Interdependency Analysis in Electric Power Systems

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Outline

- Context and objectives
- The analyzed Electrical Power System instance
  - ✓ The electrical infrastructure
  - ✓ The Information technology based control system
- The Interdependencies between EI and ITCS
- The SAN model of the EPS instance
- The analyzed case study and measure of interest
- The results of the analyses
- Final considerations and future developments

The context

- Economy, security and quality of life increasingly depend on the resiliency of a number of **critical infrastructures**
- **Interdependencies** increase vulnerability of CI, as they give rise to multiple error propagation channels from one infrastructure to another

→ **Analysis of infrastructures components interactions is crucial to understand and characterize interdependencies**

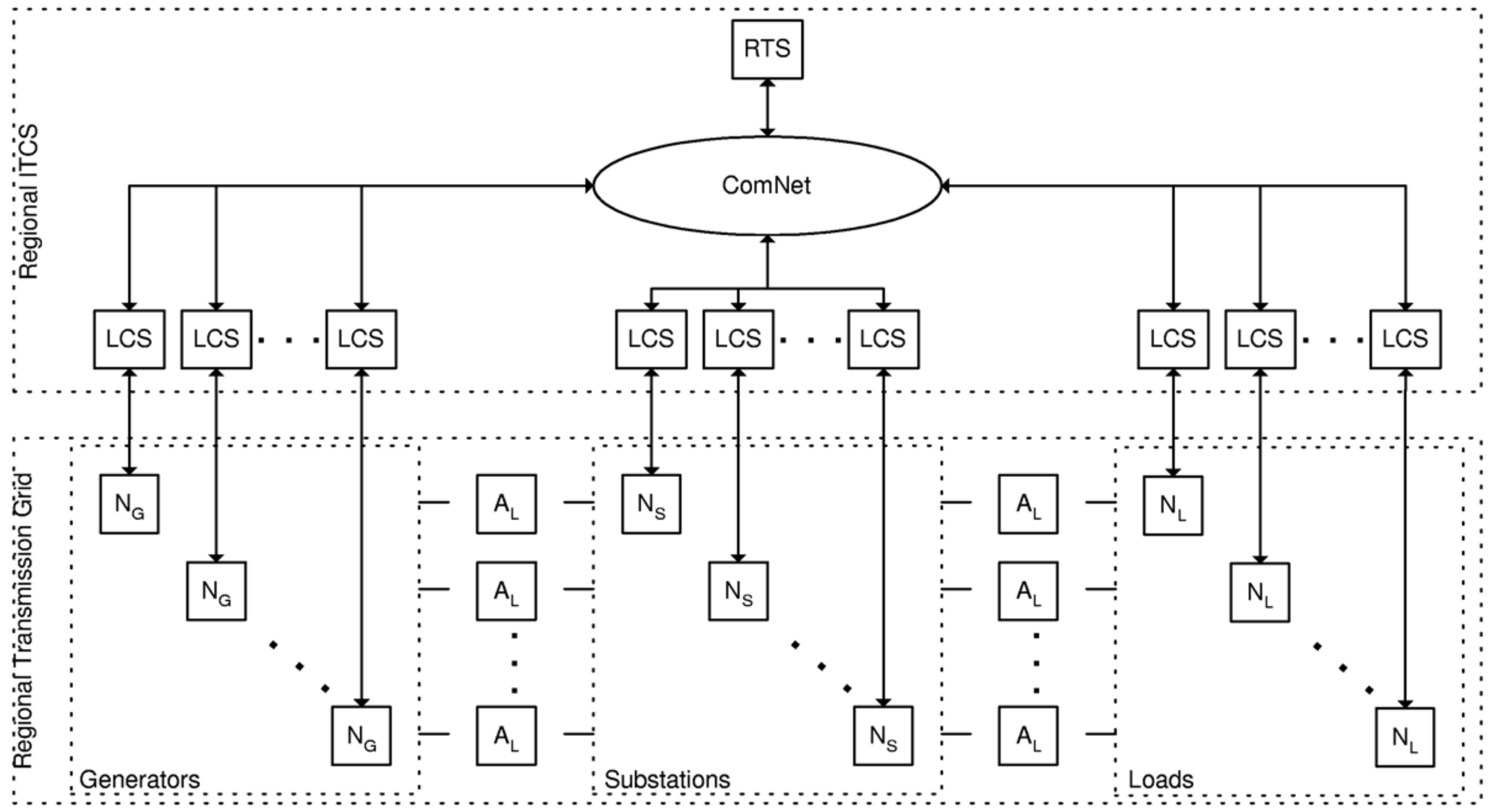
- **Electrical Power Systems** are prominent representatives of CI
- Interdependencies between the electrical power grid (**EI**) and the control system infrastructure (**ITCS**) have been responsible of major power grid blackouts
- The EU STREP 027513 **CRUTIAL** project is addressing the analysis and management of interdependencies and of the resulting operational risk

