Methodology for Management of Power System Emergency Situations

@ RiskTeam

GRID

ALSTOM

Blackout: not so unusual events … & correlated

Power Grid infrastructure is highly vulnerable to targeted terrorism attacks

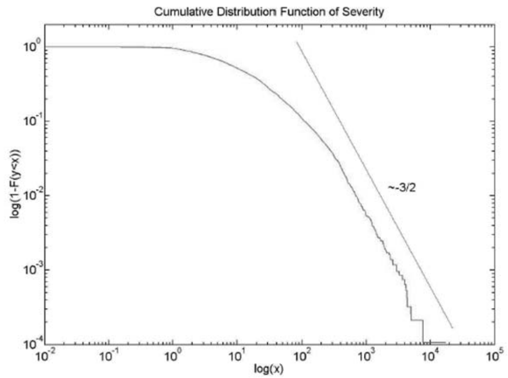
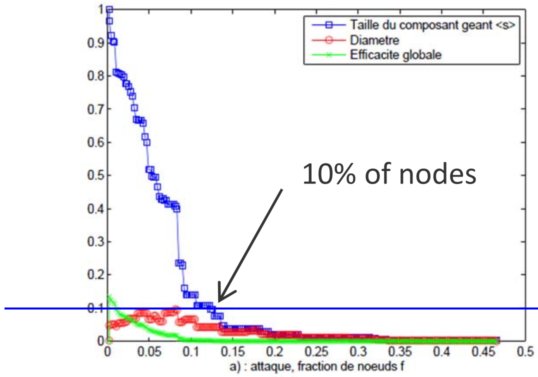


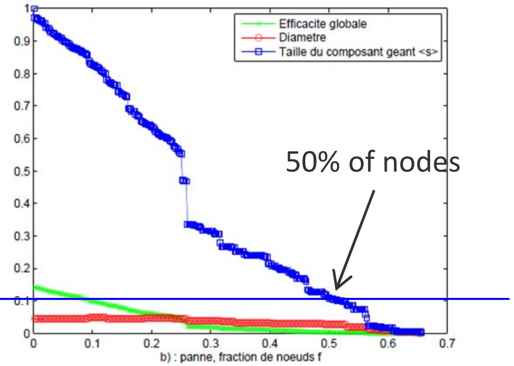
Fig. 9. Cumulative Distribution Function of DNS (KWh)

Grid Efficiency



Nb. of Targeted Attacks

Grid Efficiency



Nb. of random failures

Experience from ISO/TSO Colombia:
We particularly coordinate the operation with the army in conflict zones and also establish for the regions which are under attack an analysis of contingency n-2 or n-3.

GRID | ALSTOM

Statistical Power Flow Model : a way to quantify risk

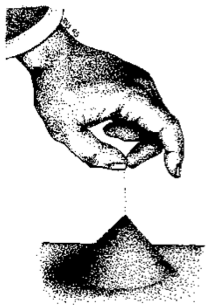
Power Grid → DC/AC Power Flow + optimization

Power Grid + **random events** → + Statistical Estimation

Power Grid + **random events** + **environment** → Improvements in operating policies, maintenance, equipment, controls, …

+ Decision support Feedback

Self Organized Criticality – Power Flow model



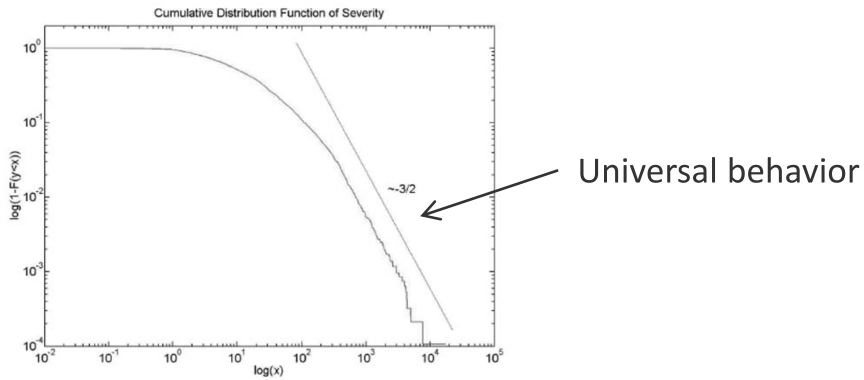
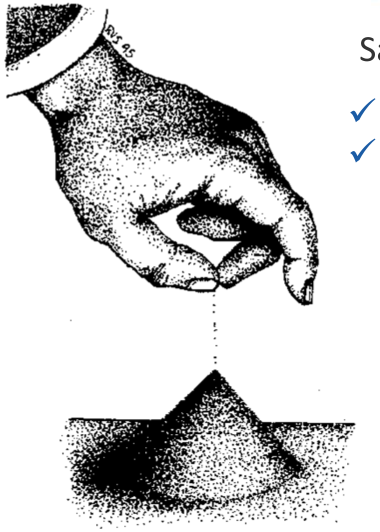


Fig. 9. Cumulative Distribution Function of DNS (KWh)

To reproduce "the life of a power network" over a large sequence of events with a SOC phenomenon

- ✓ 1 fast dynamic, i.e. avalanche phenomena (sequence of events, time resolution: second, minute)
- ✓ 1 slow dynamic (sequence of events, time resolution : day)

Self-Organized Criticality (SOC)



Sandpile model: 2 dynamics & 2 opposing forces

P. Bak, 1987
I. Dobson, 2000

- ✓ slow dynamic: continuous pouring of sand
- ✓ fast dynamic (avalanche)
  - oscillating variations of the slope of the sandpile
  - avalanche phenomenon to reach a new equilibrium status: Self Organized Criticality

Analogy between Sandpile and Electrical Grid dynamics

Power system	**Variables**	**Sandpile**
fractional overloads	system state	gradient profile
load increase	driving force	addition of sand
line improvements	relaxing force	gravity
line limit or outage	event	sand topples
cascading lines	cascade	avalanche

The grid is a dynamic system, managed by two opposing forces (load plan and “response to incident"), in the critical regime or not (subcritical, critical, super-critical)

The power law behaviour observed experimentally finds its origin in this competition (universal behaviour)

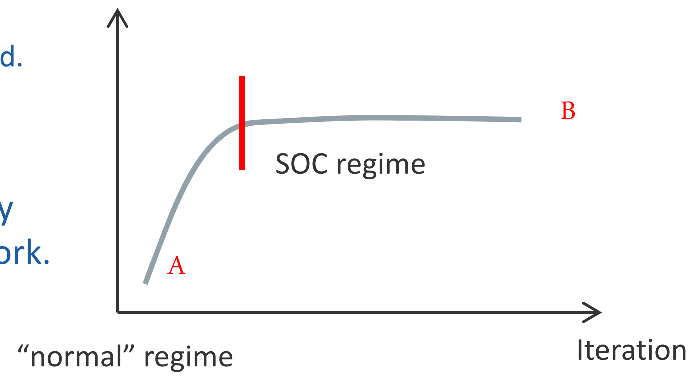
GRID | ALSTOM

SOC regime limitation

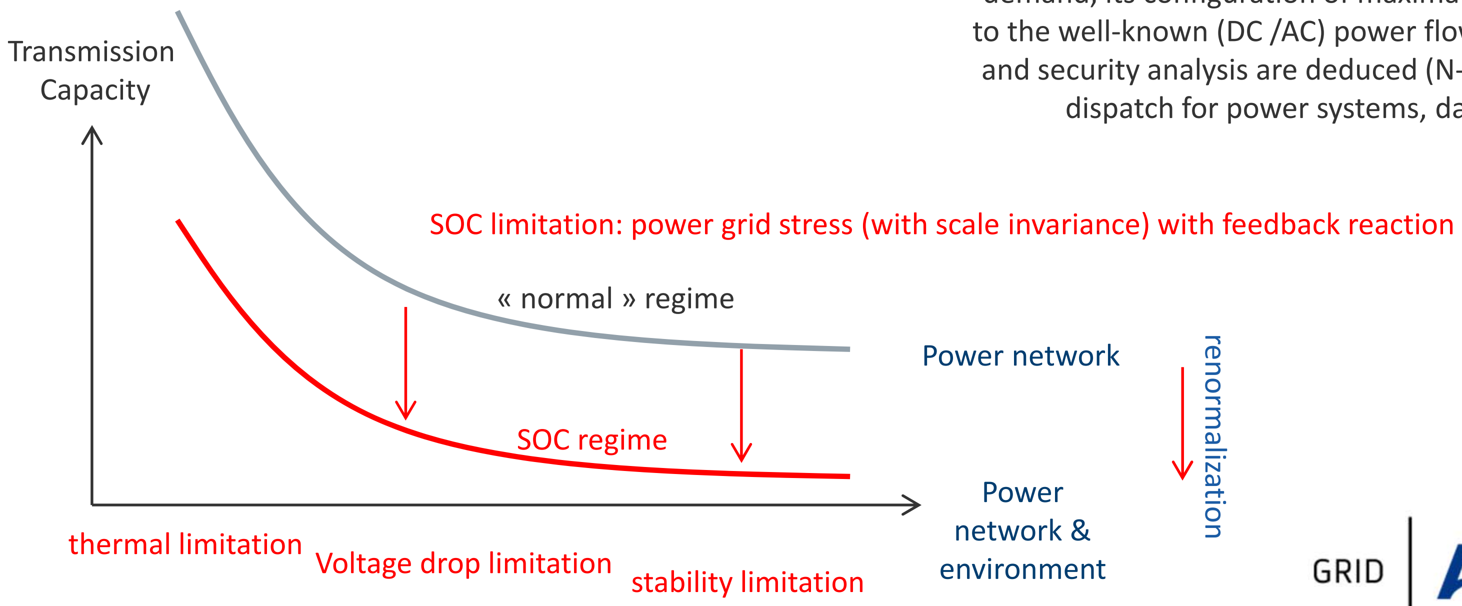
SOC regime:

- ✓ power grid interacts with its surrounding and is close to its limits operating condition
- ✓ feedback reaction to any dysfunction can be operational policy control (control room), human intervention, maintenance operations, planning policy ... and can be quantified.

To reach the SOC regime: put the power grid under maximum stress where any random event can produce a minor failure or a major failure all over the network.



power grid with its distribution of generation sources and load demand, its configuration of maximal power flow lines, corresponds to the well-known (DC /AC) power flow analysis where contingencies and security analysis are deduced (N-1 secure generation day-ahead dispatch for power systems, day-ahead electricity markets ...).



GRID | ALSTOM

Statistical Power Flow Model (DC or AC SPFM)

SPFM model is based on a Optimal Power Flow resolution with variables of interest, the evolution of the load (nodes) and the improvement of the network (lines)

Failures or external events are randomly generated (Gaussian or not)

SOC regime limitation:

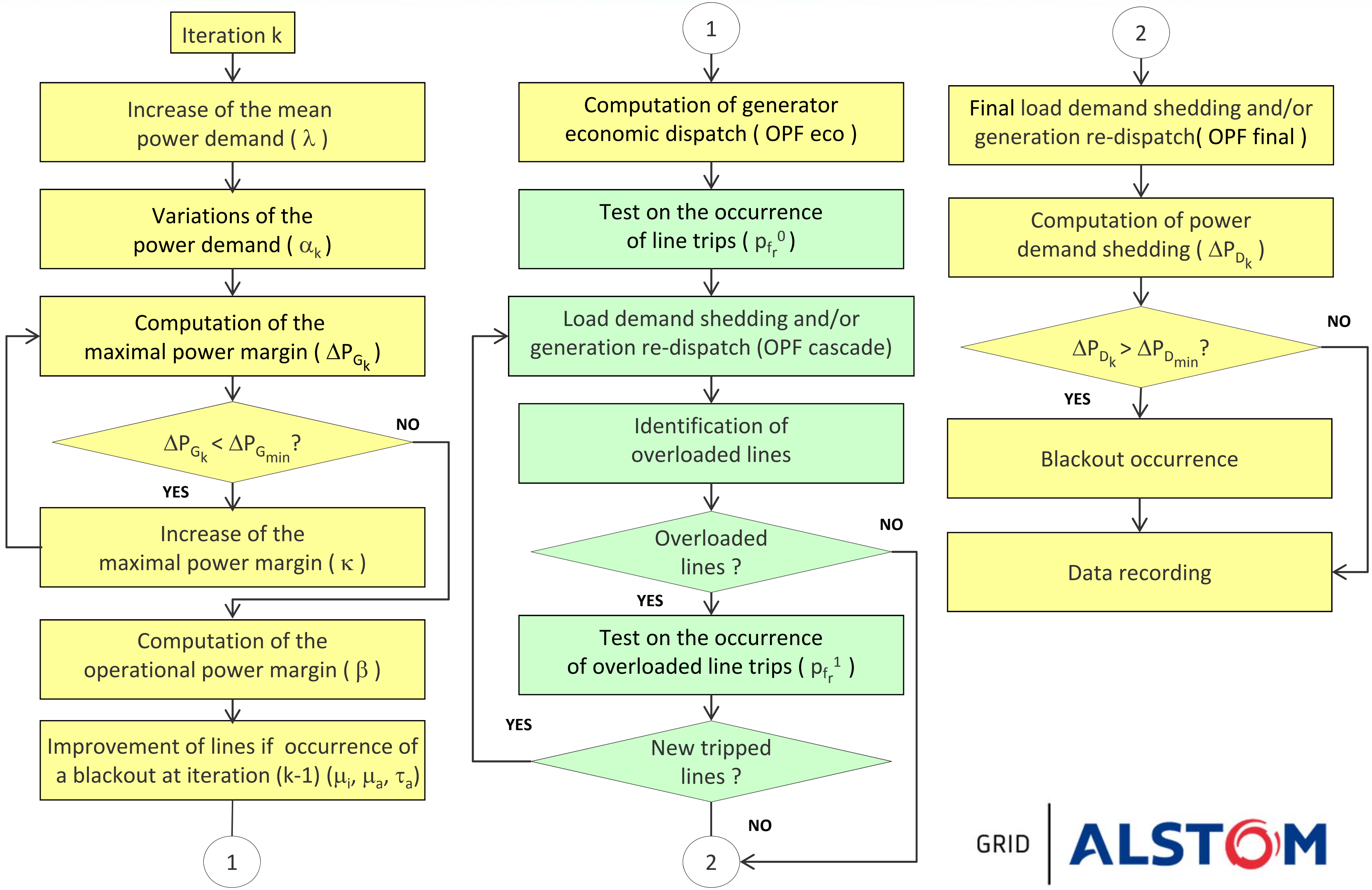
from historical data & generation /load plan

Immediate strategy response & delayed strategy response

Sequence of events

GRID | ALSTOM

DC SPFM: General Algorithm



GRID | ALSTOM

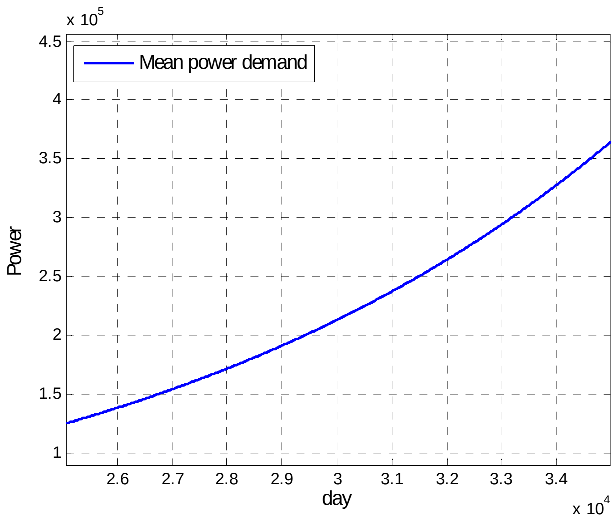
DC SPFM: Slow dynamics

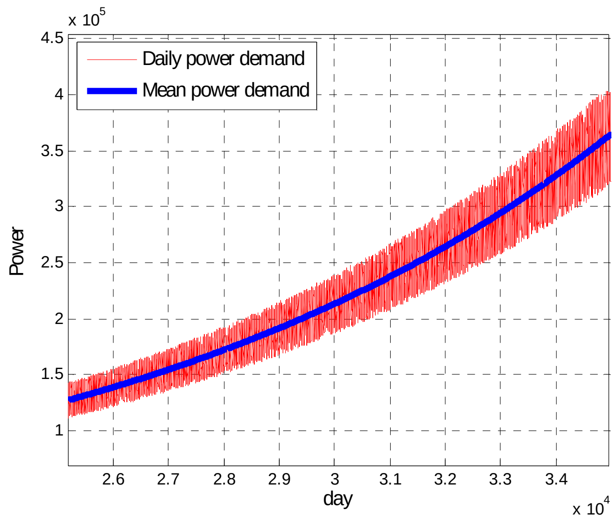
power network evolution: load power demand & power generation capability increase

$$\begin{cases} P_{D_k} = \lambda P_{D_{k-1}} \\ \overline{P}_{D_k} = \alpha_k P_{D_k} \end{cases}$$

Mean power demand evolution

Power demand random variation





GRID | ALSTOM

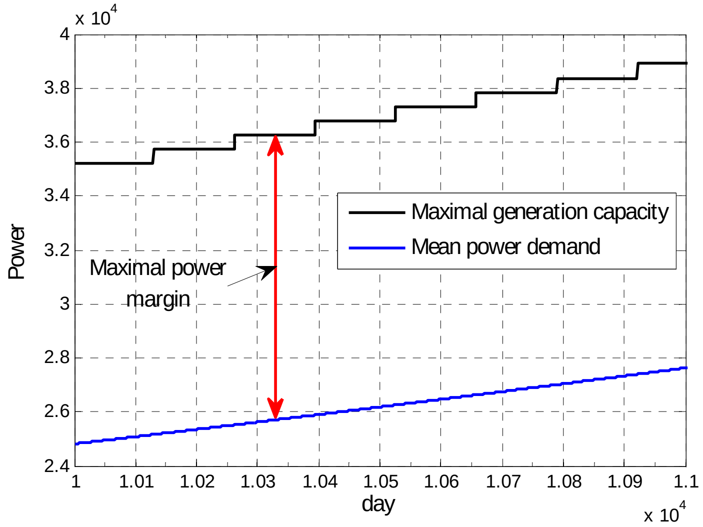
DC SPFM: Slow dynamics

we keep a constant minimal power margin

maximal power margin

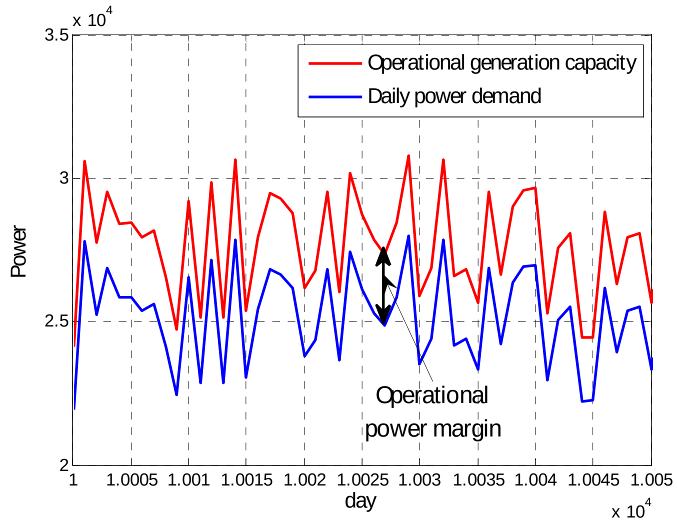
$$\Delta P_{G_k} = \sum_{i=1}^{N_G} P_{G_{\max_i}} - \sum_{j=1}^{N_L} \overline{P}_{D_{kj}}$$

$$\Delta P_{G_k} \geq \Delta P_G^{\min} \qquad P_{G_{\max_i}} = P_{G_{\max_i}} + \kappa \sum_{j=1}^{N_L} \overline{P}_{D_{kj}}$$



operational power margin

$$\varepsilon = \beta \frac{\sum_{j=1}^{N_L} P_{D_{kj}}}{\sum_{i=1}^{N_G} P_{G_{\max_i}}} \qquad P^{op}_{G_{\max k_i}} = \min(\varepsilon P_{G_{\max i}}, P_{G_{\max i}})$$



GRID ALSTOM

DC SPFM: Slow dynamics

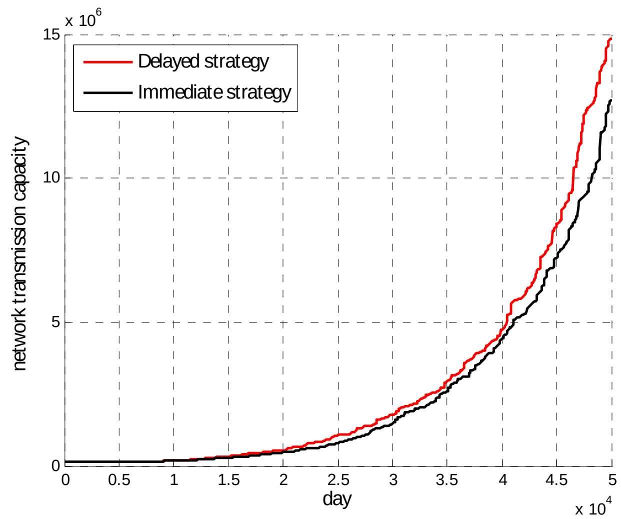
network improvement strategy: feedback actions done by TSO to improve the behavior of network

immediate strategy approach (at k + 1)

$$T_{L_{\max_r}} = \mu_i \, T_{L_{\max_r}} \qquad \begin{cases} Z_r = Z_r / \mu_i \\ B_{sh_r} = \mu_i \, B_{sh_r} \end{cases}$$

delayed strategy approach (at k + τ_a)

$$T_{L_{\max_r}} = \mu_a \, T_{L_{\max_r}} \qquad \begin{cases} Z_r = Z_r / \mu_a \\ B_{sh_r} = \mu_a \, B_{sh_r} \end{cases}$$



line impedances adapted to be coherent with line maximal flux improvement

GRID | ALSTOM

DC SPFM: Slow dynamics

Generation economic dispatch is performed in order to determine, on the basis of generation costs, the generator dispatch that will be considered during the following cascade phenomena step.

Optimal Power Flow (OPF eco), to minimize a given cost objective function.

criteria to be minimized

$$J_{eco}(x_{eco}) = \frac{1}{2} P_G^T H P_G + C^T P_G + D$$

optimization variables

$$x_{eco} = [\theta, P_G]^T$$

network physical constraints

$$\begin{cases} P(\theta) - P_G + P_D = 0 \\ T_L(\theta) - T_{L_{\max}} \leq 0 \end{cases}$$

optimization variable lower and upper bounds

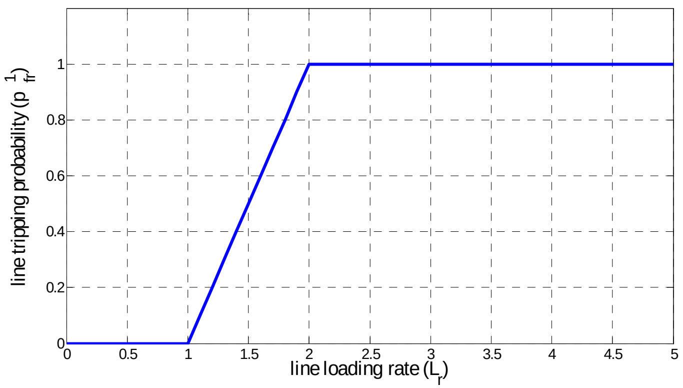
$$\begin{cases} \theta_{\min} \leq \theta \leq \theta_{\max} \\ P_{G_{\min}} \leq P_G \leq P_{G_{\max}} \end{cases}$$

GRID | ALSTOM

DC SPFM: Fast dynamics

Cascade phenomena are consequence of initial tripping events occurring in the network (line tripping occurrences). -> could be associated to weather conditions (e.g. storms), network bad maintenance (e.g. line contacting trees, aged components), human errors, network attacks (e.g. terrorism actions), …
initial line tripping events are depending on a given line fault probability introduced through a constant initial fault probability associated to each line .

