A Modelling Framework for Quantitative Analysis of Interdependencies in Electrical Power Systems

in the context of the EU CRUTIAL project

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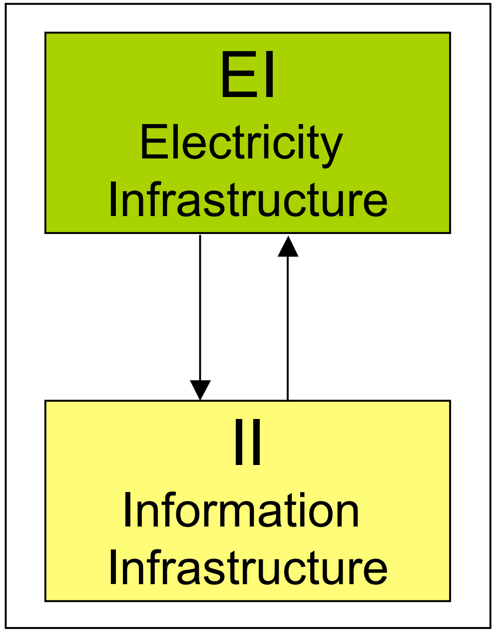
Objective

- Define a conceptual **modeling framework** well suited to characterize and analyze the **interdependencies** between
    - the information infrastructure
    - the controlled power infrastructure
- The focus is on **interdependence-related failure**:
    - Cascading failures
    - Escalating failures
    - Common-cause failures
- The goal is to **quantitatively assess** their impact on the resilience of these infrastructures
- The aim is to have a **general evaluation framework**, populated by building blocks, representing basic events, and composable to potentially represent any EPS configurations

Hierarchical modeling framework for the quantitative evaluation of interdependencies



EI

Electricity Infrastructure

II

Information Infrastructure

- Capture structural and behavioral aspects of EI and II components
- Major modelling framework characteristics:
  - Hierarchical composition using reusable generic submodels
  - Different formalisms for different submodels
  - Discrete and hybrid state representation
  - Performability measures for quantifying the impact of interdependencies
  - Combination of analytical and simulation solution techniques

Feasibility studies

Two directions:

- Investigation of the framework’s feasibility using the multi-formalism, multi-solution tool Möbius and SAN formalism
- Development of an ad-hoc simulator, as a useful support to better understand specific phenomena

Investigation of the framework's feasibility using Möbius and SAN

The basic modeling mechanisms have been implemented using **Stochastic Activity Networks** and **Möbius** tool, focusing on:

- ☐ **Electrical Infrastructure components:**
  - **Nodes** (Substations, Generators and Loads)
  - **Power Lines**
  - **Protections**
- ☐ **Information Infrastructure components:**
  - **Local operations RS_1()** (performed by LCS), and
  - **Global operations RS_2()** (performed by RTS)
  - **TSOcomNetw**: public or private network