Objective

- Define a conceptual **modeling framework** well suited to characterize and analyze the **interdependencies** between
  - the information infrastructure
  - the controlled power infrastructure
- With focus on **interdependence-related failures**
- Aiming at **quantitatively assessing** their impact on the resilience of EPS
- Adopting a compositional approach, where building-blocks represent basic components/events, and through their composition potentially any EPS configurations can be represented

- **In this paper**
  - **application of the developed modeling framework to a case study**
  - **to assess a blackout-related indicator**
  - **under different system conditions**

Logical structure of the analyzed EPS instance



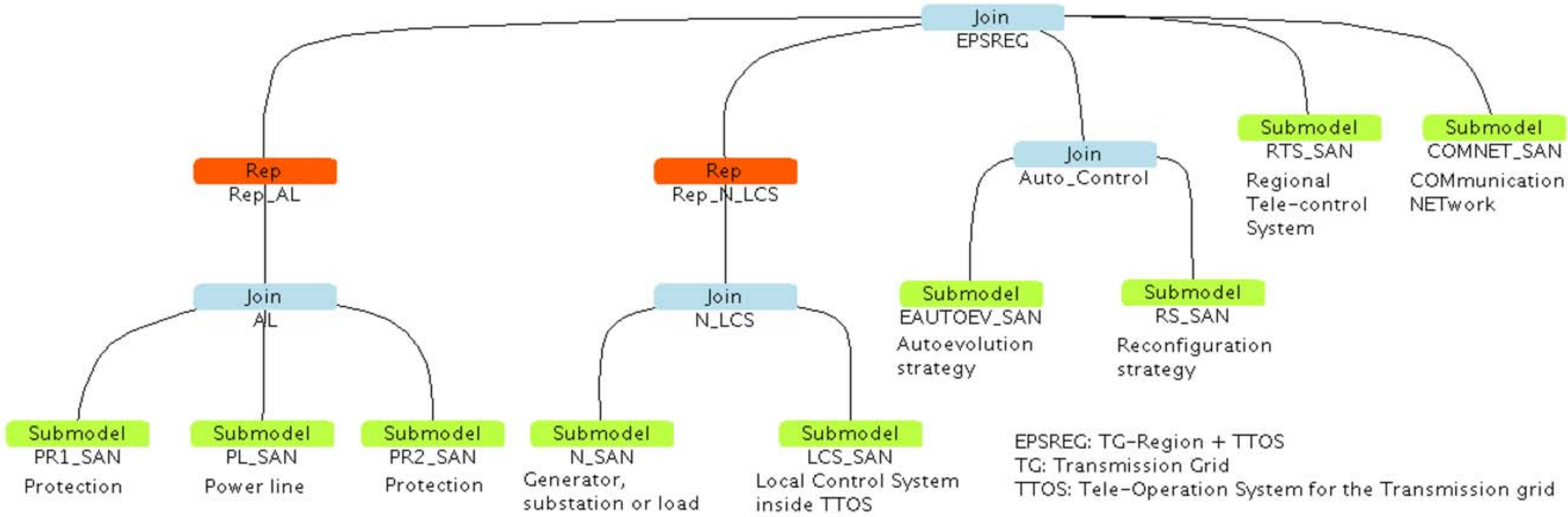
Interdependencies

- S_{ITCS} ➔ S_{EI}
  - Impact on topology and/or the electric values
    - ✓ E.g. a value failure of LCS (incorrect closing or opening of the power line A_L)
- S_{EI} ➔ S_{ITCS}
  - E.g. A failure in the EI causes a partial black-out that could reduce the performance of the private or public networks used by ITCS, or isolate part of the ITCS.