Line trip initial occurrence	constant initial fault probability	$p^0_{f_r}$
Overloaded line trip occurrence	line loading rate	$L_r = \dfrac{\lvert T_r \rvert}{T_{\max_r}}$
	line overloading condition	$L_r \geq L_r^{th}$
	overloaded line fault probability	$p^1_{f_r}$ or $p^1_{f_r} = f(L_r)$



DC SPFM: Fast dynamics

Load power demand shedding and/or generation power re-dispatching process
During cascade phenomena, power flowing through lines cannot be controlled and could be greater than maximal allowed power flows.
As far as one or several lines tripped, it could be necessary to re-dispatch generation power and, potentially, to shed load power demand to assure network stability (OPF)

criteria to be minimized

$$J(x) = \sum_{j=1}^{N_L} \omega_{D_j} (P_{D_{0_j}} - P_{D_j})^2 + \sum_{i=1}^{N_G} \omega_{G_i} (P_{G_{0_i}} - P_{G_i})^2$$

optimization variables

$$x = [\theta, P_G, P_D]^T$$

network physical constraints

$$\begin{cases} P(\theta) - P_G + P_D = 0 \\ T_L(\theta) - T_{L_{\max}} \le 0 \end{cases} \quad \text{or} \quad P(\theta) - P_G + P_D = 0$$

optimization variable lower and upper bounds

$$\begin{cases} \theta_{\min} \le \theta \le \theta_{\max} \\ P_{G_{\min}} \le P_G \le P_{G_{\max}} \\ 0 \le P_D \le P_{D_0} \end{cases}$$

GRID ALSTOM

DC SPFM: Slow dynamics

When the cascade phenomena phase ended, we compute the network final power balance (final load power demand shed and/or generation power re-dispatch) taking into account the tripped lines.
As far as one or several lines tripped, it could be necessary to re-dispatch generation power and, potentially, to shed load power demand to assure network stability (OPF)

criteria to be minimized

$$J(x) = \sum_{j=1}^{N_L} \omega_{D_j} (P_{D_{0_j}} - P_{D_j})^2 + \sum_{i=1}^{N_G} \omega_{G_i} (P_{G_{0_i}} - P_{G_i})^2$$

optimization variables

$$x = [\theta, P_G, P_D]^T$$

network physical constraints

$$\begin{cases} P(\theta) - P_G + P_D = 0 \\ T_L(\theta) - T_{L_{\max}} \leq 0 \end{cases}$$

optimization variable lower and upper bounds

$$\begin{cases} \theta_{\min} \leq \theta \leq \theta_{\max} \\ P_{G_{\min}} \leq P_G \leq P_{G_{\max}} \\ 0 \leq P_D \leq P_{D_0} \end{cases}$$

Power demand shedding event is identified when the amount of shed power demand is greater than a defined shed power demand threshold

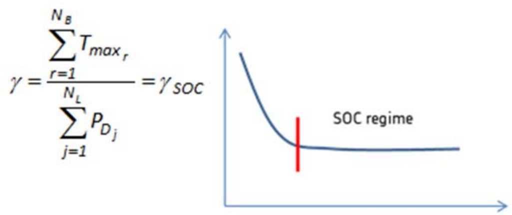
$$\Delta P_D = \sum_{j=1}^{N_L} (P_{D_{0_j}} - P_{D_j}) \geq \Delta P_D^{\min}$$

SOC condition

To get a distribution of line maximal capacities which set the power network in maximal stress operating conditions, corresponding to the natural SOC behavior observed from real historical data analysis

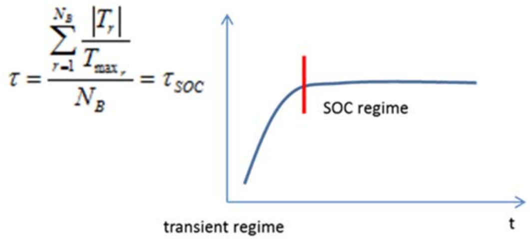
A constant ratio between the sum of line power flow maximal capacities and the sum of node load demands

$$\gamma = \frac{\sum_{r=1}^{N_B} T_{\max_r}}{\sum_{j=1}^{N_L} P_{D_j}} = \gamma_{SOC}$$



A constant mean lines loading rate

$$\tau = \frac{\sum_{r=1}^{N_B} \frac{|T_r|}{T_{\max_r}}}{N_B} = \tau_{SOC}$$



GRID | ALSTOM

SOC condition setting process

To determine the distribution of line maximal transmission capacities $T_{\max_r}^{final}$

network topology

final power demand set point $P_{D_j}^{final}$

final generation power dispatch set point $P_{G_i}^{final}$

Define an initial network state

$$P_{D_j}^{init} = \frac{P_{D_j}^{final}}{r_P} \quad P_{G_i}^{init} = \frac{P_{G_i}^{final}}{r_P} \quad T_{\max_r}^{init} = \frac{T_{\max_r}^{AC}}{r_T}$$

$$P_{G_{\max_i}}^{init} = \frac{P_{G_{\max_i}}^{final}}{r_P}$$

such that

$$\gamma_{init} = \frac{\sum_{r=1}^{N_B} T_{\max_r}^{init}}{\sum_{j=1}^{N_L} P_{D_j}^{init}} > \gamma_{SOC} \qquad \tau_{init} = \frac{\sum \frac{|T_r|}{T_{\max_r}^{init}}}{N_B} < \tau_{SOC}$$

Power demand and generation power **linear evolution** until the final mean power demand is reached

$$P_{D_{k_j}} = P_{D_{k-1_j}} + \Delta P_{D_j} \qquad P_{G_{k_i}} = P_{G_{k-1_i}} + \Delta P_{G_i} \qquad P_{G_{\max k_i}} = P_{G_{\max k-1_i}} + \Delta P_{G_{\max_i}}$$

immediate strategy approach (at k+1) $T_{L_{\max_r}} = \mu_i \, T_{L_{\max_r}}$

delayed strategy approach (at k+τ_a) $T_{L_{\max_r}} = \mu_a \, T_{L_{\max_r}}$

$$T_{L_{\max r}}^{final} \leq T_{L_{\max r}}^{AC}$$

GRID | ALSTOM

Application to day-ahead risk assessment

The main assumption made is that most of information about system behavior can be deduced from the SOC condition setting process, computed for given power demand set point, given generation dispatch set point and given network topology, corresponding to the studied day-ahead network operating conditions

Case of the Colombian Electrical Network, with high voltage (i.e. 110 kV, 220 kV and 500 kV) transport network 392 buses (or nodes), 94 "generator" nodes, 647 lines

3 generation dispatches:

- **"Ideal Dispatch"** (ID), only economical cost objective as well as areas power balance constraints. This dispatch is optimal from an economical point of view. However, it does not consider any network constraints and must be assessed in this sense
- **"Network Dispatch"** (ND) with network topology constraints, such as line maximal transportation capacities and N-1 contingency, in a simplified DC based approach
- **"Coordinated Dispatch"**, which takes into account additional network requirements (e.g. voltage and stability constraints), while seeking being as close as possible to previous dispatches for minimizing the "cost loss" due to dispatch modification

GRID | ALSTOM

Application to day-ahead risk assessment

Day 1 characterized by:

$$\sum_{j=1}^{N_L} P_{D_j}^{final} = \sum_{i=1}^{N_G} P_{G_i}^{final} = 8949\ MW$$

- A high level of power demand (stressed network)
- A power generation dispatch based on both hydraulic and thermal plants
- The three generation power dispatches are considered and compared

Day 2 characterized by:

$$\sum_{j=1}^{N_L} P_{D_j}^{final} = \sum_{i=1}^{N_G} P_{G_i}^{final} = 7598\ MW$$

- A lower power demand level
- A more hydraulic based power generation dispatch
- Only “Ideal” and “Coordinated” generation power dispatches are considered and compared

No generation power re-dispatch is considered (i.e. maximal generation power limit is set equal to the initial generation dispatch)

No line maximal transmission capacity constraints are considered during cascade phenomena

GRID | ALSTOM

DC SPFM input parameters setting

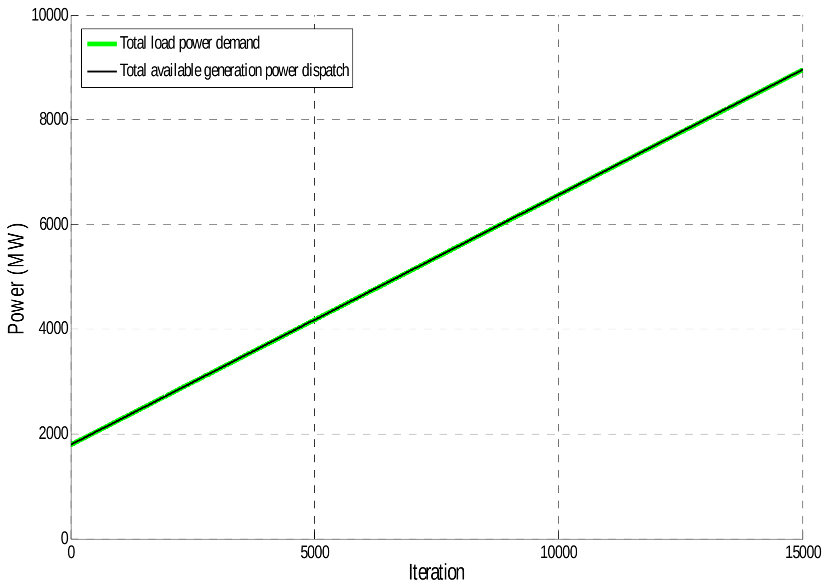
Day 1 with higher power demand level and N-k contingencies

"Network Dispatch" issued from Colombian TSO database

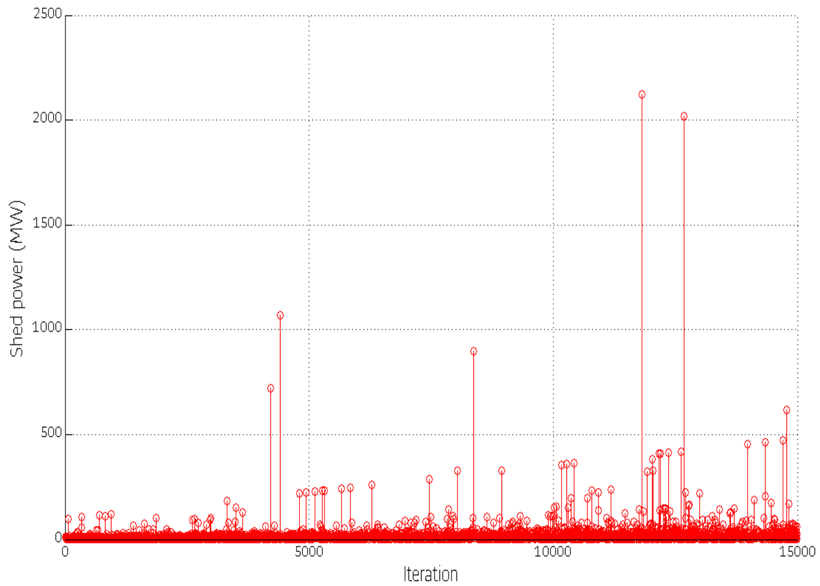
λ : not used (linear variations of power demand)	$\alpha_k = 1$	$\beta = 100$
$\Delta P_D^{\min} = 0.01\,\%\ of \sum_{j=1}^{N_L} P_{D_j}$	$\Delta P_G^{\min} = 0$ (no generation power re-dispatch is allowed)	$\kappa = 2\,\%$ (not be used in day-ahead analysis)
$\mu_i = 1.05$	$\mu_a = 1.50$	$\tau_a = 150\ iterations$
$p_{f_r}^0 = 0.0015$ for $r \in [1 \ \cdots \ N_B]$	$p_{f_r}^1 = f(L_r)$ |	$L_r^{th} = 0.99$ for $r \in [1 \ \cdots \ N_B]$
$r_P = 5$	$r_T = 5$	$Nb_{iter} = 15000$

