Dr. Dirk Van Hertem ⊿

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Reliable Power Systems Making Maximum Use of System Flexibility

TECHNICAL SESSION 1

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TEXAS A&M UNIVERSITY at QATAR

About the Speaker

Dirk Van Hertem

- Master of Science in Engineering technology (2001) in electro-mechanics from KHK Geel (now KU Leuven), Belgium
- Master Science in engineering (2003) in electrical power systems from KU Leuven, Belgium
- PhD in electrical power engineering (2009) from KU Leuven, Belgium
- Post-doc Researcher at KU Leuven (2009 & 2011) and Royal institute of technology, KTH (2010), Sweden
- (associate) Professor at KU Leuven from 2012
  - Leading a team of > 20 researchers in the field of HVDC, power system reliability, decision support for grid operators and RES integration
- Active involvement with IEEE

Objectives of this talk

1. What is reliability management in power systems?
2. Limitations in maintaining current approach?
3. How changing reliability management through the use of flexibility (in different forms) using stylized examples
4. Highlighting the need for new approaches and tools
5. Challenge the status quo concerning power system reliability

Outline

Introduction reliability in a changing environment

- Reliability criterion
- Moving from N-1 to a probabilistic, risk based approach

Reliability enhancement through advanced modeling and flexibility

- Reliability process: modeling uncertainty

Addressing reliability through the use of flexibility & control

- Providing reliable energy supply: a conceptual investment example
- Indices to measure reliability
- Use of controllable devices (HVDC, FACTS, PST) for reliability
- Control flexibility by taking decisions closer to real time
- Short term reactive power support
- Managing congestion in low voltage distribution systems

Fair reliability

- Load shedding
- Reliability management making use of VoLL

2000 → 2019: changes in the power sector

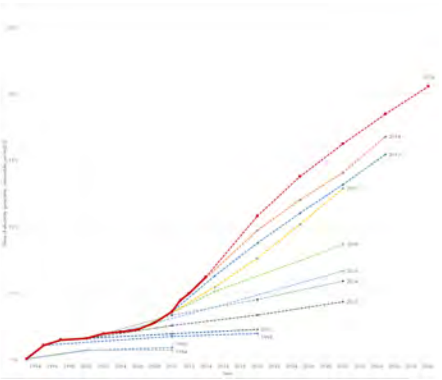
- Liberalization of the power sector
  - From idea to implementation
  - New organizations (TSO, DSO, . . . , aggregator,. . . , regulator)
  - Energy market
  - New products (reserves markets,. . .)
- European level
  - ENTSO-E and ACER, but also Coreso, TSC
  - ⇒ Grid codes and TYNDP
  - Energy is traded on a European level
- Technology developed
  - Re-emergence of HVDC
  - Smart meters and smart grids
  - Electric vehicles, heat pumps,. . .
- RES penetration Europe (eurostat, EU28)
  - Wind: from 212 PJ (2004) to 1090 PJ (2016) (× 5, 14.6 %/a)
  - Solar from 2.6 PJ (2004) to 379 TJ (2016) (× 144, 51.5 %/a)

Fundamental changes in the power system

- The changes have shaken the entire sector:
  - New technology
  - New system behaviors
  - New organizations
  - New functions
  - New responsibilities

2019 → 2035 - 2050

- 100 % electric cars
- No more nuclear?
- No classic generation with inertia
- (near) 100 % renewables (450 GW offshore by 2050)
- Increased dependence on international flows
- Asset ageing
- Storage (central or decentral)
- “Digital” power systems
- Quasi-autonomous power systems
- Flexibility
- Towards hybrid power systems
- . . .



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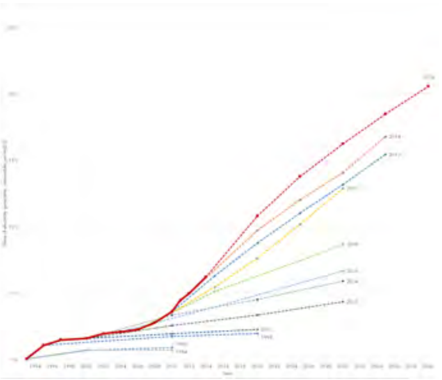
- Towards hybrid power systems
- . . .
- the current system was able to deal with the changes up to now(?)



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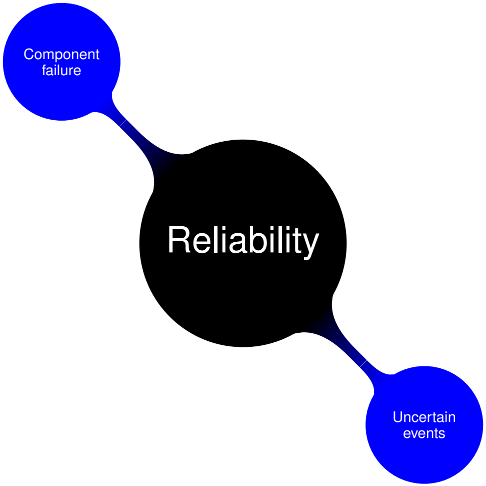
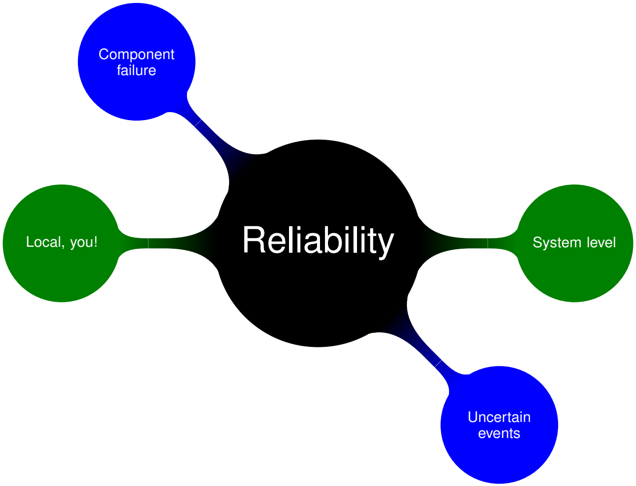
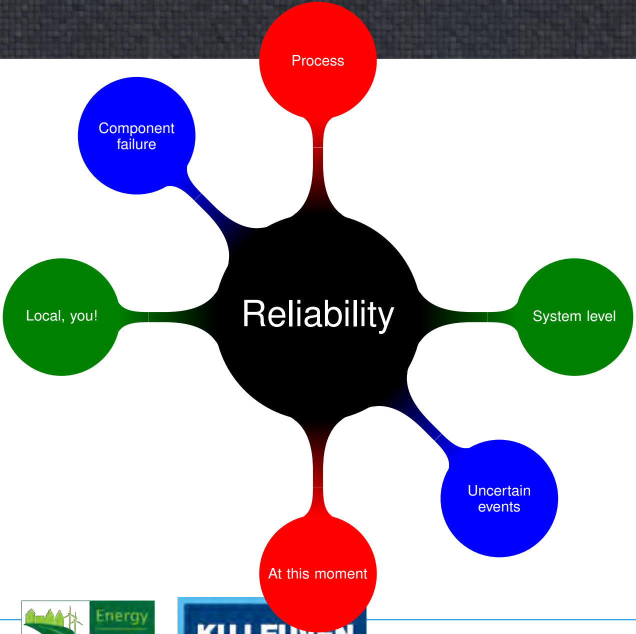
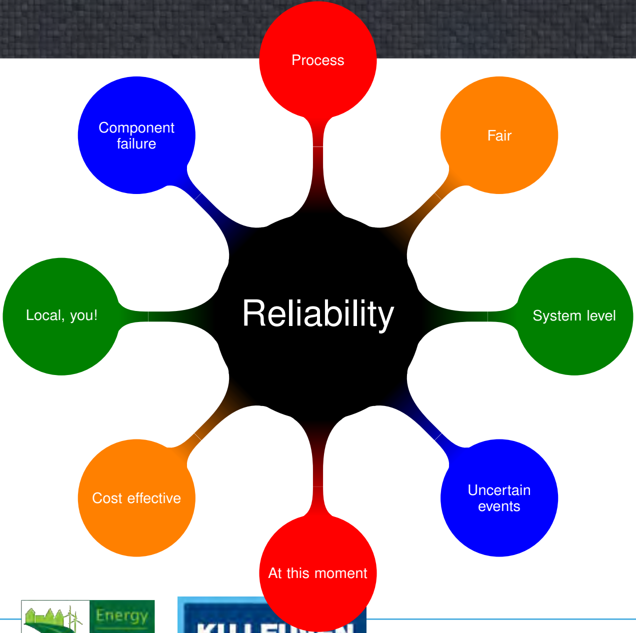
Reliability