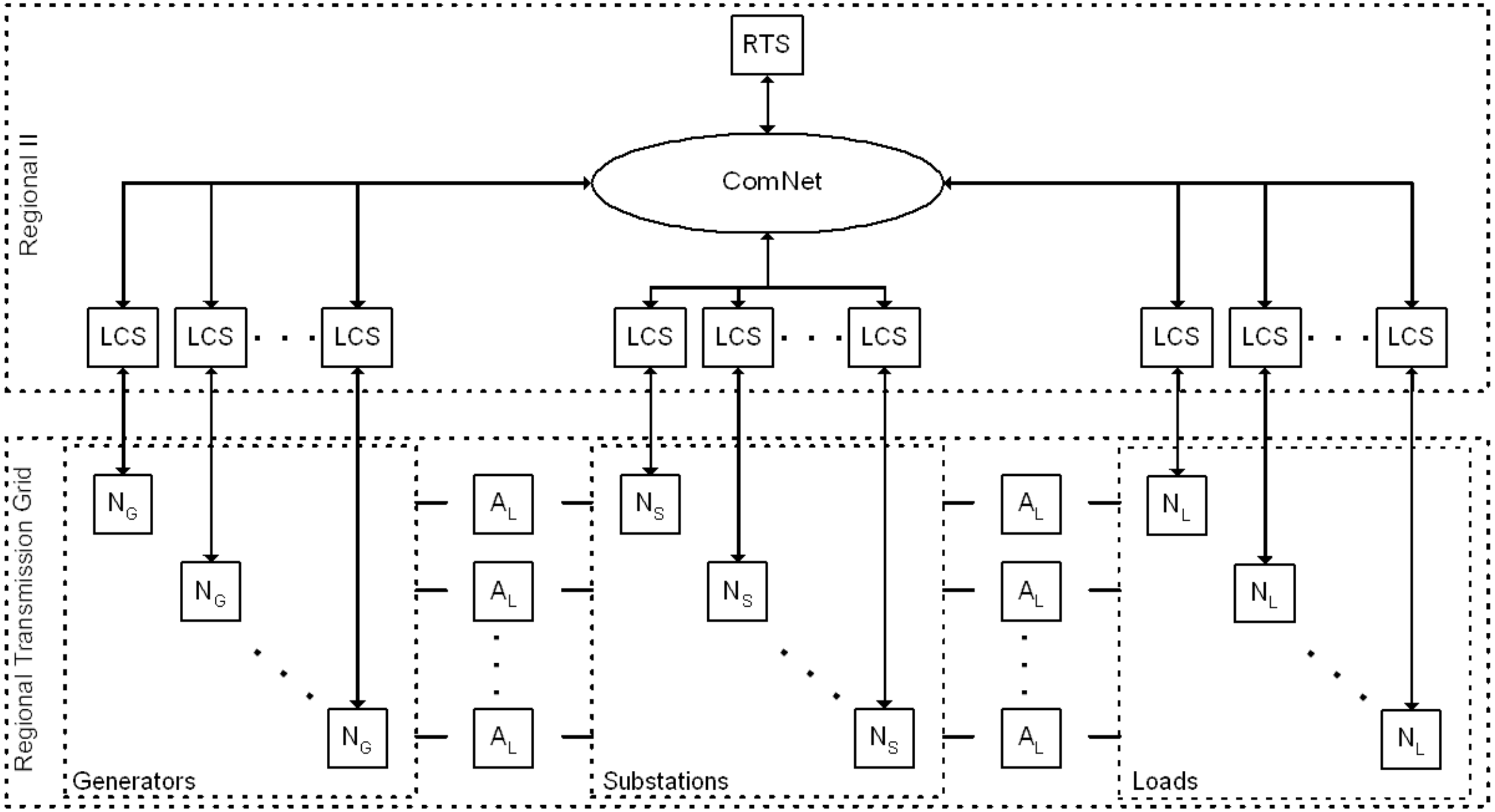
And accounting for

- Power overload and propagation
- EI components failures
- II components failures