GRID | ALSTOM

Day 1: Simulation results for N-k contingency



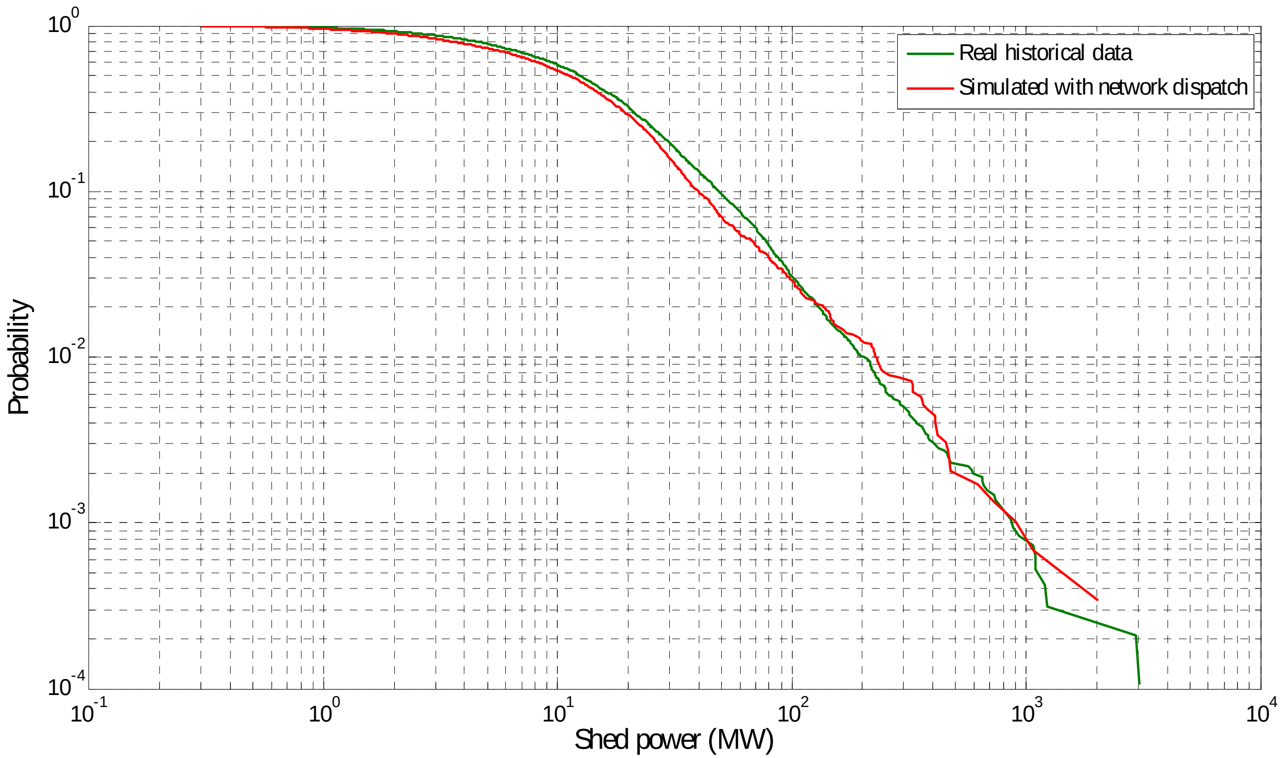
Evolution of total load power demand and total available generation power (SOC process)



Distribution of shed power demand (N-k) contingency, “network dispatch)

GRID ALSTOM

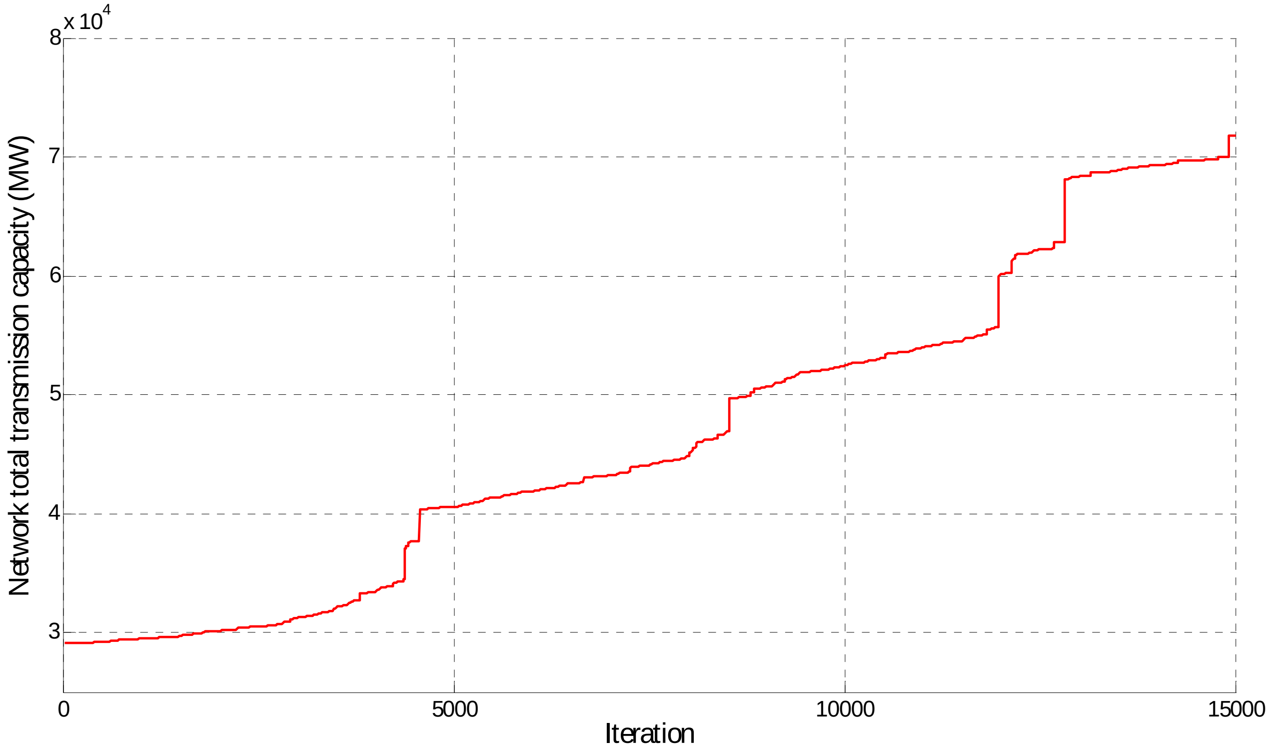
Day 1: Simulation results for N-k contingency



CDF of shed power demand

GRID ALSTOM

Day 1: Simulation results for N-k contingency

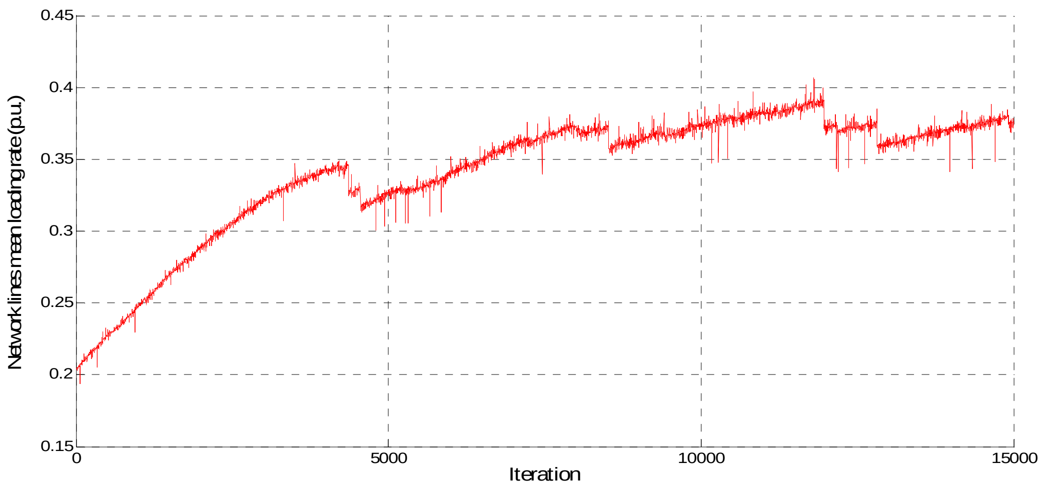


Network total transmission capacity (SOC process)

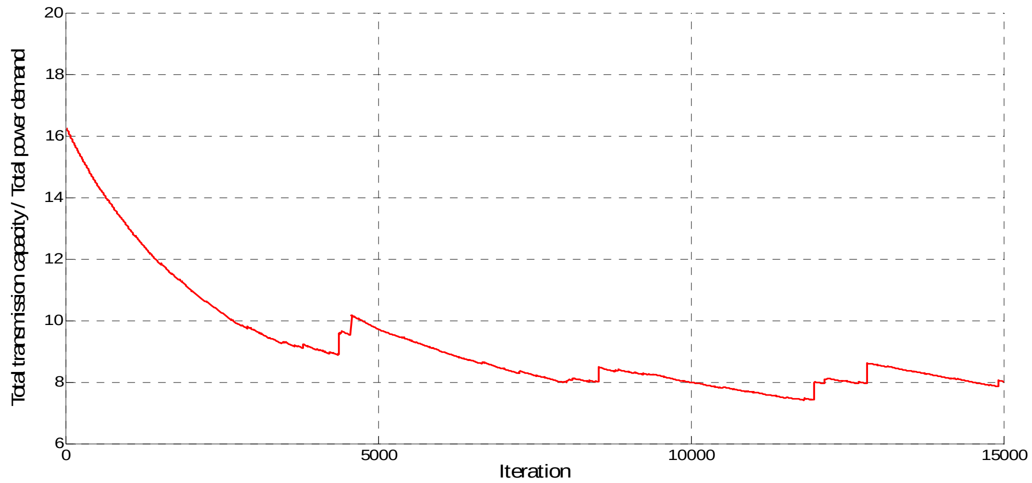
GRID ALSTOM

Day 1: Simulation results for N-k contingency

Evolution of network lines mean loading rate (SOC parameter τ)



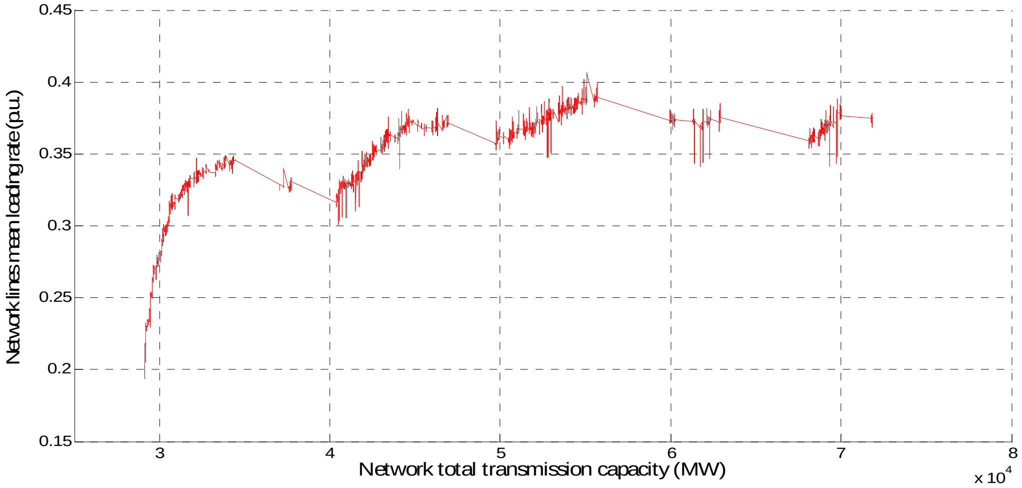
Evolution of the ratio total transmission capacity over total power demand (SOC parameter γ)



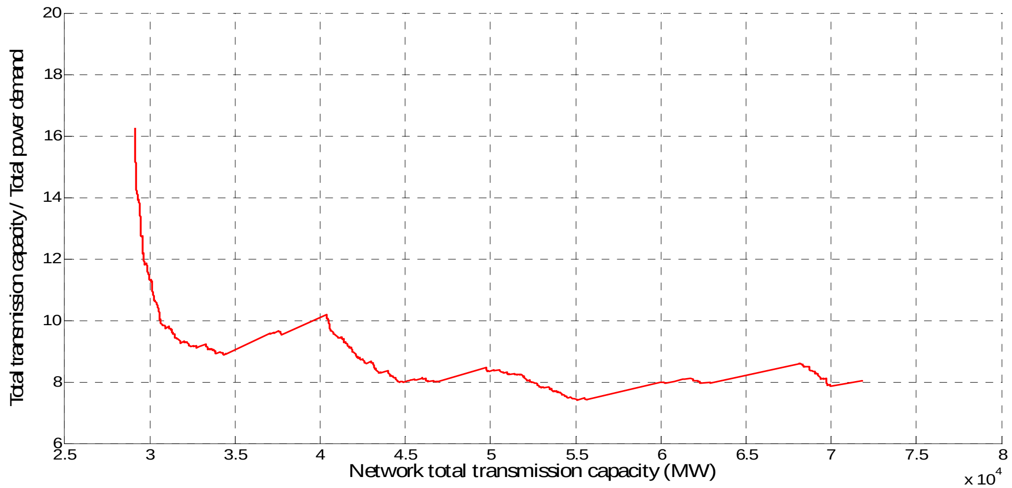
GRID ALSTOM

Day 1: Simulation results for N-k contingency

Normalized evolution of network lines mean loading rate (τ) / network total transmission capacity