Component failure
Reliability
Uncertain events


Reliability
Component failure
Local, you!
System level
Uncertain events


Process
Component failure
Local, you!
Reliability
System level
Uncertain events
At this moment


Reliability
Process
Fair
System level
Uncertain events
At this moment
Cost effective
Local, you!
Component failure

Introduction

- Electric power systems are extremely complex:
  - Large (physical size)
  - Widely dispersed (geographically)
  - International context
  - (Quasi) Non-storable energy source
  - Equipment fails
  - Unpredicted behavior at one point in the system may have a major impact at large distances
  - . . .
- Power systems have been developed over decades. Primary objective: reliable and economic supply of electrical energy
- Spare and redundant capacities in generation and network have been built in to ensure adequate and acceptable continuity of supply during normal operation and contingencies
- Main question: “How much redundancy, and at what cost”
- Balance between over-investing and under-investing
- The system cannot be designed to manage all contingencies

Reliability vs. reliability management

- Reliability is a measure of the ability of a system to deliver power to all points of utilization within acceptable standards and in amounts desired (Cigré, short)
  - typically expressed in indicators, such as outages/year, min outage/year, MWh not supplied,. . .
- Reliability = adequacy (resources) + security (sudden changes)
- Reliability criterion sets the boundary between acceptable and unacceptable
  - Example: N-1
- Reliability management is the set of actions performed by the system operator to stay within the reliability boundaries:
  - Planning: Cable or OHL, HVDC or FACTS, single or double busbar,. . .
  - Operation: Redispatch, load or generation curtailment, HVDC or PST controls, line switching, demand response,. . .
  - Can be preventive or corrective

Adequate level of reliability

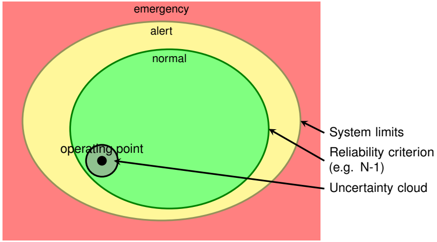
- Today's bulk power system is planned and operated to provide "an adequate level of reliability" (ALR). Overall, this ALR means (NERC definition):
  - The system is controlled to stay within acceptable limits during normal conditions.
  - The system performs acceptably after credible contingencies. The system limits the impact and scope of instability and cascading outages when they occur.
  - The system's facilities are protected from unacceptable damages by operating them within facility ratings.
  - The system's integrity can be restored promptly if it is lost.
  - The system has the ability to supply the aggregate electric power and energy requirements of the electricity consumers at all time, taking into account scheduled and (common) unscheduled outages of system components.

What is an adequate level of reliability?

- what are the “acceptable limits” of the different states of the power system?
- what are “credible contingencies”?
- what is the sense of “unacceptable damages”?
- what is the time line allowed to restore failing systems?

Graphical representation

- At a given point, the power system is operating in a certain state, defined by its state variables
- These variables are bounded (limits)



Operating point
$= f(U,P,Q,\alpha,P_{HVDC},Switches,\ldots)$

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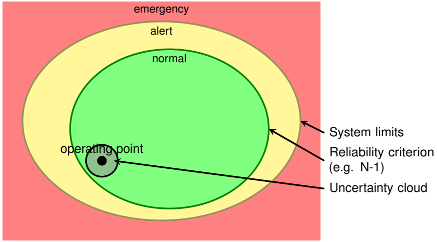

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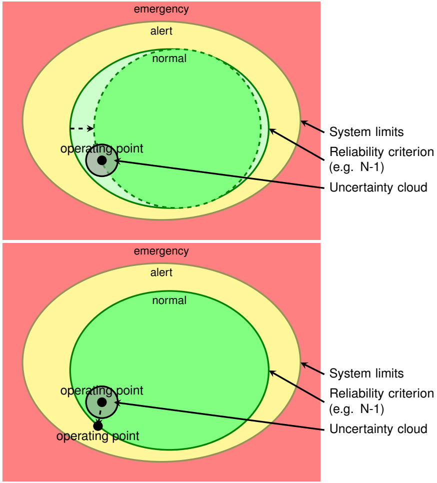
- In case of small incidents, the system can be still within the security constrained bounds, or beyond



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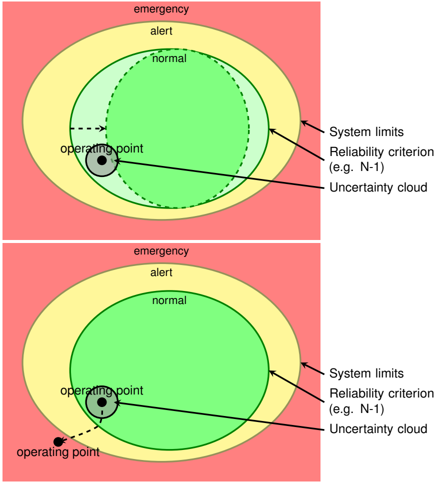

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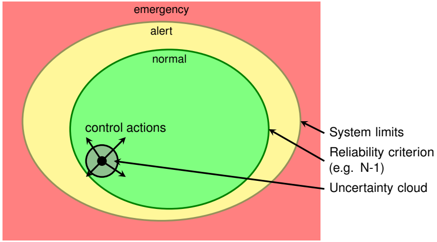
- The incident can be so severe that the operating point is no longer inside the secure zone
- To secure the system, the operating point must be changed and/or the limits must be moved
- Optimal use of the system means (typically) operating close to the limits



N-1 criterion

- The N-1 criterion is used to operate the system under sufficient reliability
- A definition:
  - **Network Code on Operational Security:** (N-1)-Criterion means the rule according to which elements remaining in operation [ ] after a Contingency [ ] must be capable of accommodating the new operational situation without violating Operational Security Limits
  - A network element can be a transmission line, a breaker, generator, busbar,. . .
- The N-1 criterion inherently assumes that the probability of two events at the same time is not credible and that events are independent
  - Assume a system with 1000 lines
  - Probability of unavailability of a single line: 10^{-4}
  - Probability of one line not being available: 0.0905
  - Probability of two lines not being available: 0.0045

N-1 in practice

- The concept of N-1 is simple, transparant and acceptable
- Several implementations exist:
  - What contingencies to take into account: lines, busbars, pylon, generators,. . .
  - Sometimes multiple definitions within one company
- When being N-1 secure, it is not necessarily so two contingencies lead to an outage
- One can choose to consider N-1 taking into account actions pre-incident (preventive actions) or post-event (curative or corrective actions)
- Often N-1 calculations only consider a subset of contingencies (the most critical ones)
- Not all systems operate under N-1:
  - Too expensive in some cases (rural areas in north of Norway)
  - Too insecure in some cases (near major cities or BASF Antwerp)
- Even when operating in N-1, there still might be bigger than expected outages:
  - Hidden failures (e.g. breakers that do not open)
  - Dependent faults (incorrectly assumed to be independent and not taken into consideration)
  - Multiple (near) simultaneous events

N-1, cornerstone of power system reliability?

BUT

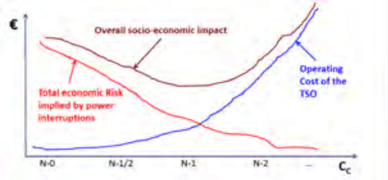
- Does not consider probability of failures
- Does not consider consequences of failures (or distinguish between different consequences)
- Difficult/impossible to handle the comprehensive uncertainties in a large interconnected system
- Favors preventive actions
- Binary
- Volatility caused by RES increasingly necessitates probabilistic approaches
- Hard to handle new devices that enable fast corrective actions

⇒ There is no such thing as optimal N-1

⇒ Risk-based is (in theory) much better!

