are  
the property of Siemens AG, its affiliates,  
or their respective owners.

Subject to change without prior notice.  
The information in this document contains  
general descriptions of the technical options  
available, which may not apply in all cases.  
The required technical options should therefore  
be specified in the contract.