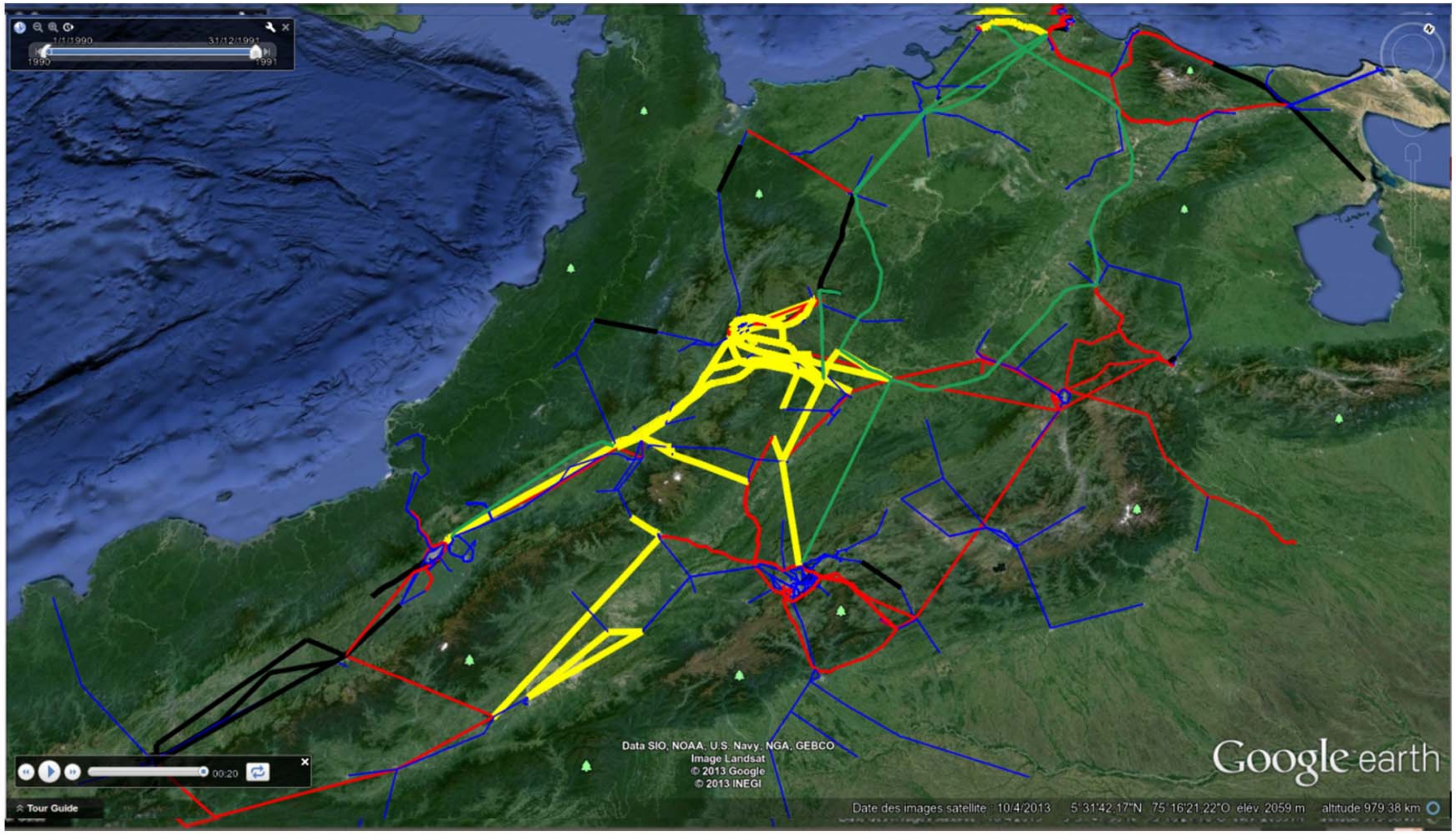
Normalized evolution of the ratio total transmission capacity over total power demand (γ) / network total transmission capacity



GRID ALSTOM

Cascading phenomena

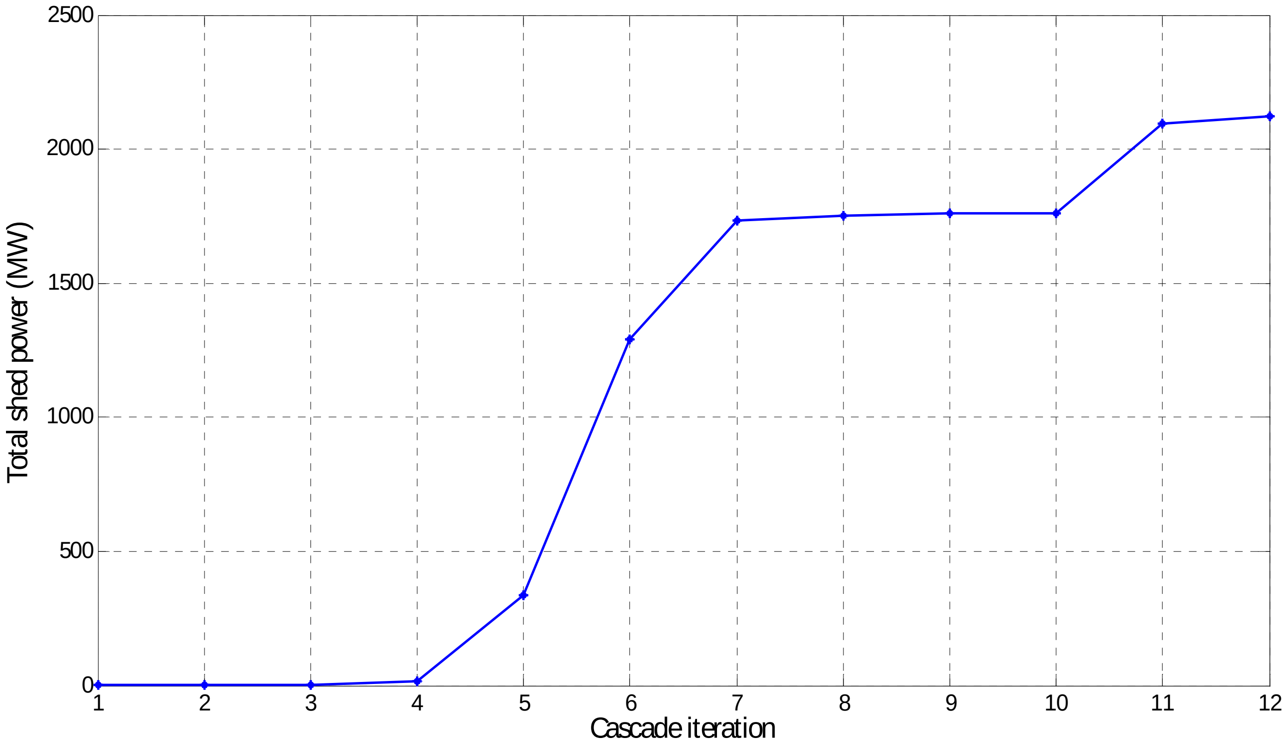
2013/10/13



GRID ALSTOM

Day 1: "Network Dispatch": Fast dynamics cascade analysis

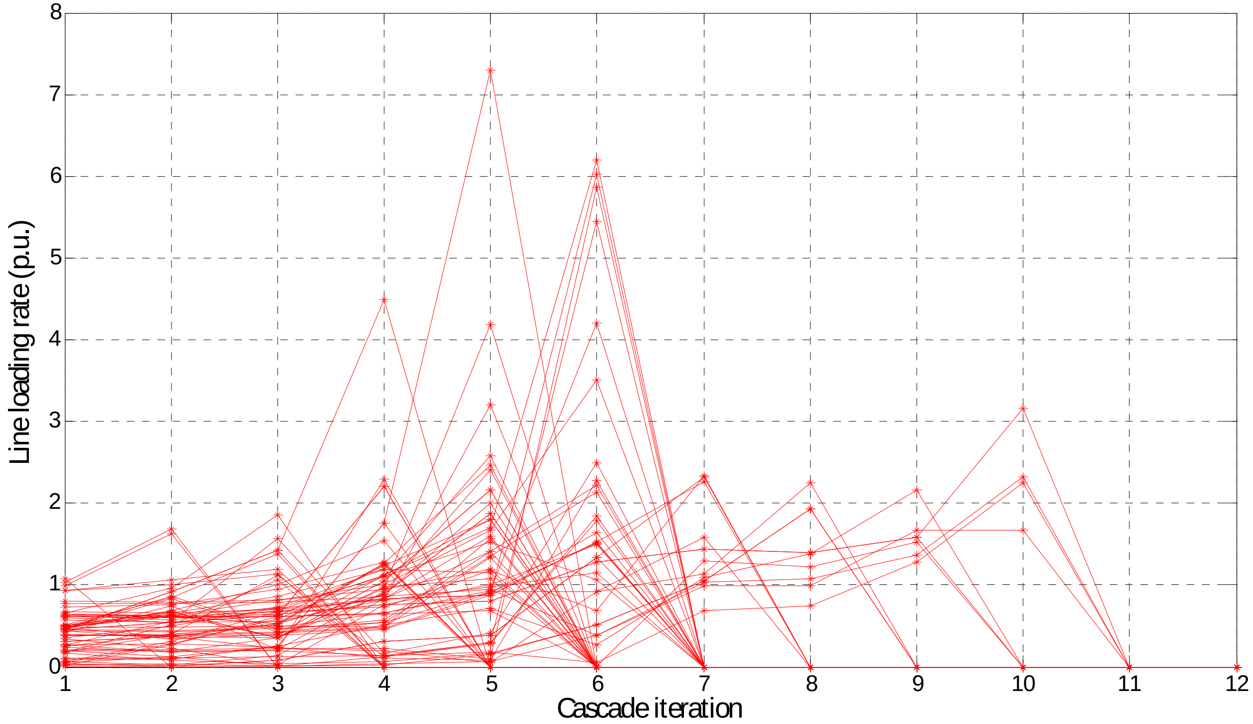
Particular case: Iteration 11815 $\Delta P_D = 2121\,MW$



Evolution of network total shed power demand during cascade sequence

GRID | ALSTOM

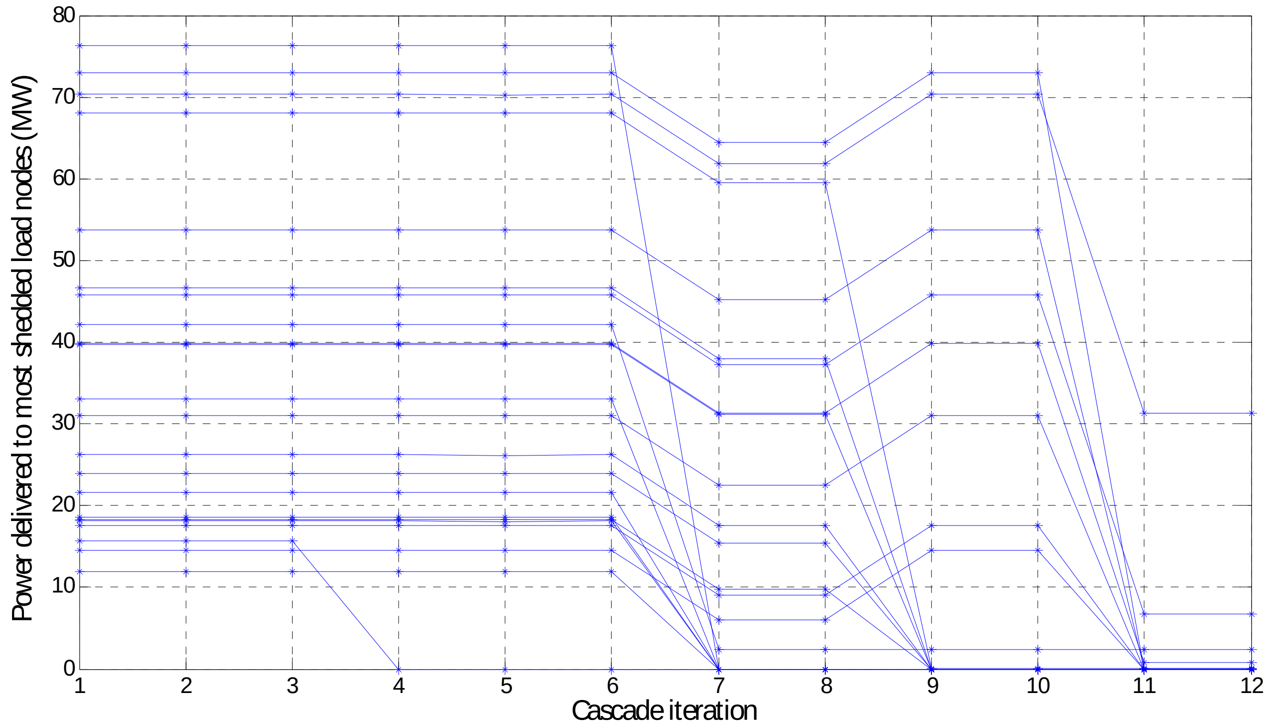
Day 1: "Network Dispatch": Fast dynamics cascade analysis