N-1, cornerstone of power system reliability?

Design:



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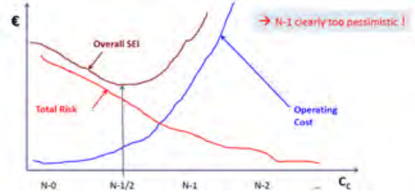
Calm day, low load:



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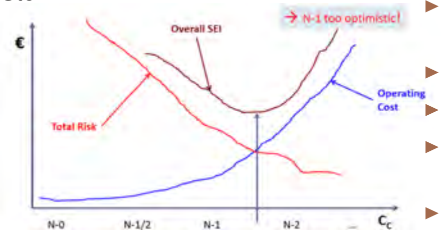
Storm:



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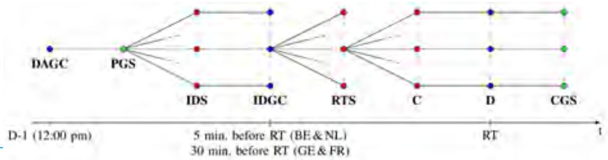
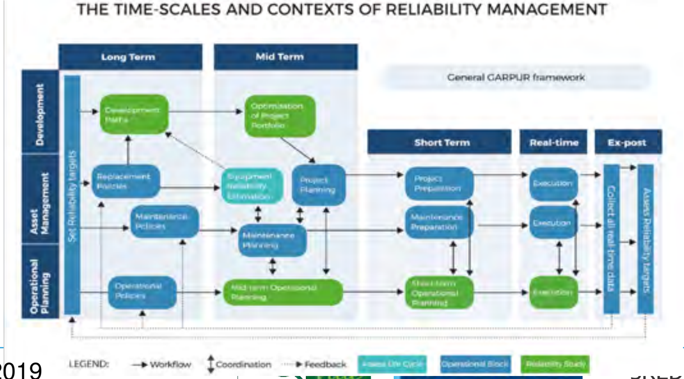
Why still using N-1/Deterministic approaches?

- Works well!
  - In particular with the (old) system which did not change much
- Unclear how to formulate an alternative method
- We don't do N-1, but N-1 with exceptions/expansions/. . .
- Although the fundamental problem is known from the 70's, it is still very *hard to compute* risk-based reliability management
  - Stochastic optimization, non-linear, non-convex, mixed-integer, Exploding trees,. . .
  - New tools are needed
- Fundamental change in how we work required (in a conservative/risk averse business)
  - Stepwise approach needed



Development of a new generic RMAC

- RMAC: Reliability Management Approach and Criterion
- Reliability management in the three time-scales
- Characterizing existing processes built on years of experience (TSO involvement!)
- General building block: SCOPF: Security Constrained Optimal Power Flow



Development of a new generic RMAC (II)

Key aspects

- Socio-economic objective, including stakeholder effects
- Discarding principle (risk based requires in theory to consider all possibilities)
- Reliability target based on risk-based/probabilistic method
- Relaxation of the problem if needed
- Different time horizons

Certains events can be discarded (ignored) provided that their total risk falls below a defined threshold.

Reliability Target

If needed, the threshold can be increased (relaxed) so more events can be discarded until a satisfactory option can be found.

GQP: Garpur Quantification Platform

- How to evaluate whether one method/approach/threshold is superior? (different paths)
- Developed tool for generic testing
- ‘DC’ Optimal Power Flow implementation TSO N-1 operation and new RMAC
- The prototype was tested on small benchmarks and on a real medium-size power system

- Situation is problematic in case of high imports.
- The important generating units are in limited number/costly
- Hydro and RES variations (Photovoltaic)
- Cross border PST with Italy
- Specific hours and seasonal aspects to consider (Winter/Summer Load, Summer storms/fires)
- Present operating rule:
  - The N-2 Tavel-Realtor is taken into account depending on weather conditions

Transition to risk-based reliability management

- In a conservative business, moving from deterministic to probabilistic/risk based approaches will not happen over night
- Six groups of reliability criteria based on four characteristics developed and compared

	(a)	(b)	(c)	(d)	(e)	(f)
Objective function	Deterministic	Deterministic	Probabilistic	Probabilistic	Probabilistic	Probabilistic
Set of considered states	N-1 failures of components	Adapted set of failures of components	Failures of components and forecast errors	Failures of components and forecast errors	Failures of components and forecast errors	Failures of components and forecast errors
	Deterministic	Probabilistic or risk based	Probabilistic or risk based	Probabilistic or risk based	Probabilistic or risk based	Probabilistic or risk based
Set of actions	Preventive	Preventive	Preventive Corrective	Preventive Corrective Curtailment	Preventive Corrective Curtailment	Preventive Corrective Curtailment
Non-technical constraints	/	/	/	/	Limit on total power curtailed	Limit on individual power curtailed

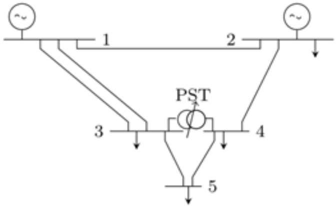
(a) Deterministic with N-1 contingency set
(b) Deterministic with different set of contingencies
(c) Probabilistic without curtailment
(d) Unconstrained probabilistic
(e) Probabilistic with aggregated constraints
(f) Probabilistic with individual constraints

Heylen E., Ovaere M., Proost S., Deconinck G., Van Hertem D., “A Multi-Dimensional Analysis of Reliability Criteria: From Deterministic N-1 to a Probabilistic Approach.” Electric Power Systems Research, 167, 290 – 300, 2019.

Performance trilemma

	Criteria					
	(a)	(b)	(c)	(d)	(e)	(f)
ETC_{rel} [%]	100	87.34	34.62	26.63	33.83	34.50
RLC [min]	0.0046	0.0077	0.0046	18.87	1.83	0.19
U_{ENS} [/]	0.741	0.613	0.569	0.811	0.794	0.604
Input info	+++	++	+	+	-	-
Ease of use	+++	++	+	+	-	-
Type	Det.	Det.	Prob.	Prob.	Prob.	Prob.
# of states	19	28	196	196	196	196
# info	+++	++	+	+	-	-

(a) Deterministic with N-1 contingency set
(b) Deterministic with different set of considered states
(c) Probabilistic without curtailment
(d) Probabilistic
(e) Probabilistic with aggregated constraint on load curtailment
(f) Probabilistic with individual constraint on load curtailment



- D-1 and real-time operation
- Modelled using security constrained optimal power flow

ETC_{rel} = Relative expected total cost
RLC = Relative load curtailment
U_{ENS} = Inequality index

Heylen E., Ovaere M., Proost S., Deconinck G., Van Hertem D., "A Multi-Dimensional Analysis of Reliability Criteria: From Deterministic N-1 to a Probabilistic Approach." Electric Power Systems Research, 167, 290 – 300, 2019.

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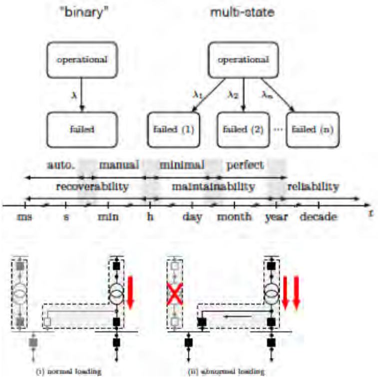
Reliability process with uncertainty and maintenance

Most practical approaches (over-)simplify modeling

1. Practical reliability problems lead to multi-state problems
2. Time constants associated with reliability vary widely (ms – s – min – h – year)
3. Important stochastic dependance of components.