- (S_{EI} and S_{ITCS}) ➔ (S_{EI} or S_{ITCS})
  - E.g. An ITCS component fails (omission failure) and does not isolate an EI component affected by a disruption ➔ the grid topology changes (the disruption propagates and a set of contiguous EI components may become disrupted)

Major implementation assumptions

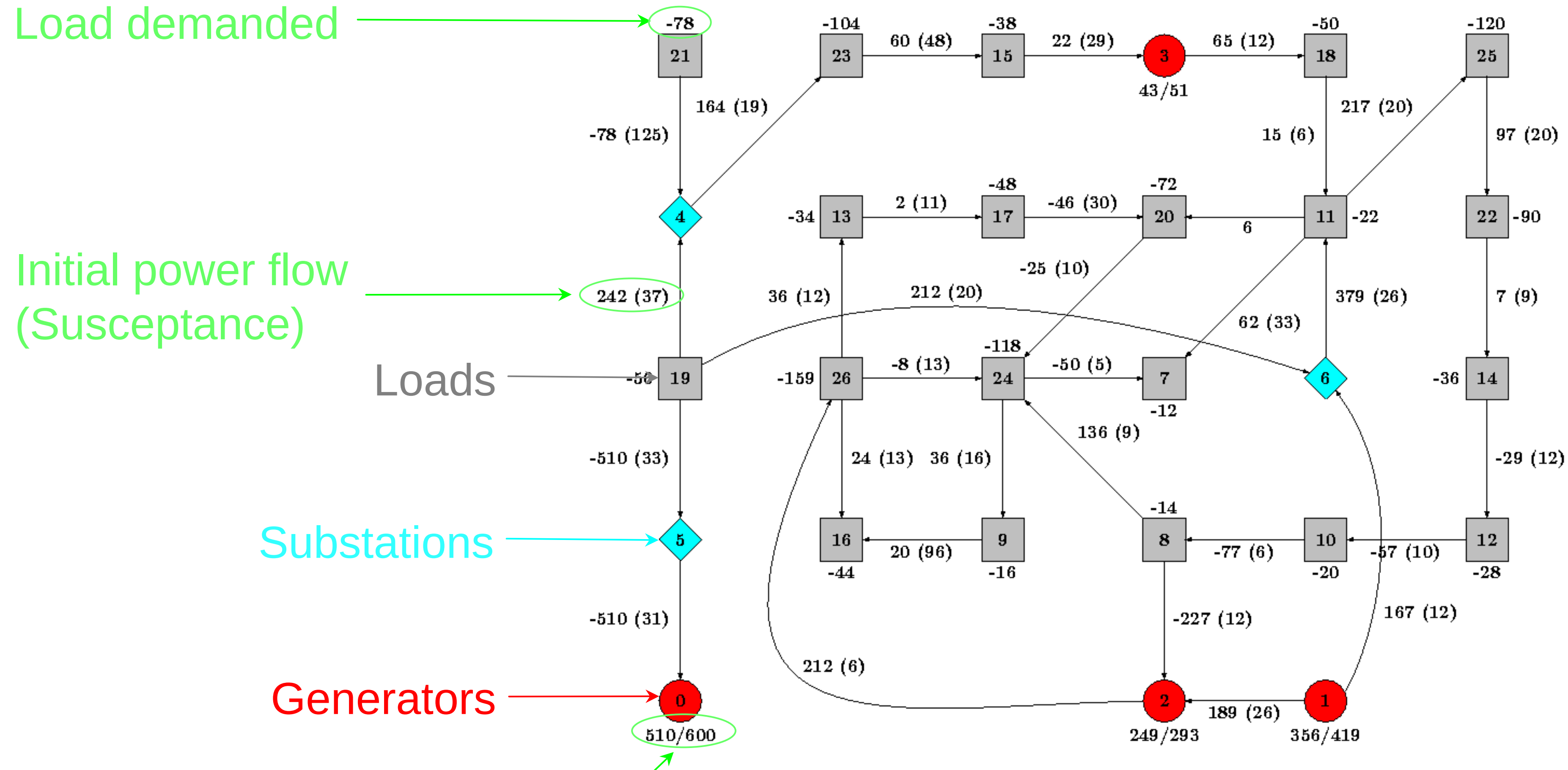
- **On EI:**
  - The EI state and evolution is determined by the equations for the DC power flow approximation (derived from the standard AC circuit equations), which give a linear relationship to assure equilibrium between:
    - ✓ the power at the nodes (generators, loads or substation) and
    - ✓ the power flow on the lines
- **On ITCS:**
  - **Local operations** performed by LCS **are represented by the reconfiguration function $RS_1()$,** while
  - **Global operations** performed by RTS **are represented by the reconfiguration function $RS_2()$**
  - definition of **$RS_1()$** and **$RS_2()$** depends on the policies and algorithms adopted by the Regional ITCS. They are obtained by solving a linear programming problem while minimizing a cost function
    - ✓ 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 **$T_2>0$**