Evolution of loading rate of lines tripped during cascade sequence

GRID | ALSTOM

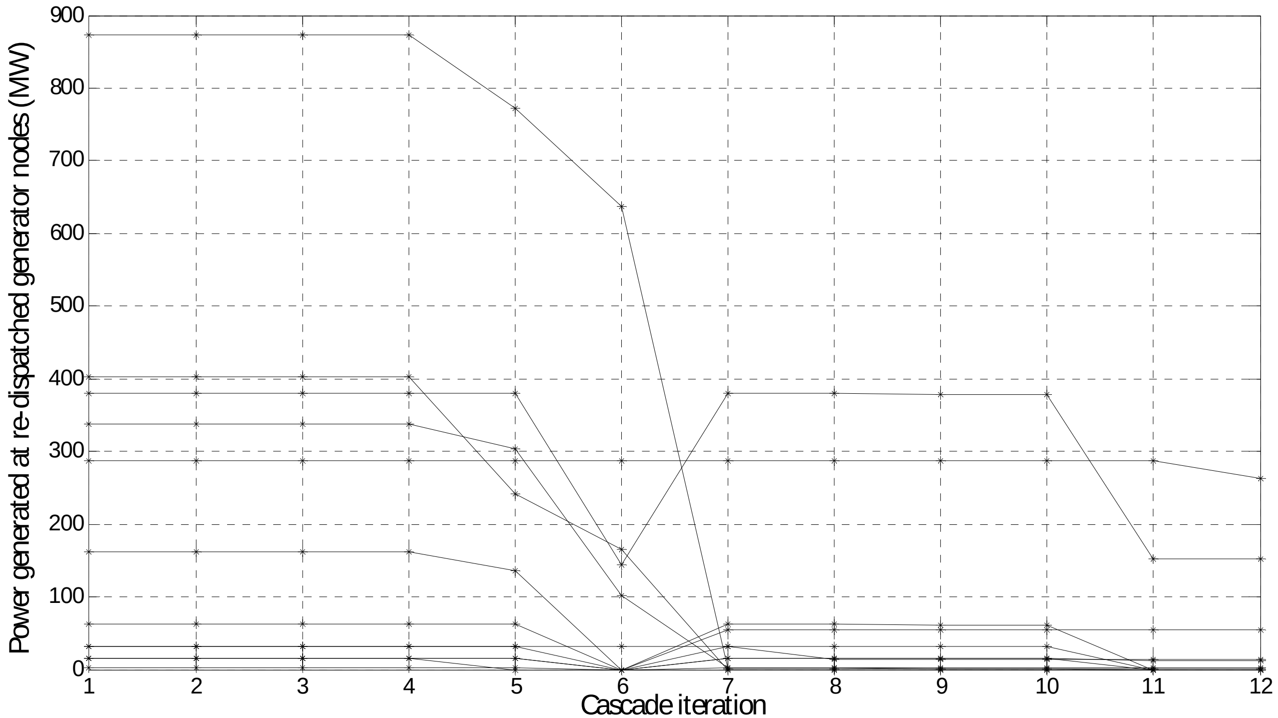
Day 1: "Network Dispatch": Fast dynamics cascade analysis



Evolution of power delivered to most shed load nodes: $\Delta P_{D_j} \geq 10MW$

GRID ALSTOM

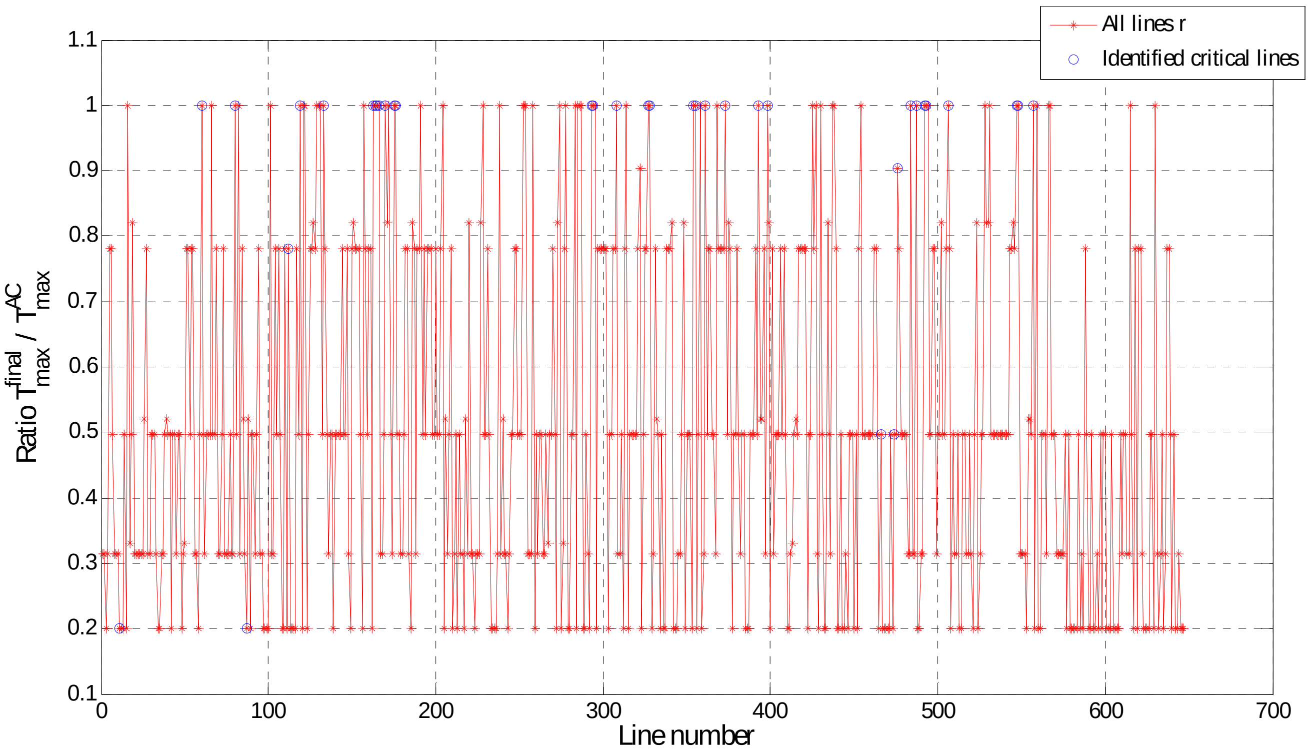
Day 1: “Network Dispatch”: Fast dynamics cascade analysis



Evolution of generation power produced at each re-dispatched generator nodes

GRID ALSTOM

Day 1: "Network Dispatch": Fast dynamics cascade analysis



Evolution of the ratio $T_{\max}^{final} / T_{\max}^{AC}$ for each line

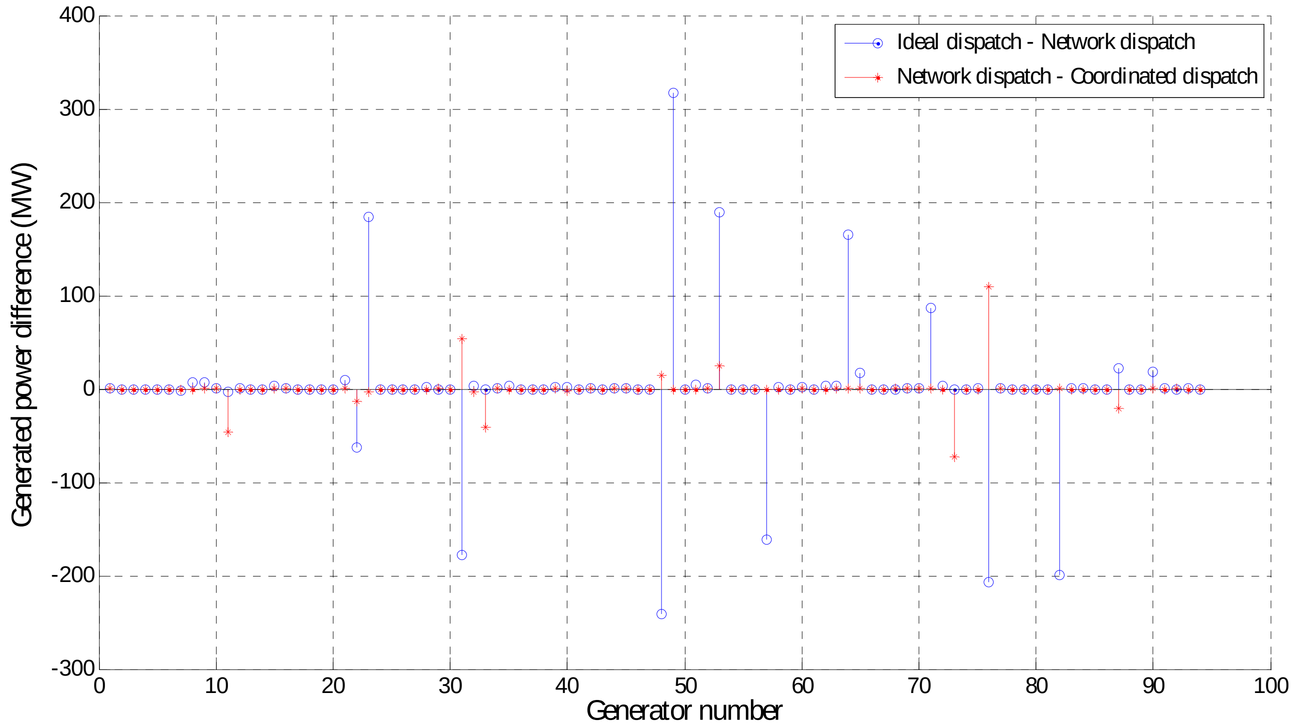
GRID ALSTOM

Day 1: "Network Dispatch": Fast dynamics cascade analysis

Line number	Line number	Line number	Line number	Line number	Line number
11	133	175	328	398	492
60	***163***	176	354	***466***	493
80	***164***	293	355	474	506
87	165	294	361	***476***	547
112	166	***308***	373	484	548
119	170	327	393	***487***	557