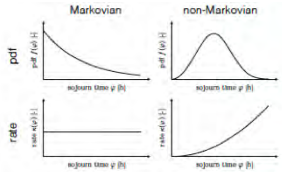


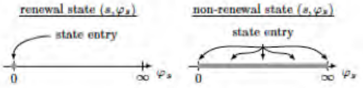
Non-Markovian, non-renewal, stochastic process

Reliability process with uncertainty and maintenance

Most practical approaches (over-)simplify modeling

1. Practical reliability problems lead to multi-state problems
2. Time constants associated with reliability vary widely (ms – s – min – h – year)
3. Important stochastic dependance of components.
4. Typical distribution is not normal nor exponential (e.g. outage duration), Non-Markovian
5. Different maintenance strategies and efficiencies, i.e. state entry at a non-zero sojourn time.
6. Failure characteristics are time-dependent

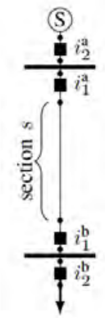


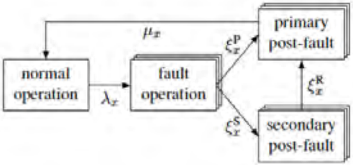


Non-Markovian, non-renewal, stochastic process

Solving general Non-Markovian non-renewal process

Example: simple single feeder (I)





Symbol	Type	p [-]	χ [h]	ψ [h]
λ_x	Failure	1.0	$a_x^{\chi} \cdot 10^4$	-
ξ_x^P	Primary fault clearing	0.8	10^1	0.08
ξ_x^S	Secondary fault clearing	0.2	10^1	0.08
ξ_x^R	Topological action	1.0	10^2	0.08
μ_x	Maintainability action	1.0	10^3	10

Van Acker T., Van Hertem D. (2018). Stochastic Process for the Availability Assessment of Single-Feeder Industrial Energy System Sections. IEEE TRANSACTIONS ON RELIABILITY

Solving general Non-Markovian non-renewal process

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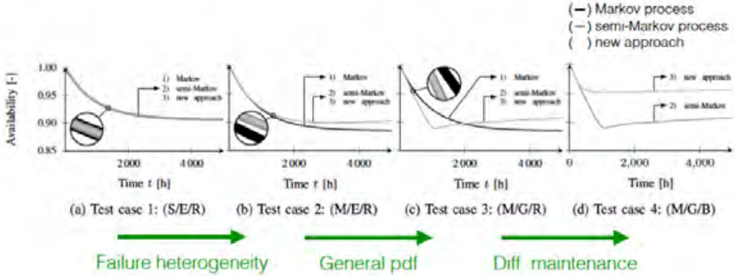


Four test cases, each defined by a three letter code:

First letter - number of failures: S - single failure / M - multi-failure
Second letter - underlying pdf: E - exponential / G - general
Third letter - maintenance type: R - only perfect / B - both minimal as perfect

Van Acker T., Van Hertem D. (2018). Stochastic Process for the Availability Assessment of Single-Feeder Industrial Energy System Sections. IEEE TRANSACTIONS ON RELIABILITY

Solving general Non-Markovian non-renewal process

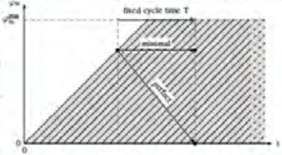
1 - Reduce the state-transition diagram by merging all post failure states of a cycle into one single merged state.

2 - Integrate the merged state probability expression in the normal operation state probability.

$$\frac{\partial p_n}{\partial t} + \frac{\partial p_n}{\partial \varphi_n} = - \sum_{(f,c)\in \mathcal{R}} \lambda_f(\varphi_n) p_n(t, \varphi_n) + \sum_{(f,c)\in \mathcal{R}^M} \lambda_f(\varphi_n)(f_c * p_n)(t, \varphi_n),$$

$$p_n(t, 0) = \sum_{(f,c)\in \mathcal{R}^P} \int_0^{\infty} \lambda_f(\varphi_f)(f_c * p_n)(t, \varphi_f) \mathrm{d}\varphi_f.$$

3 - Solve resulting PDDE with non-local boundary condition using a cohort approach [3].

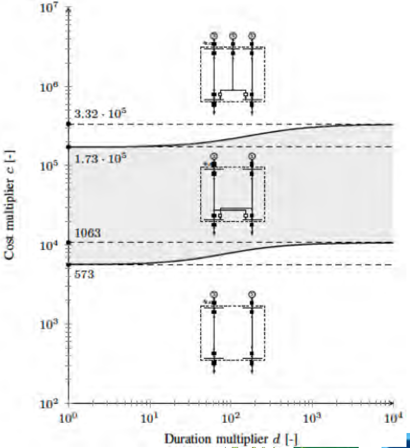


$t = \alpha + \phi$

[3] L. Abia and J. Lopes-Marcos, "Runge-Kutta methods for age-structured population models", Appl. Numer. Math., vol. 17, no. 1, (pp. 1–17), 1995.

Solving general Non-Markovian non-renewal process

Re-evaluating grid concepts and topologies!



Van Acker T., Van Hertem D. (2018). Iterative Availability Assessment Approach for Multi-Feeder Industrial Energy System Sections. In: 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS) Presented at the 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)

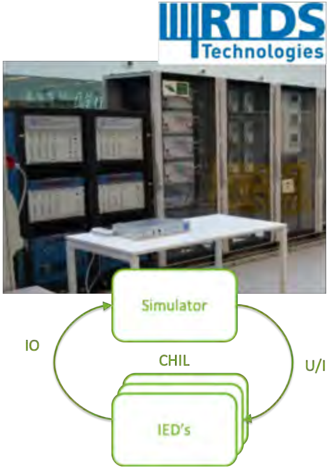
Reliable digital substations

Why digital substations?

- Digital substations interface substation equipment using standardised protocols (e.g. IEC 61850)
- Analogue/copper cabling replaced by network cables running communication protocols: easier wiring
- New features possible
- Higher reliability

However. . .

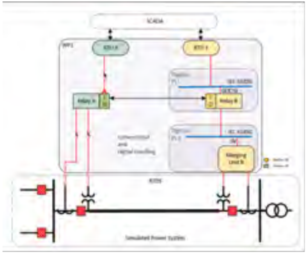
- Interoperability can be an issue. Multi-vendor and multi-generation
- Requires combined power systems and IT knowledge
- How to assure that it really is more reliable?
- Cybersecurity

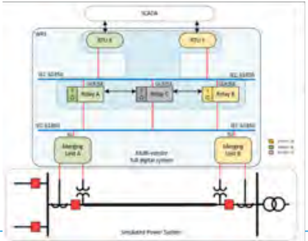


Reliable digital substations

Addressing reliability concerns

- Develop methodology to assess the reliability of digital substations
  - Benchmark with traditional system
  - Develop standardized tests
  - Interact directly with suppliers and users
- Reduce substation engineering time through development of automated test procedures
- Faster deployment and better acceptance of digital substation technology through establishing a neutral competence centre
- Lab environment to test new turn-key technologies





Outline

Introduction reliability in a changing environment

- Reliability criterion
- Moving from N-1 to a probabilistic, risk based approach

Reliability enhancement through advanced modeling and flexibility

- Reliability process: modeling uncertainty

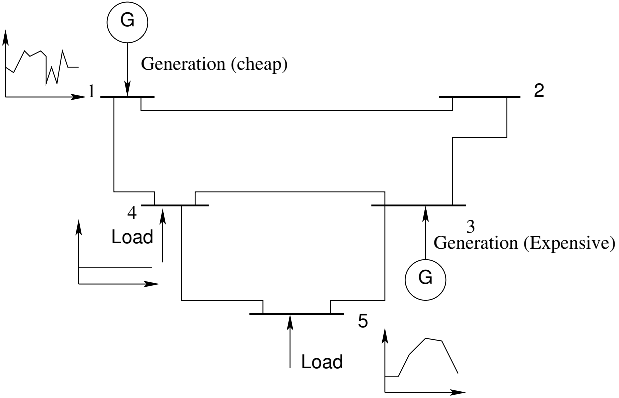
Addressing reliability through the use of flexibility & control

- Providing reliable energy supply: a conceptual investment example
- Indices to measure reliability
- Use of controllable devices (HVDC, FACTS, PST) for reliability
- Control flexibility by taking decisions closer to real time
- Short term reactive power support
- Managing congestion in low voltage distribution systems