The Composed Model using Möbius and SAN



- Rep_AL: nA non anonymous replicas of the model AL
- Rep_N_LCS: nN non anonymous replicas of the model N_LCS
- The submodels interact through common places

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



Line overload if power flow >= 620 MW

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 has been obtained as the load shed (i.e., the not served power due to a load shedding) divided by the power demand.

Analyzed scenario

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

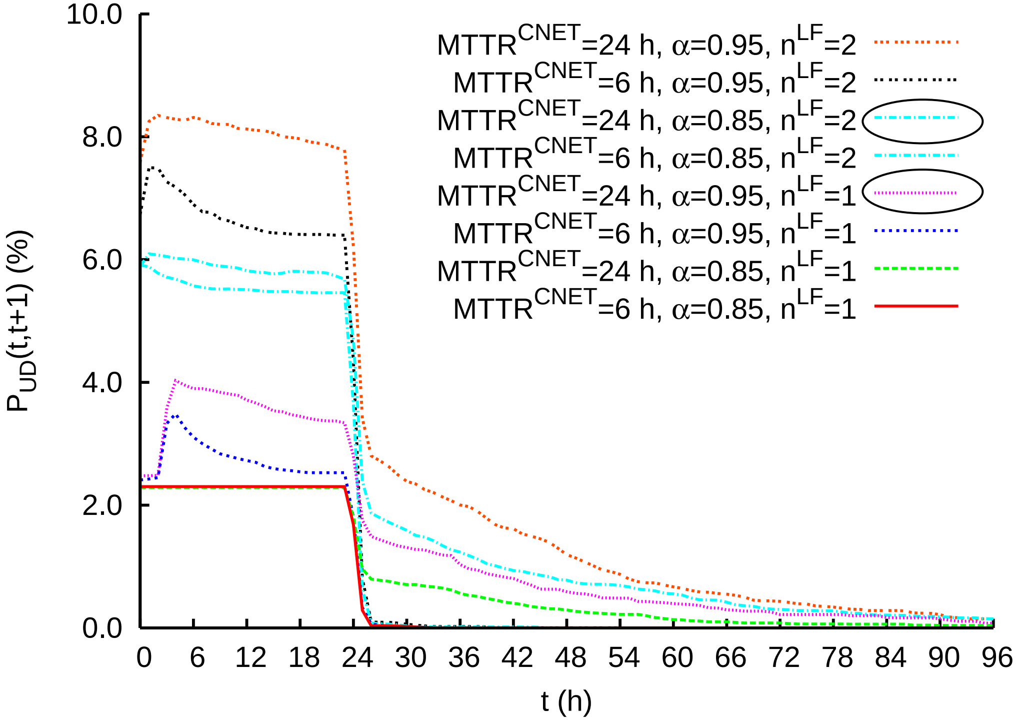
More in detail:

- 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

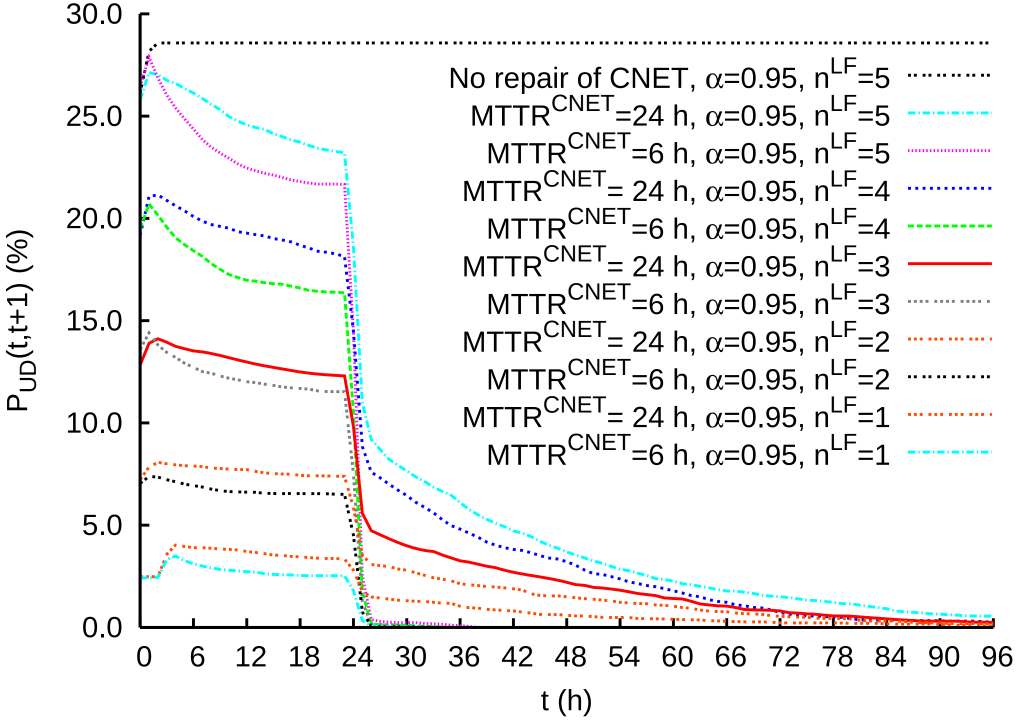
- A sensitivity analysis has been performed on the following parameters:
  - $MTTR^{CNET}$, thus **varying the duration of the DoS attack** affecting the communication network. $MTTR^{CNET}$ induces a delay on RTS operation (RTS omission failure).
  - n^{LF}, thus **varying the severity of the overall 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 α=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)