Day 1: "Network Dispatch": Fast dynamics cascade analysis

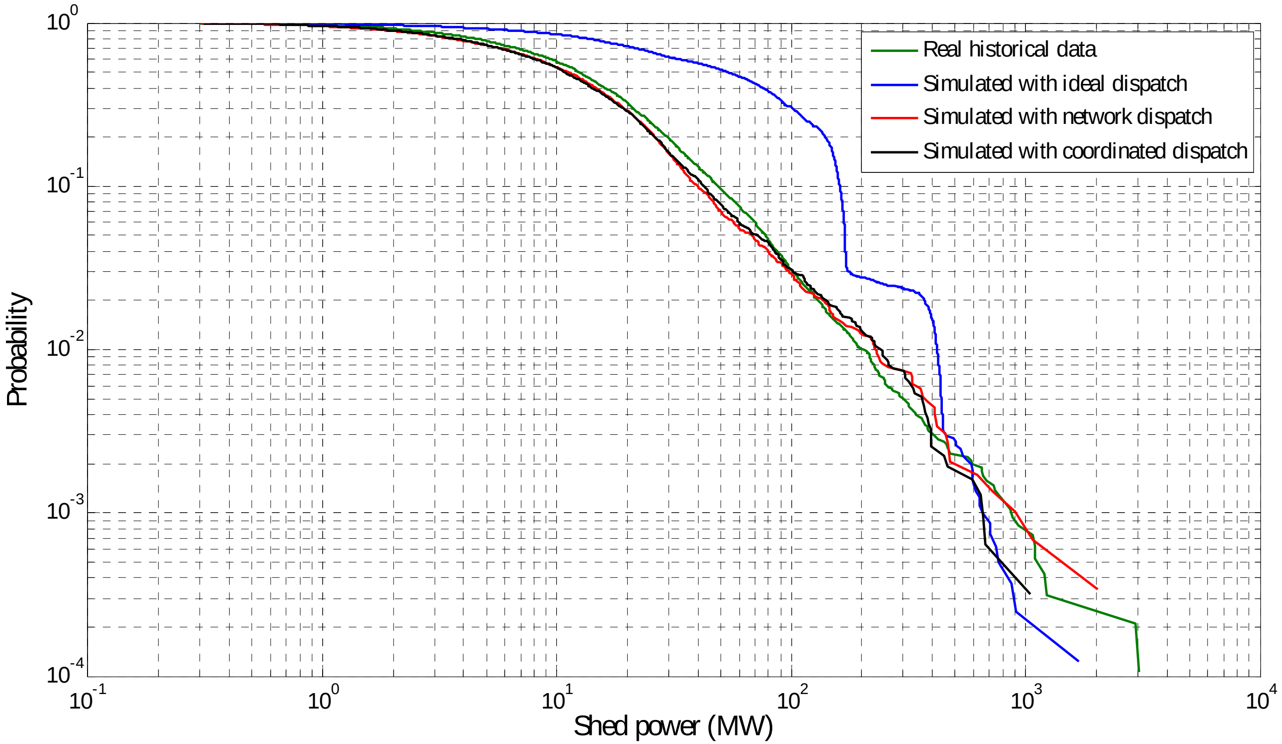
Comparison of the three dispatches



- 11.9% generated power modification from "Ideal" to "Network"
- 2.3% generated power modification from "Network" to "Coordinated"

GRID | ALSTOM

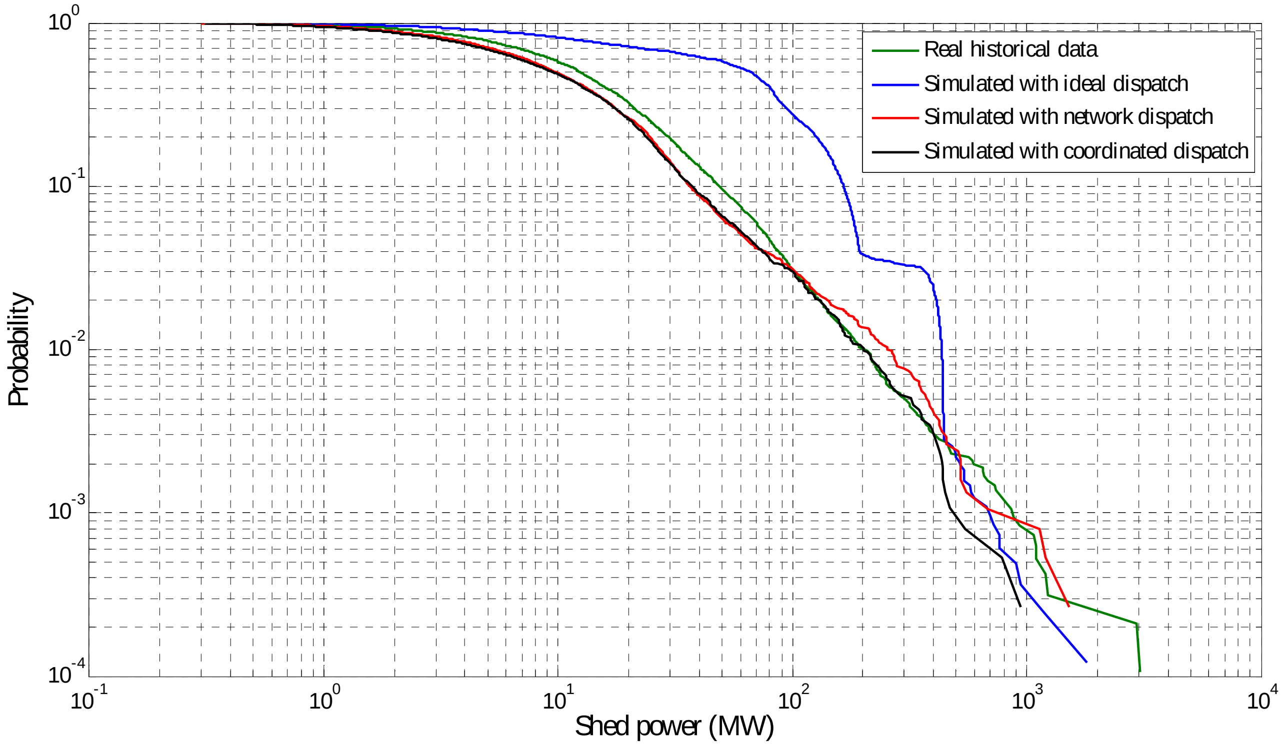
Day 1: "Network Dispatch": Fast dynamics cascade analysis



Comparison of shed load power demand distributions: N-k contingencies

GRID | ALSTOM

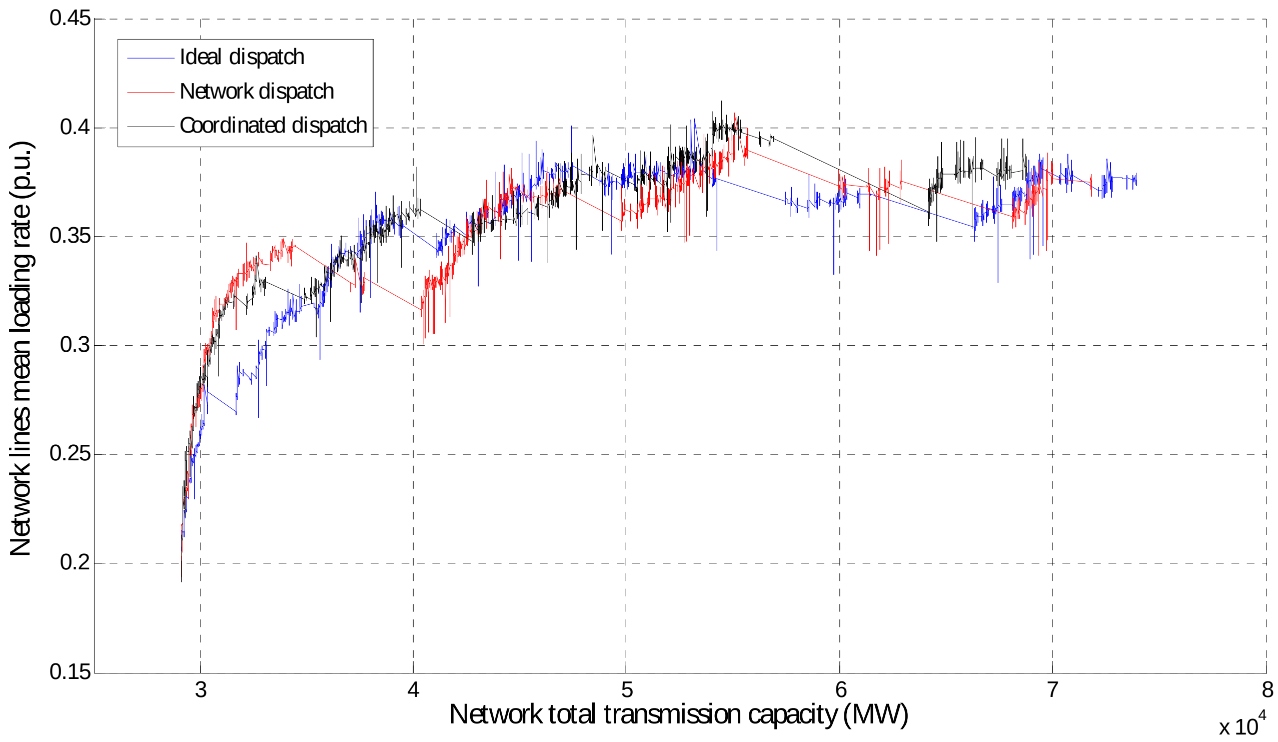
Day 1: "Network Dispatch": Fast dynamics cascade analysis