Fair reliability

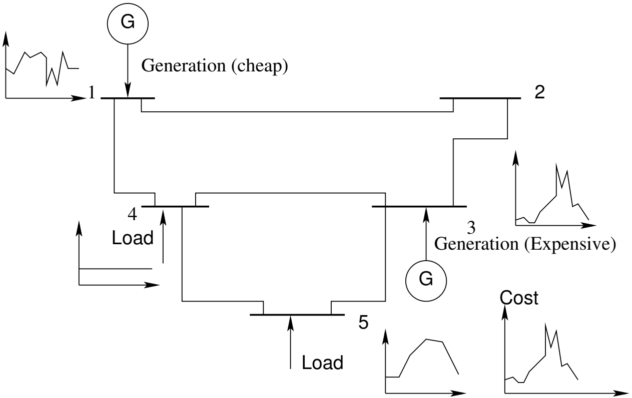
- Load shedding
- Reliability management making use of VoLL

Providing reliable energy supply: a conceptual investment example



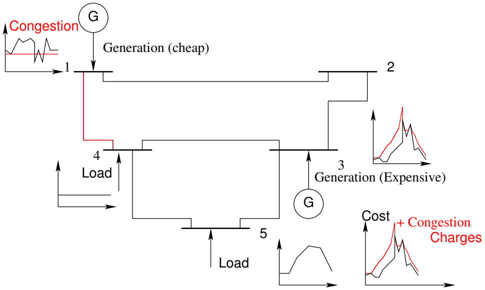
Generation in north and east, load centers in the south
Variable generation and load

Providing reliable energy supply: a conceptual investment example



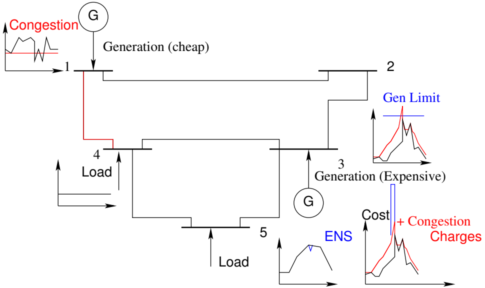
Unit commitment results in a generation pattern and consequent cost

Providing reliable energy supply: a conceptual investment example



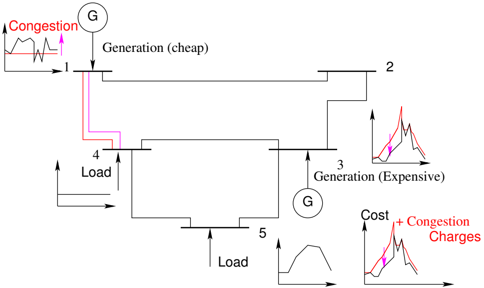
- Congestion in the power system can occur
- More expensive generators are used
- Congestion charges may apply

Providing reliable energy supply: a conceptual investment example



- Congestion in the power system can occur
- More expensive generators are used
- Congestion charges may apply
- Generator limits might result in load shedding (ENS)
- Additional increase in costs

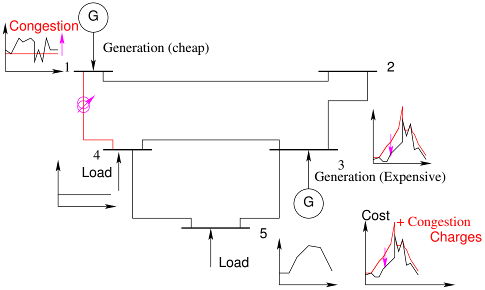
Providing reliable energy supply: a conceptual investment example



Solutions:

- Additional transmission lines
- OHL, Cables,. . .

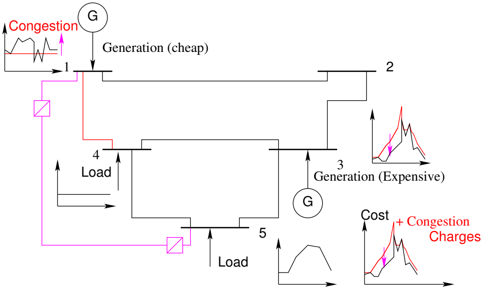
Providing reliable energy supply: a conceptual investment example



Solutions:

- Additional transmission lines
- OHL, Cables,. . .
- Phase shifting transformers, Dynamic line rating

Providing reliable energy supply: a conceptual investment example



Solutions:

- Additional transmission lines
- OHL, Cables,. . .
- Phase shifting transformers, Dynamic line rating
- HVDC Lines

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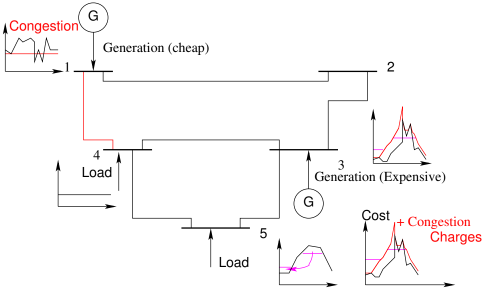

Solutions:

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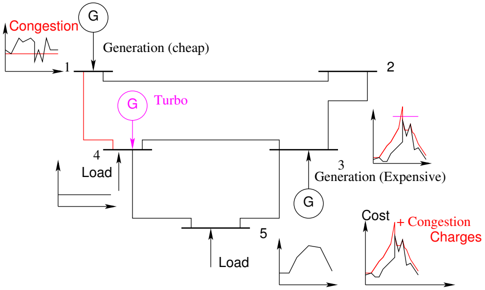
- HVDC Lines
- Demand side management, no additional grid investments

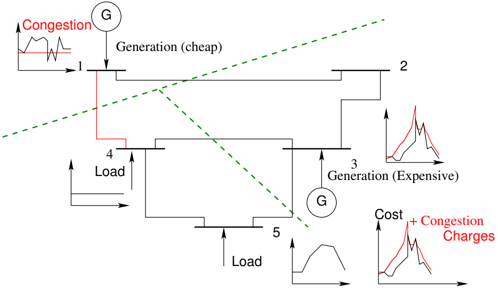
Providing reliable energy supply: a conceptual investment example



Solutions:

- Additional transmission lines
- OHL, Cables,. . .
- Phase shifting transformers, Dynamic line rating
- HVDC Lines
- Demand side management, no additional grid investments
- Traditional generation investments or storage?

Providing reliable energy supply: a conceptual investment example



Additional difficulties:

- Different zones
- Different time horizons
- Investment in one zone has effect on the neighbors
- Different stakeholders in competition

Optimal grid to accommodate the generation system?

- Investment decision is optimization taking into account the various aspects:
  - Each investment needs to be cost-effective for the investor
  - Stochastic variables
  - Controllable elements in the grid and in generation and load
  - Investment risks (timing, competition,. . .)
  - Ecological and social effects (CO_2, visibility,. . .)
  - Return on investment also depends on remuneration scheme
- Remuneration scheme for grid investments
  - Grid tariffs need to be fair
  - Different market players see different benefits (and losses)
  - Accounting for energy and/or power (capacity)
  - Value of controllability?
  - How to take multi-zonal effects into account?
- Over-investing (copper plate) or under-investing (Congestion and price differences)
  - ⇒ where is the balance?
  - ⇒ optimal social welfare

Power flow controlling devices

- Different controllable devices (phase shifting transformers and HVDC) are placed in the system
- Placed at strategic points
- Each with different objectives and regulations
- Coordination exists, but is limited

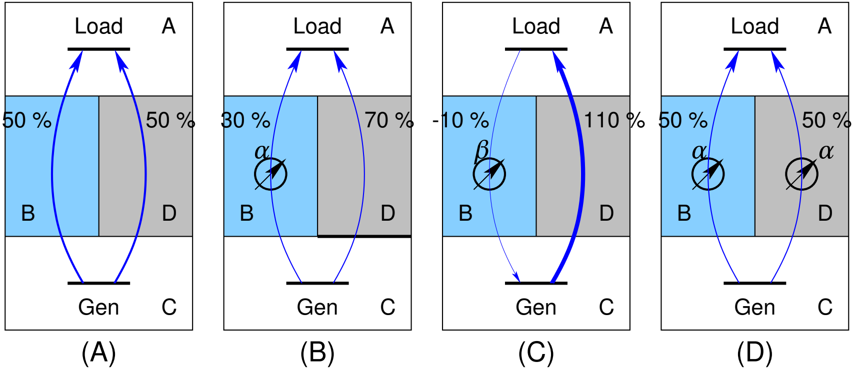
Power flow controlling devices

(source: UCTE)