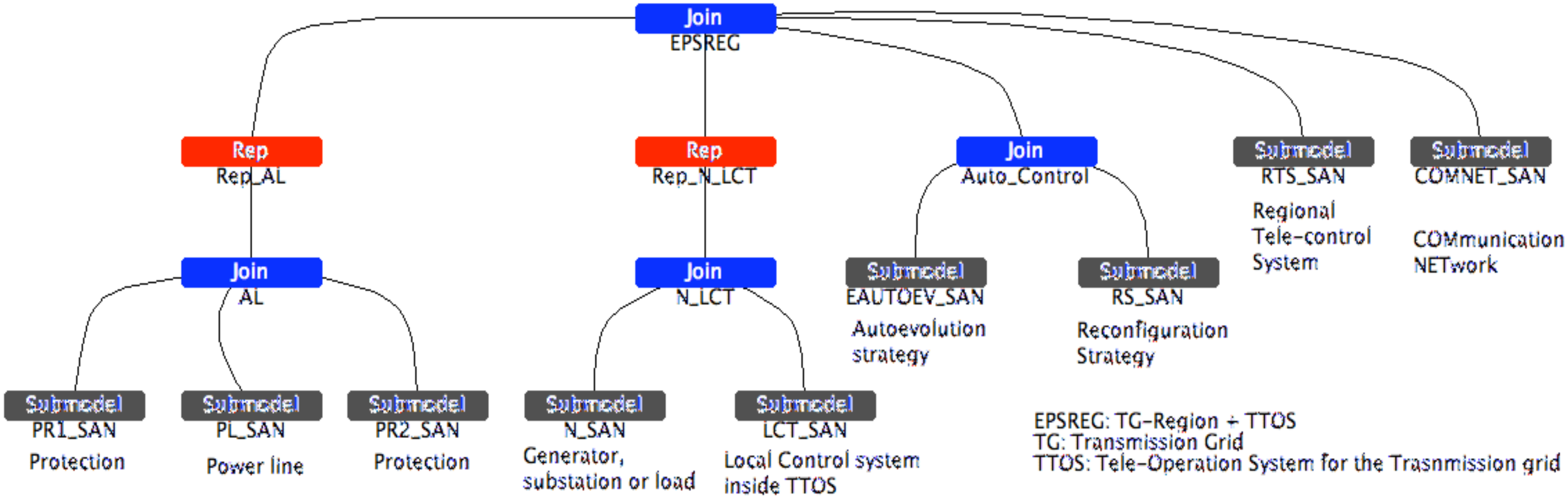
Major assumptions

- The EI state is determined by the equations for the DC power flow approximation (derived from the standard AC circuit equations), which give a linear relationship between:
  - the power at the nodes and
  - the power flow on the lines
- The definition of **RS_1()** and **RS_2()** depends on the policies and algorithms adopted by II. They are obtained by solving a linear programming problem
  - The new state determined by **RS_1()** is suboptimal wrt **RS_2()** (being based on local information);
  - **RS_1()** completes in time **$T_1=0$**, while **RS_2()** in time **$T_2>0$**