Comparison of shed load power demand distributions: N-1 contingencies

GRID ALSTOM

Day 1: "Network Dispatch": Fast dynamics cascade analysis

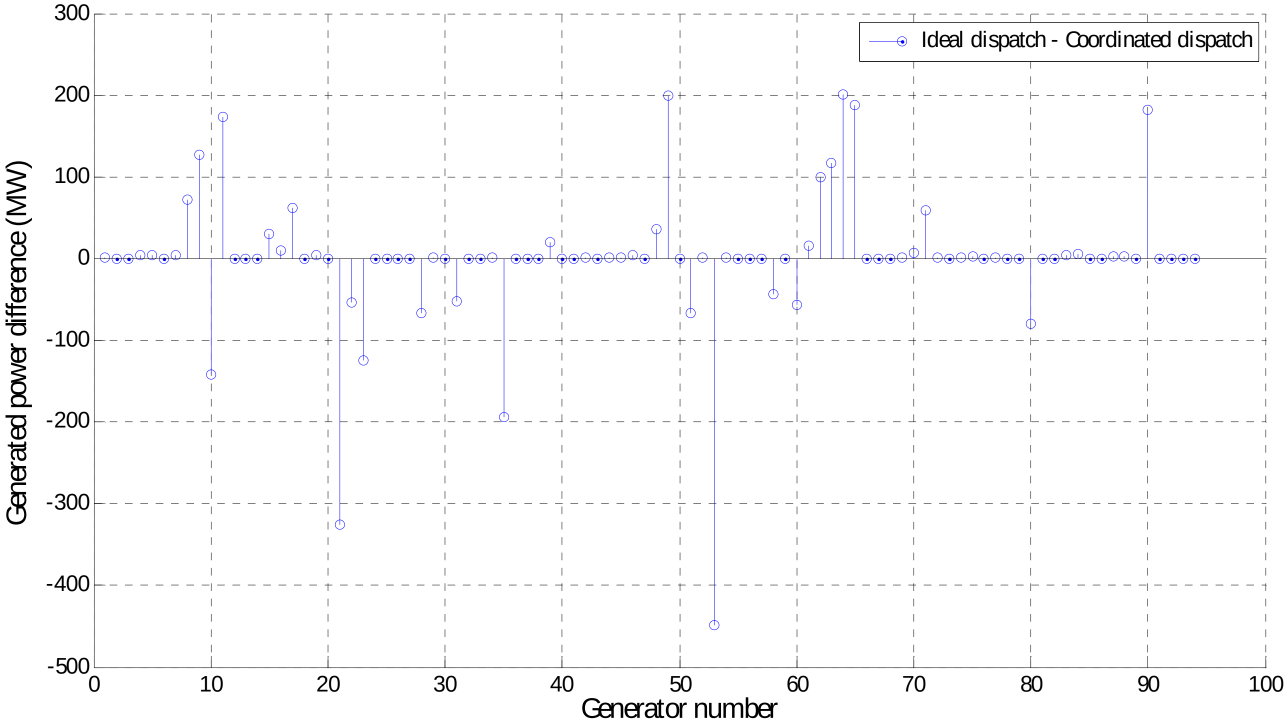


$\tau_{SOC} \approx 0{,}38$

Comparison of SOC condition characteristics parameters

Day 2: Day-ahead successive generation dispatches

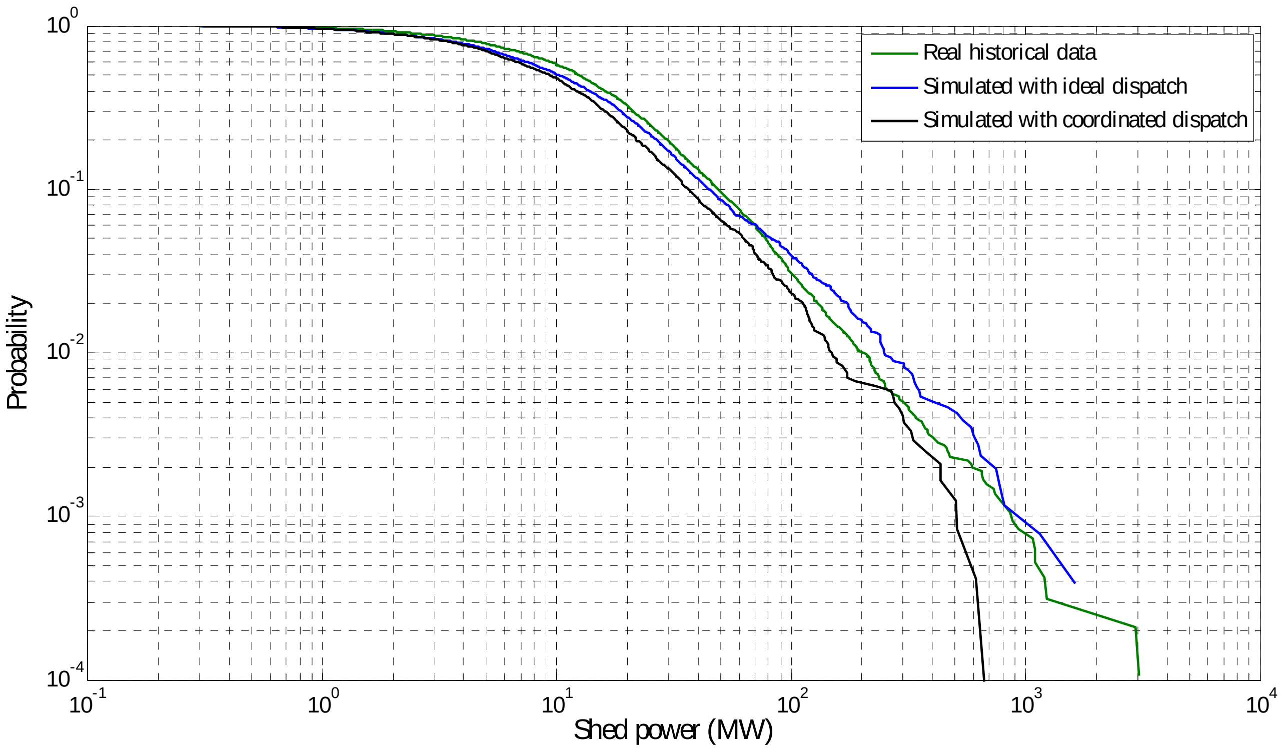
Comparison of the two dispatches



21.8% generated power modification from “Ideal” to “Coordinated”

GRID ALSTOM

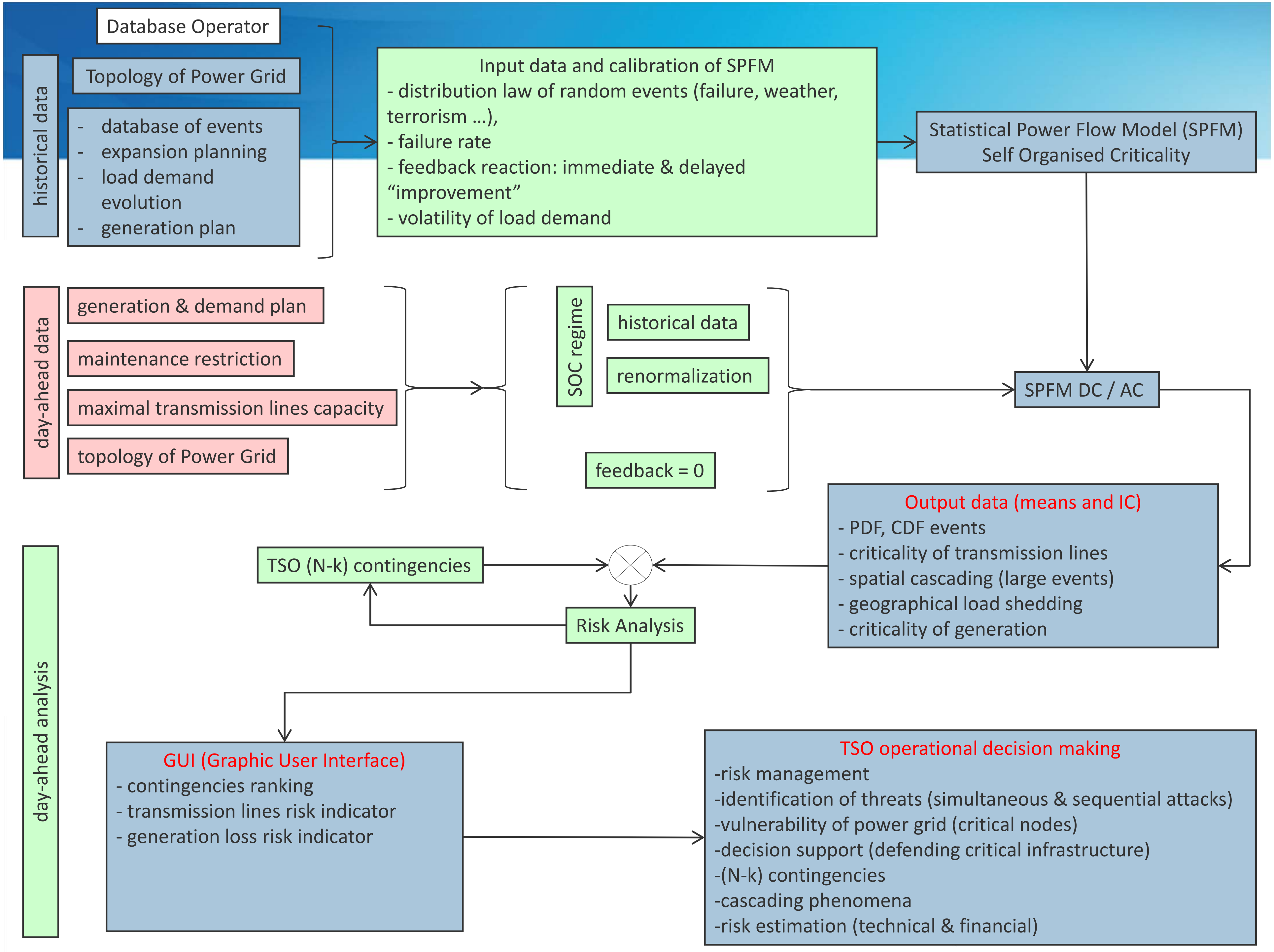
Day 2: Day-ahead successive generation dispatches

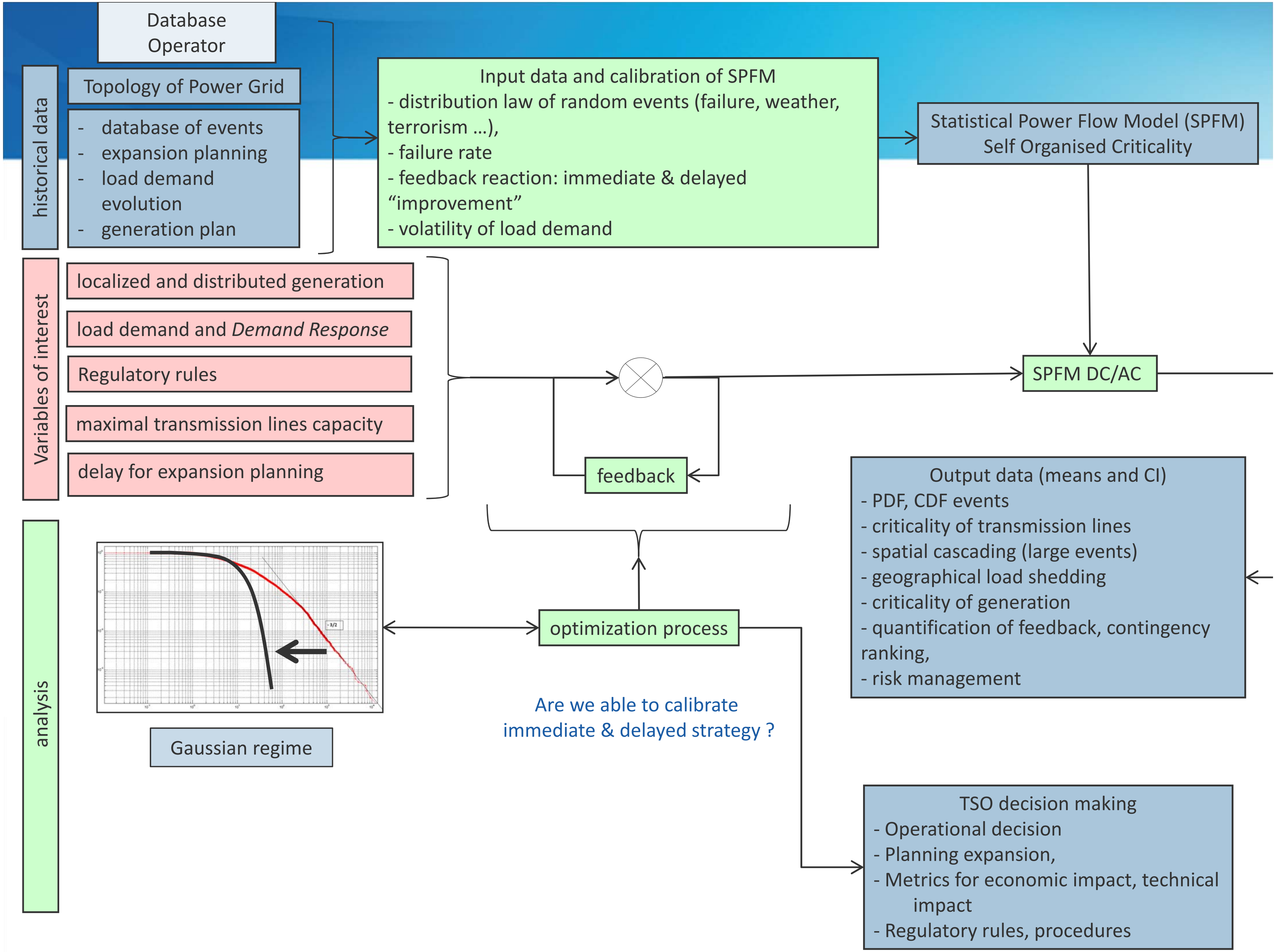


Comparison of shed load power demand distributions: N-k contingencies

Line number	Line number	Line number	Line number	Line number	Line number
27	82	227	318	398	476
29	125	308	327	418	507
67	165	313	361	473	630

GRID ALSTOM


Database Operator
historical data
Topology of Power Grid
- database of events
- expansion planning
- load demand evolution
- generation plan
Input data and calibration of SPFM
- distribution law of random events (failure, weather, terrorism …),
- failure rate
- feedback reaction: immediate & delayed "improvement"
- volatility of load demand
Statistical Power Flow Model (SPFM)
Self Organised Criticality
day-ahead data
generation & demand plan
maintenance restriction
maximal transmission lines capacity
topology of Power Grid
SOC regime
historical data
renormalization
feedback = 0
SPFM DC / AC
Output data (means and IC)
- PDF, CDF events
- criticality of transmission lines
- spatial cascading (large events)
- geographical load shedding
- criticality of generation
TSO (N-k) contingencies
Risk Analysis
day-ahead analysis
GUI (Graphic User Interface)
- contingencies ranking
- transmission lines risk indicator
- generation loss risk indicator
TSO operational decision making
-risk management
-identification of threats (simultaneous & sequential attacks)
-vulnerability of power grid (critical nodes)
-decision support (defending critical infrastructure)
-(N-k) contingencies
-cascading phenomena
-risk estimation (technical & financial)


Database Operator
historical data
Topology of Power Grid
- database of events
- expansion planning
- load demand evolution
- generation plan
Input data and calibration of SPFM
- distribution law of random events (failure, weather, terrorism …),
- failure rate
- feedback reaction: immediate & delayed “improvement”
- volatility of load demand
Statistical Power Flow Model (SPFM)
Self Organised Criticality
Variables of interest
localized and distributed generation
load demand and *Demand Response*
Regulatory rules
maximal transmission lines capacity
delay for expansion planning
feedback
SPFM DC/AC
Output data (means and CI)
- PDF, CDF events
- criticality of transmission lines
- spatial cascading (large events)
- geographical load shedding
- criticality of generation
- quantification of feedback, contingency ranking,
- risk management
analysis
Gaussian regime
optimization process
Are we able to calibrate immediate & delayed strategy ?
TSO decision making
- Operational decision
- Planning expansion,
- Metrics for economic impact, technical impact
- Regulatory rules, procedures