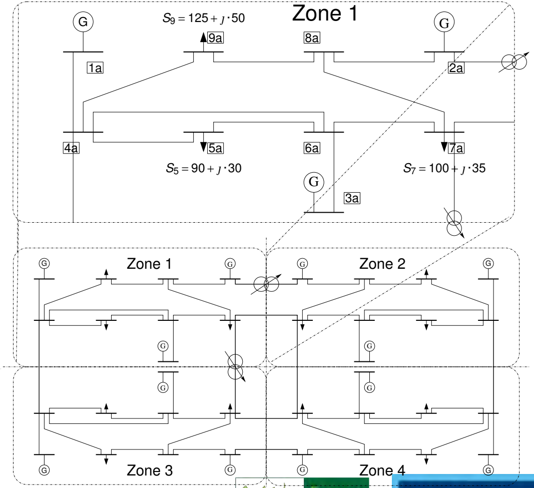
1. HVDC interconnector UK-FR
2. Meeden PSTs (2×) + (2×)
3. Gronau PST
4. Monceau PST
5. Norned HVDC
6. Van Eyck PSTs (2×)
7. Zandvliet PST (2×)
8. Diele
9. BritNed (2011)
10. NEMO (2019)
11. Alegro (2020)
12. Cobra and/or Norned 2 (201?)

Power flow controllers in multi-zonal systems

- PST and HVDC act as fully controllable "valves", pushing or pulling active power through a line

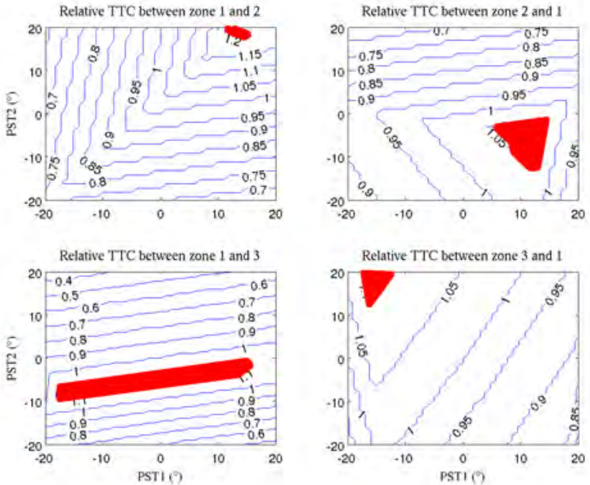


Steady-state coordination in a symmetrical system



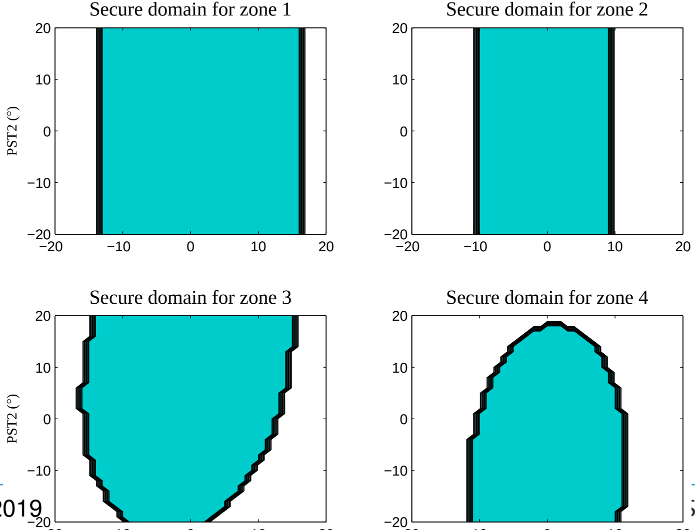
Steady-state coordination in a symmetrical system

Transmission Capacity between zones/regions



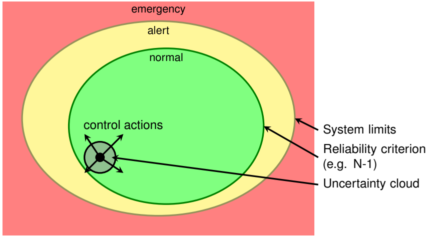
Steady-state coordination in a symmetrical system

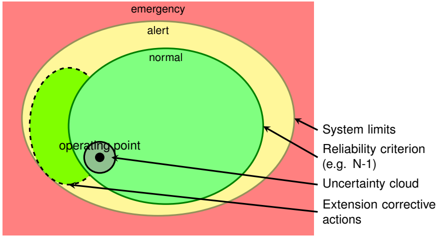
Static “perceived” security (N-1) in different zones



Reliability management when using (fast) control flexibility

- Based the expected futures, a choice is made between preventive actions (avoiding temporary insecure situations in advance) and corrective actions (ensure it is safe to act after the event)
  - Possible measures: line switching, redispatch, load shedding, control actions of FACTS, HVDC,. . .
- Typically, systems are managed taking the deterministic N-1 criterion into account
- Move towards probabilistic approaches is foreseen
- Fast control (e.g. HVDC) gives additional freedom to the system operator!





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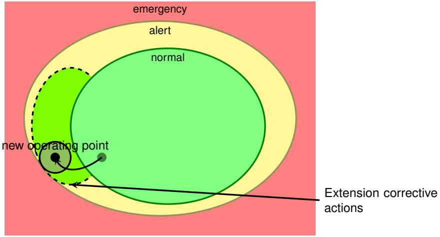
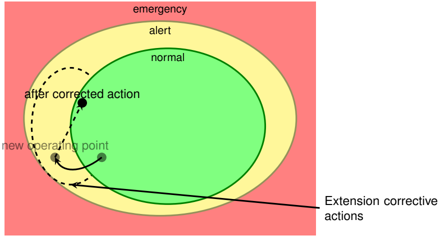
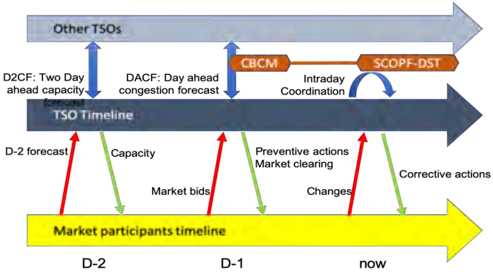




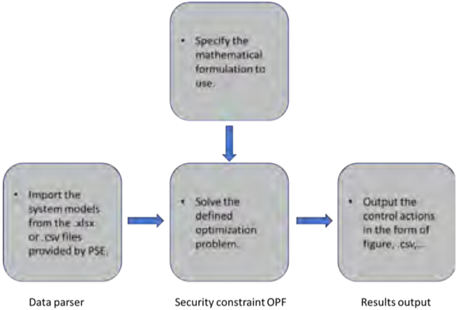
Supporting Polish system operator in decision taking process

- System operators are responsible for reliability in the system and facilitating the market
- Different decisions over time
- Different interactions with other parties
- Traditional approach relies on (conservative) preventive control
- Job of the operator is less transparent and increasingly difficult
  - Higher uncertainty
  - Faster changing behavior
  - New control means
  - Choosing between preventive security, or corrective control



Support to improve dispatch operator training

- Interface with Dispatcher Trainer Simulator
- Operators are provided with an operational situation
- Two approaches being evaluated:
  - Operators decides based on existing knowledge
  - Optimization based (SCOPF-DST) sequence of decisions are suggested
- Optimization based approach:
  - Multiple objectives
  - Preventive and corrective actions
  - Risk-based
  - Multiple actions possible
- First step: Reactive power/voltage management



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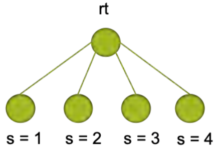

$$\min_{a^{rt}, a_s} C^{total}(a^{rt}, a_s^{cor}) \quad (1)$$

$$\text{subject to: } G_0(x_0, a^{rt}, y_0) = 0 \quad (2)$$

$$H_0(x_0, a^{rt}, y_0) \geq 0 \quad (3)$$

$$G_s(x_s, a_s^{cor}, y_s) = 0 \quad \forall s \in S \quad (4)$$

$$H_s(x_s, a_s^{cor}, y_s) \geq 0 \quad \forall s \in S \quad (5)$$

$$|a_s^{cor} - a^{rt}| \leq \Delta a_s \quad \forall s \in S \quad (6)$$

$$C^{total}(a^{rt}, a_s^{cor}) = C(a^{rt}) + \sum_{s \in S} p_s \cdot [C^{cor}(a_s^{cor})] \quad (7)$$