Logical structure of the analyzed EPS instance



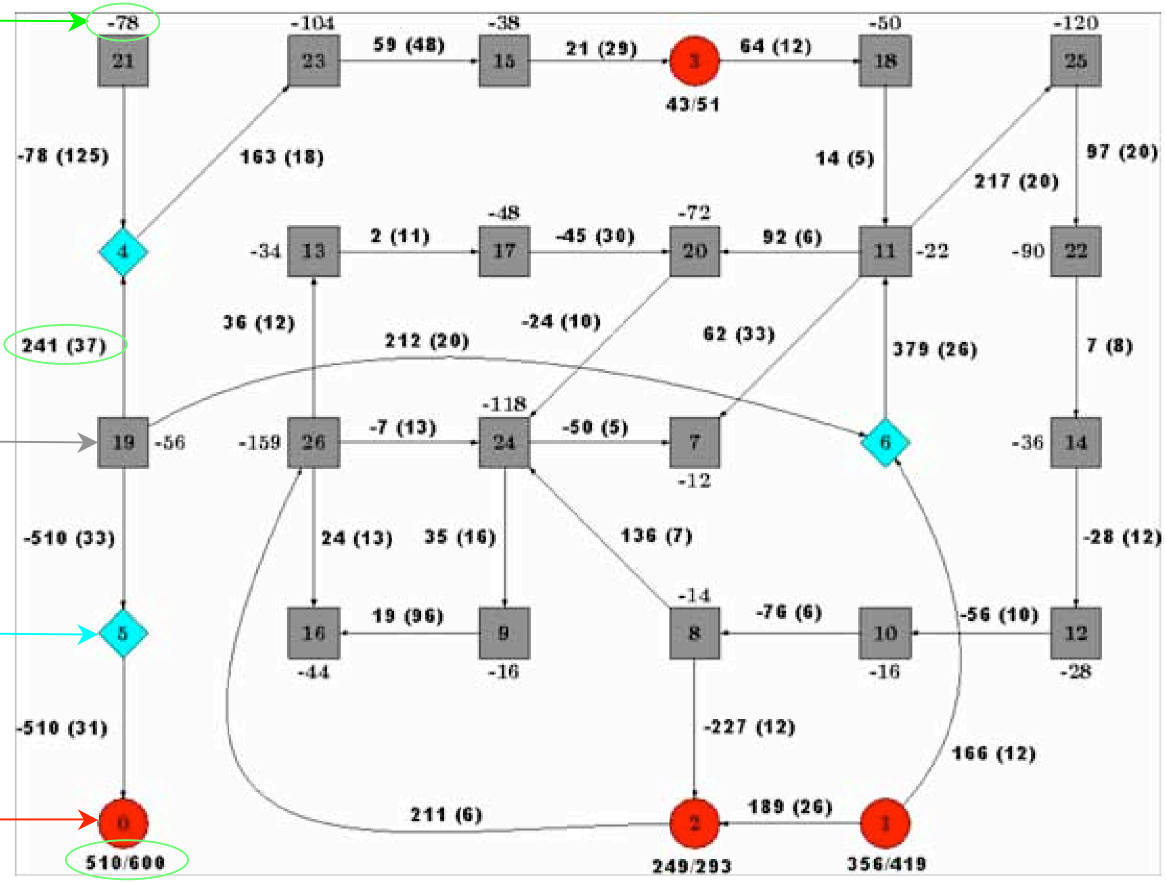
The Composed Model



EPSREG: TG-Region + TTOS
TG: Transmission Grid
TTOS: Tele-Operation System for the Trasnmission grid

- Rep_AL: nA not anonymous replicas of the model AL
- Rep_N_LTC: nN not anonymous replicas of the model N_LCT
- The submodels interact through common places

Diagram of the EI grid (a portion of the IEEE 118 Bus Test Case)



Load demanded

Initial power flow (Susceptance)

Loads

Substations

Generators

Initial power / Maximum power

Maximum power flow through the lines = 620

Measure of interest

- **$P_{UD}(t,t+1)$**: *percentage of the mean power demand that is not met in the interval [t,t+1]* hours

  (the symbol 'UD' stands for 'Unsatisfied Demand').

  It is a user-oriented measure of the blackout size and can be obtained as the load shed (i.e., the not served power due to a load shedding) divided by the power demand.

Analyzed scenario

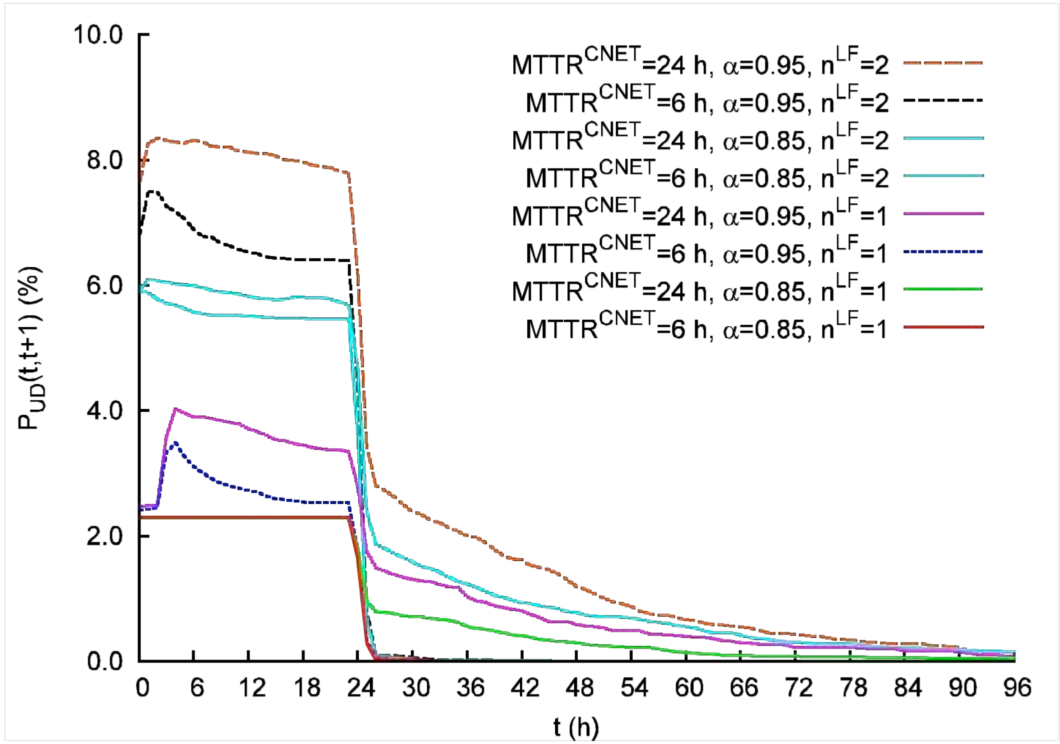
GOAL: assess the impact of the **omission failure of the communication network** (ComNet) on $P_{UD}(t,t+1)$ when a **simultaneous failure of a set of transmission lines** is occurred. More in detail:

- The grid starts in electrical equilibrium.
- At time zero, **n^{LF} power lines are simultaneously affected by a permanent failure** (e.g., due to a tree fall or a terrorist attack), thus becoming unavailable.
  - The power lines that fail are randomly (*uniformly*) selected from the set of all available power lines.
  - All the failed power lines are (*deterministically*) repaired after 24 hours.
- At the same time zero, **ComNet is simultaneously affected by a denial of service (DoS) attack**.
  - The DoS attack ends after an *exponentially* distributed time with mean $MTTR^{CNET}$, and from that time RTS can start computing the RTS reconfiguration action that will be (*deterministically*) applied after 10 minutes.

Sensitivity analysis campaign

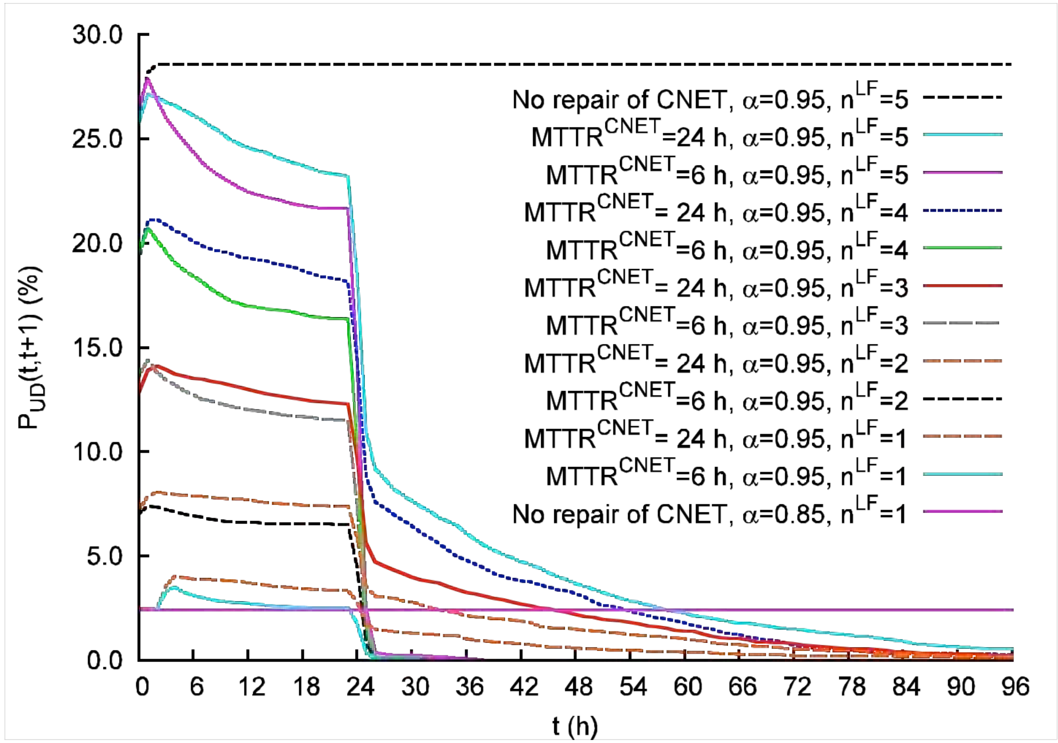
- A sensitivity analysis has been performed on the following parameters:
  - $MTTR^{CNET}$, thus **varying the duration of the DoS attack** affecting the communication network. If $MTTR^{CNET}$ goes to infinity, then we are modeling a RTS omission failure.
  - n^{LF}, thus **varying the severity of the overall EI failure**.
  - α, thus **varying the initial stress level of the power grid**.
    - ✓ For each generator i, α is defined as the ratio P_i/P_i^{max}.
    - ✓ In the initial grid setting all the ratios P_i/P_i^{max} are equal to a fixed value $\alpha=0.85$.