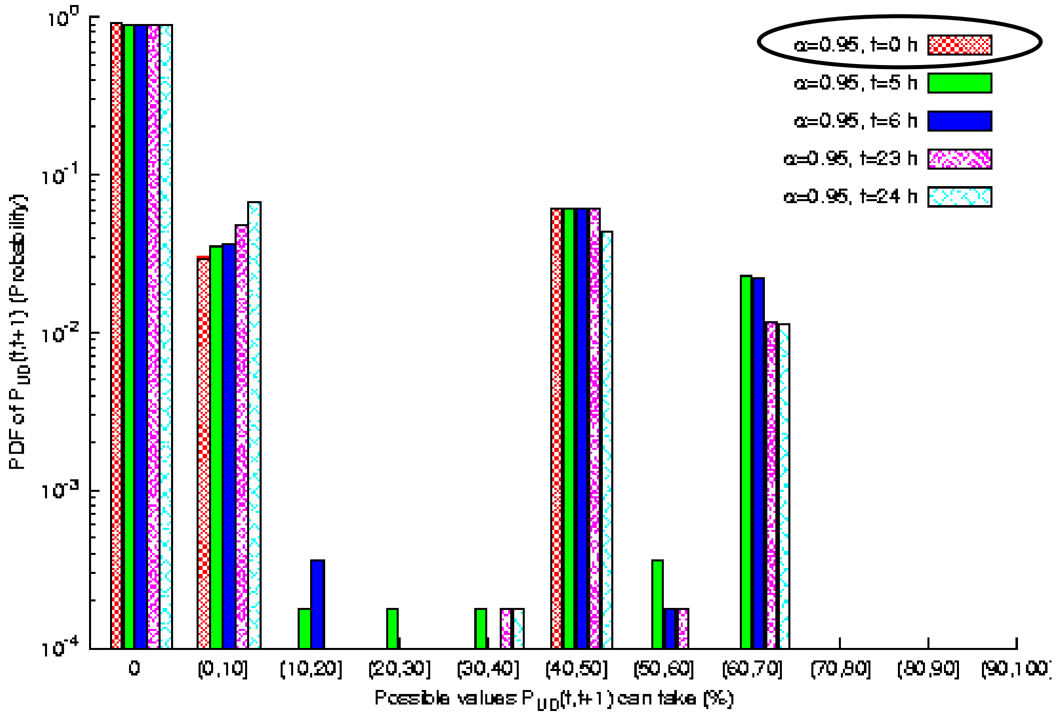
- The failure of even a single line produces and immediate increment of $P_{UD}(t,t+1)$ due to lines overloading and to too big variation of power demand to generators in a small interval of time.
- At t=24 hours there is a big improvement (the failed power lines are repaired).
- The impact of the system 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 $P_{UD}(t, t+1)$ is in the intervals (0, 10]%, (10, 20]%, … , (90, 100]%, fixing α=0.95, n^{LF}=1 and $MTTR^{CNET}$=24 hours



From previous figures $\mathbf{P_{UD}(0,1)\approx 2.5}$.

Analyzing its complete distribution:

- with a very high probability the % of undelivered power is zero;
- $P_{UD}(0,1)$ is in (0,10]% with a probability ~0.03, and it is in (40,50]% with a probability ~ 0.06;
- 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.

Some considerations

- The obtained results allow to understand some relevant dynamics in failures propagation and their impact through infrastructures interdependencies.
- ***Such insights can be usefully exploited towards proper system configurations enhancing resiliency and survivability***.
- E.g., the EPS analysis under **different stress levels** is useful to find a **proper configuration of the power grid so to limit the power lines overloading in case of failures**.
- Also, understanding the effect of **repair times** of the communication network allows to **better calibrate repair operations to enhance system availability.**

Conclusions

- We addressed the modeling of EPS and a quantitative assessment of the impact of failures through interdependencies between the information control infrastructure and the controlled electric grid.
- We have modeled an instance of EPS made up of a regional tele-operation system and the local control systems connected to it.
- Simulation analyses have been performed on a portion of the IEEE 118 Bus Test Case, to evaluate the user perceived degradation of the power demand satisfaction under varying failures and system conditions.
- Usefulness of such analyses towards improving system survivability and availability has been briefly discussed

Ongoing and future work

- Simulations to identify the most critical power lines for a given topology
- 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
    - e.g., DoS attacks restricted to the portion of ComNet connecting a subset of LCS
  - 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