External forcing inputs y	Constant parameters ϕ	State vector x	Initial conditions x_0
Load realization	Line Parameters	Generation dispatch	PST tap positions
Wind realization	Generation capacity	Load supplied	Switch positions
Component status	Credible contingencies	PST tap positions	Procured flexibility resources
		Switch positions	
	Failure probability	Voltage	
	Operational limits	Branch flow	
	Cost terms		

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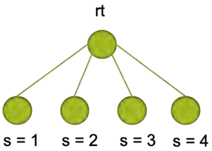
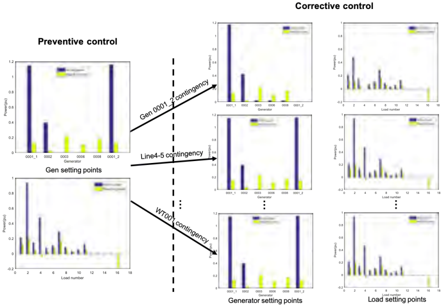
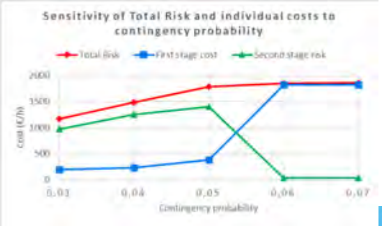
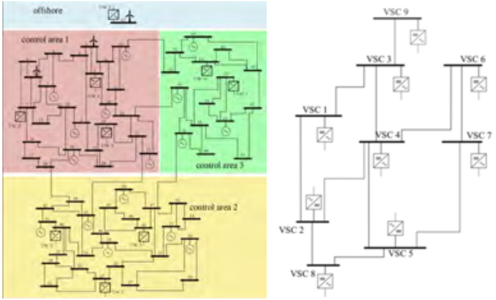




Applied to system with HVDC: preventive or corrective control

- 67 AC bus AC/HVDC Overlay system
- 17 synchronous generation units and 3 wind farms
- 9 Voltage Source Converters (VSCs)
- $\frac{CostCorr}{CostPrev} = 10$ for generators and VSCs
- 102 AC lines and 11 DC lines
- 13 critical contingencies realized





AC system DC system

Source: Sass, F., Sennewald, T., Westermann, D., "Open source AC-HVDC Test System", Working Paper, August 2016

Applied to system with HVDC: preventive or corrective control

Converters participate in preventive and corrective control

Total Risk (€/h)	First stage/Preventive cost (€/h)	Second stage/Corrective risk (€/h)
7,89	0	7,89

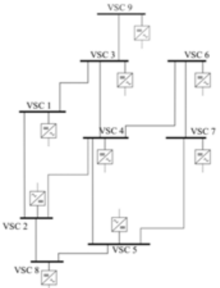
Preventive Generator Redispatch (MW)	Preventive Converter Redispatch (MW)	Corrective Generator Redispatch (MW)	Corrective Converter Redispatch (MW)
0	0	9,93	58,6

Converters participate only in preventive control

Total Risk (€/h)	First stage/Preventive cost (€/h)	Second stage/Corrective risk (€/h)
12,615	0,0336	12,581

Preventive Generator Redispatch (MW)	Preventive Converter Redispatch (MW)	Corrective Generator Redispatch (MW)	Corrective Converter Redispatch (MW)
0,00338	0	25,2	-

AC system



DC system

Source: Sass, F., Sennewald, T., Westermann, D., “Open source AC-HVDC Test System”, Working Paper, August 2016

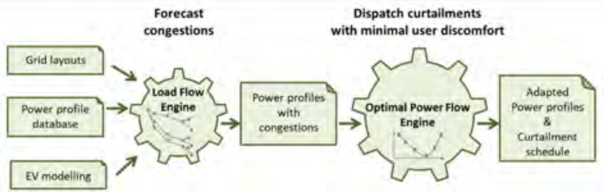
Managing congestion in low voltage distribution system

- New system on distribution level:
  - Massive integration of rooftop solar
  - Fast increase of electric vehicles
  - Unbalanced loading
  - Radial system
  - Massive amount of feeders
  - High uncertainty (few measurements, variable residential consumer)

⇒ Congestion occurs, with little oversight for the system operator

⇒ System operators lack appropriate tools

- Tasks:
  - Forecast congestion (probability)
  - Detect congestion (boundaries)
  - Provide mitigating actions
- Tested on real street level feeders

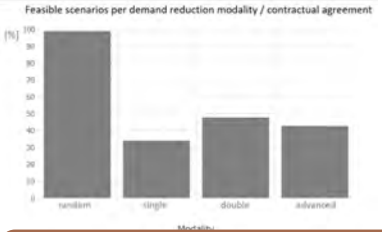


Managing congestion in low voltage distribution system (II)

Define a set of residential contractual agreement that:

- Limit the power a customer is allowed to consume
  - Only required in case of congestions detection
- Is socially acceptable (respect of user comfort):
  - A certain power consumption threshold is always guaranteed
  - Power reduction only occurs for limited time
- Among others, it is investigated if the contract terms allow:
  - The existence of feasible solutions (i.e. the grids are completely relieved from congestions if the only action available is demand reduction)
  - The need of a limited amount of participating customers

Modality name	Actions / day	Max. duration	Min. interval
Random	Indefinite	Indefinite	Indefinite
Single	1	4 h	-
Double	2	2 h/action	0
Advanced	2	2 h/action	2 h



Amount of grids for which a solution exists, given a 30 % EV rate, all EVs charging 16 A single-phase

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Fair reliability

- Load shedding
- Reliability management making use of VoLL

Designing optimal reliability

- Are all users equal?
  - Rural, city, industry
  - Loads vs generator vs prosumer
- How much diversity is acceptable?
  - Over the year
  - Between similar users at different nodes
  - How far can we operate to max social welfare?
- Which actions are available?
  - Owned by the system operator
  - Available to the system operator
- At what cost?
  - How to get reliability funded?
  - What is the appropriate level of “standard reliability”
  - How to charge for extra/premium reliability
  - How to reward for those contributing to reliability?
  - How to deal with those that benefit while not contributing?

Norway

Population

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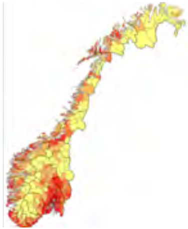

Population

Saifi

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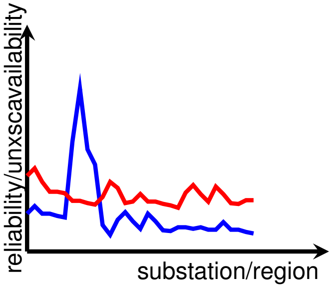

Belgian disconnection plan (shortage ’14-’15, re-used ’18-’19)

- Early 2014 ⇒ clear that there was insufficient generation capacity for next winter in Belgium
  - Simultaneous outage of several nuclear power plants
- Likely shortages (rolling blackout)
- Controversy and significant media coverage about shortage nationally and internationally
- Elia developed a plan: afschakelplan (disconnection plan)
  - Geographically spread over 5 zones
  - Blocks of ± 100 MW per zone
  - 6 steps
- App for blackout (4cast), media campaign ON-OFF, media coverage,. . .
  - No ironing in the evening, no Christmas lights,. . .
- Again controversy: **Not fair**
  - City/Harbor of Gent
  - Flanders/Wallonia

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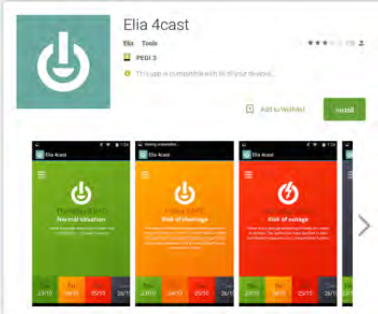
  - 6 steps
- App for blackout (4cast), media campaign ON-OFF, media coverage,. . .
  - No ironing in the evening, no Christmas lights,. . .
- Again controversy: **Not fair**
  - City/Harbor of Gent
  - Flanders/Wallonia