$P_{UD}(t,t+1)$,with t=0,1,…,96 h., for different values of $MTTR^{CNET}$ (6,24 h.), n^{LF} (1,2) and α (0.85,0.95)



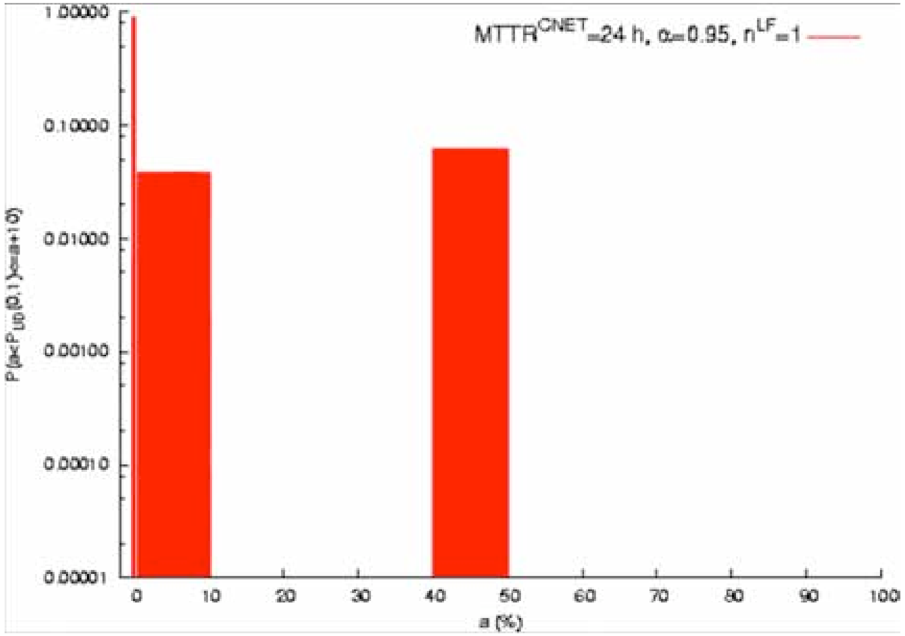
- ☐ Unless for the lowest curves (α=0.85, n^{LF}=1), the failure of even a single line at time zero produces and increment of $P_{UD}(t,t+1)$ until the reconfiguration is applied.
- ☐ At t=24 hours there is a big improvement (the failed power lines are repaired).
- ☐ The impact of the system stress level α is less heavy than the failure of power lines

$P_{UD}(t,t+1)$,with t=0,1,…,96 hours, for different values of $MTTR^{CNET}$ (6,24 h.) and n^{LF} (1,…,5), fixing α=0.95



- $P_{UD}(t,t+1)$ increases considering higher n^{LF} values, and fixing the value for n^{LF}, $P_{UD}(t,t+1)$ gets worse in the case in which the DoS attack has a longer duration (24 hours).
- After 24 hours the disrupted power lines are repaired, and consequently $P_{UD}(t,t+1)$ rapidly decreases until reaching the zero value.
- The top most curve represents the case of RTS omission failure

Probability that $P_{UD}(0,1)$ is in the interval (a,a+10]%, with a=0,10,…,90, fixing α=0.95, n^{LF}=1 and $MTTR^{CNET}$=24 hours



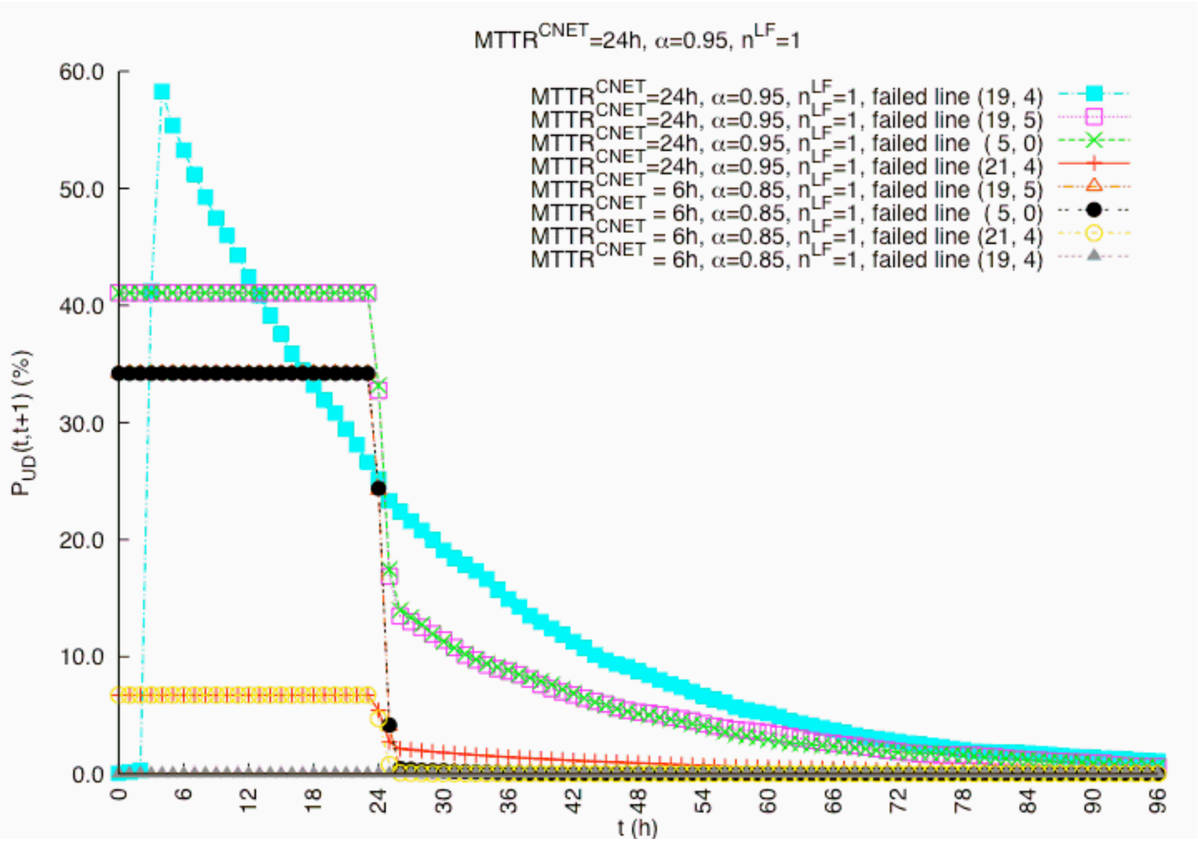
From the analysis of the previous figures, we know that **$P_{UD}(0,1)\approx2.5$**.

Analyzing its complete distribution we note that:

- with a very high probability the percentage of undelivered power is equal to zero;
- $P_{UD}(0,1)$ is in the interval (0,10]% with a probability of about 0.05, and it is in the interval (40,50]% with a probability of about 0.07;
- all the other probabilities are almost zero.

A mean loss of 40-50% of delivered power in the first hour of the system can happen, for example, when the power line affected by the failure is directly connected to a generator.

$P_{UD}(t,t+1)$ at varying the failed power line, with $t=0,1,\ldots,96$ hours, for different values of $MTTR^{CNET}$ (6,24 h.) and α (0.95, 0.85)



- **Only power lines for which $P_{UD}(t,t+1) > 0$ are displayed**
- **Allows to determine critical power lines**

Ongoing and future work

- Detailed analysis and description of the EI grid's evolution through observing simulation runs
- Extension of the experimental campaign
  - by including the failures of other EI components
    - ✓ e.g., protections
  - by including other kinds of failures
    - ✓ e.g., lightning affecting power lines
  - by introducing other patterns of components failures
    - ✓ e.g., sequences of clusters of simultaneous failures
  - by enriching the set of measures of interest for the analyses
    - ✓ e.g., time to reach a certain black-out level
    - ✓ e.g., number of failed power lines/nodes in a certain interval of time