Belgian disconnection plan (shortage ’14-’15, re-used ’18-’19)

- Early 2014 ⇒ clear that there was insufficient generation capacity for next winter in Belgium
  - Simultaneous outage of several nuclear power plants
- Likely shortages (rolling blackout)
- Controversy and significant media coverage about shortage nationally and internationally
- Elia developed a plan: afschakelplan (disconnection plan)
  - Geographically spread over 5 zones
  - Blocks of ± 100 MW per zone
  - 6 steps
- App for blackout (4cast), media campaign ON-OFF, media coverage,. . .
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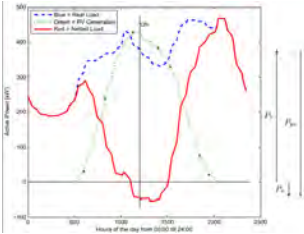
Distributed generation and UFLS (load shedding)

- Feeder behavior changes during the day (evening peak)
- Relays are typically set once, rarely updated
- Massive infeed of solar in some regions
- Infeed is not homogeneously distributed over feeders
- Disconnection of high solar infeed increases worse frequency dip
- Avoid disconnection of solar with minimal customer impact?
- Avoid always switching of same feeder (poorer neighborhoods)?
- Decentral activation - Central optimization
- Different methodologies, requiring different hardware and communication infrastructure can be used:
  - Direction of current
  - Seasonal/Daily settings
  - Smart grid approach

Typical sunny day profile



Changes in disconnection order in French region when taking solar injections into account

[%]	1	2	3	4	5	6	7	8	Orig.
1	[illegible]	0	0	0	0.14	0.95	0	[illegible]	9.7
2	[illegible]	[illegible]	0	0	[illegible]	[illegible]	0	[illegible]	[illegible]
3	0	3.48	[illegible]	0	[illegible]	[illegible]	0	[illegible]	9.32
4	0	0	5.24	2.5	[illegible]	[illegible]	0	0	9.41
5	0	0	0	7.33	[illegible]	[illegible]	0	[illegible]	[illegible]
6	0	0	0	[illegible]	7.47	[illegible]	0	[illegible]	[illegible]
7	0	0	0	0	0	0	[illegible]	[illegible]	[illegible]
8	0	0	0	0	0	0	0	[illegible]	27.15
New	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

De Boeck S., Van Hertem D. Integration of Distributed PV in Existing and Future UFLS Schemes

Using detailed VoLL data to reduce reliability costs

- VoLL data has been collected over time in different countries
- Separate values, methods and levels of details are used
- Values differ substantially
- Differenciated VoLL data can be used to optimize reliability management

United States VoLL as a function of time and consumer group characteristics [2015 €/kWh]

	Summer							
	Weekday				Weekend			
	Morning	Afternoon	Evening	Night	Morning	Afternoon	Evening	Night
Residential	3.4	2.6	2.4	2.4	4	3	2.9	2.9
Small C&I	307	373	197	196	189	237	112	110
Large C&I	17.8	25	21	15.7	12.8	18	14.9	11
	Winter							
	Weekday				Weekend			
	Morning	Afternoon	Evening	Night	Morning	Afternoon	Evening	Night
Residential	2.4	1.7	1.4	1.4	2.8	2	1.6	1.6
Small C&I	423	531	249	245	250	324	136	132
Large C&I	14.5	21.4	16.2	12.2	10	15	11	8.2

How detailed value of lost load data impact power system reliability decisions: a trade-off between efficiency and equity Ovaere Marten, Heylen Evelyn, Proost Stef, Deconinck Geert, Van Hertem Dirk; EPSR.

Using detailed VoLL data to reduce reliability costs (II)

- Applied to a single (small) system
- Equivalent year
- Differentiated VoLL values:
  - V: Single VoLL
  - v_t: time of day
  - v_n: per node and time of day
  - v_c: per consumer group and time of day

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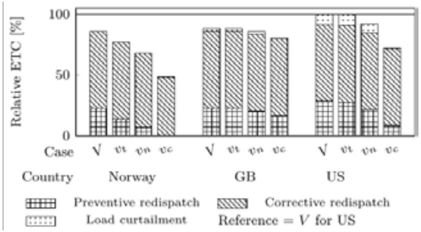
Relative expected total system cost savings for three countries using VoLL with different levels of detail

ΔETC [%]	V	v_t	v_n	v_c
Norway	0	-10.68	-20.27	-43.28
GB	0	-0.01	-3.03	-9.37
US	0	-0.95	-11.14	-29.52



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Detailed VoLL leads to considerable cost savings!

Different (type of) control actions are taken

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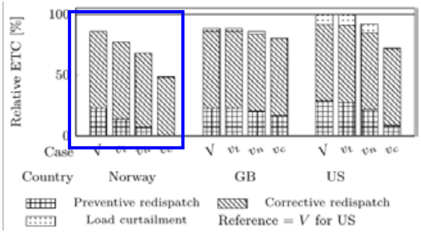
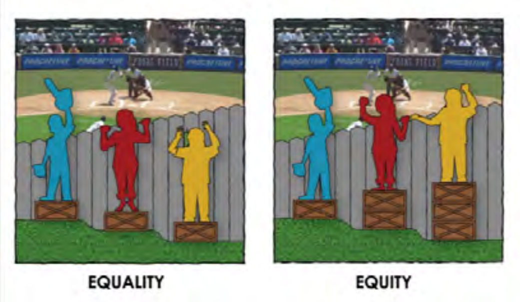
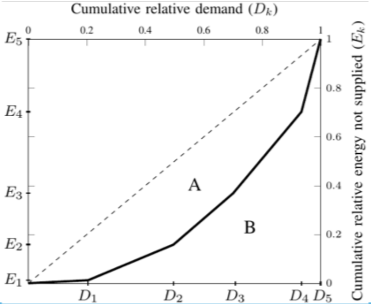


Using detailed VoLL data to reduce reliability costs: Equity?

- Making use of detailed VoLL data ⇒ switching of cheaper loads first
- Is this fair?
- They pay the same (or more) for their electricity
- Equity index based on GINI coefficient ($GINI = \frac{A}{A+B}$)
- GINI = 0, perfect equality; GINI = 1, perfect inequality





Using detailed VoLL data to reduce reliability costs (III)

- Applied to a single (small) system
- Equivalent year
- Differentiated VoLL values:
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  - v_t: time of day
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US	0	-0.95	-11.14	-29.52

Inequality [/]	V	v_t	v_n	v_c
Norway	0.66	0.58	0.81	0.75
GB	0.7	0.7	0.82	0.74
US	0.68	0.64	0.85	0.73

How detailed value of lost load data impact power system reliability decisions: a trade-off between efficiency and equity Ovaere Marten, Heylen Evelyn, Proost Stef, Deconinck Geert, Van Hertem Dirk; EPSR.

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Detailed VoLL leads to considerable cost savings!

Higher inequality!

Relative expected total system cost savings for three countries using VoLL with different levels of detail

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Conclusions

- Reliability is a choice!
  - And when moving to more probabilistic approaches, you need to make more choices
- Better to talk about the “Quality of Service (QoS)” of grids.
  - Adaptive behavior: buying gensets, companies change processes,. . .
- Reliability is a multi-facetted problem, where flexiblity can offer several options
- Optimal = Cost-effective, Reliable and Fair
- Changing power system will change the manner in which we manage the reliability of the power system
  - Grid topology
  - Decision taking process, much closer to real-time
  - How we (are) compensate(d) reliability
- Solving these problems is computational hard and requires new tools!
  - Non-linear
  - Binary decision variables
  - Different actors
  - Scale of the power systems
  - Making them acceptable to be run in the control room
  - . . .

Questions?

This presentation was not possible without the work of:
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And of our sponsors:

`Dirk Van Hertem`
`Dirk.VanHertem@esat.kuleuven.be`
`Dirk.VanHertem@energyville.be`

Thank You ⊿

Feedback and Interest Survey ⊿

Dr. Dirk Van Hertem

Dirk.vanhertem@esat.kuleuven.be

Dirk.vanhertem@energyville.be

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