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Analysis of cascading failures in power grids via network-based structure-preserving models

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VECTORS - ADVANCED NETWORK CONTROL OF FUTURE SMART GRIDS

Information about the presenter

BIOSKETCH: Mattia Frasca was born in Siracusa, Italy, in 1976. He graduated in Electronics Engineering in 2000 and received the Ph.D. in Electronics and Automation Engineering in 2003, at the University of Catania, Italy. Currently, he is associate professor at the University of Catania, where he also teaches process control and complex adaptive systems. His scientific interests include nonlinear systems and chaos, control of complex networks and bio-inspired robotics. He is involved in many research projects and collaborations with industries and academic centers. He is referee for many international journals and conferences, Associate Editor of the Journal of Complex Networks and Editor of Chaos, Solitons and Fractals. He served as Associate Editor for IEEE Transactions on Circuits and Systems I in 2012-15 and as Associate Editor of the International Journal of Bifurcations and Chaos. He was one of the organizers of the 10th “Experimental Chaos Conference”, co-chair of the 4th International Conference on Physics and Control and chair of the European Conference on Circuit Theory and Design 2017. He is coauthor of one research monograph with Springer, three with World Scientific, and one book on Optimal and robust control and one on Nonlinear Cicruits with CRC Press. He published more than 250 papers on refereed international journals and international conference proceedings and is co-author of two international patents. He is member of the IEEE CAS Education Technical Committee and IEEE CNN Technical Committee. He was selected as member of the IEEE Forum for Leading Researchers, Amsterdam, in 2013. He is the President of the Italian Society for Chaos and Complexity (SICC) and member of the Accademia Gioenia.

Motivation of the work

- Models used in the field of control theory/nonlinear dynamics are sometimes *too simplicistic* to model power networks (cit. power systems engineers)

- Models used in the field of power systems are sometimes *too complicated*, or just *simulation-based* (cit. control engineers/physicists)

- Is there a trade-off? Which issues absolutely need to be incorporated? Can we find a *not-too-complicated*, but yet *realistic* model for power networks and bus/node faults

- We decided to use a structure-preserving model based on Differential Algebraic Equations (DAEs), and to set-up a simulator that could investigate any power network and most common faults

Review of existing models for failures in power grids

Three classes of models

1. Purely topological approaches

2. Static approaches

3. Dynamical approaches

Review of existing models for failures in power grids

1) Purely topological approaches

- This class comprises models that do not incorporate any description of the electrical phenomena taking place in the power grid, but only consider the structural properties of the network of interconnection
- The failure is generally modeled by removing a component of the network, and then investigating what happens in terms of the new load distribution after the failure
- Different assumptions are done to model the loads, either at the level of a node or of an edge of the network
- Sophisticated inter-dependencies between different structures taking into account, for instance, the physical network of the power grid and the overlying communication network have been also addressed using model-based multi-layer structures

Review of existing models for failures in power grids

2) Static approaches

- This class includes models that take into account the physical properties of the power grid, but limited to the steady-state equilibrium

- Two approaches for power flow calculation:
  - DC power flow equations
  - AC power flow equations

- Relying on a quite simple but tractable description of the electrical mechanisms underlying power grids, the models prompt for the definition of optimization-based methods for the identification of the lines leading to the worst-case cascading failures

Review of existing models for failures in power grids

3) Dynamical approaches

- This class comprises models that explicitly take into account the dynamics of the electro-mechanical phenomena occurring in the power grid

- The level of description of these phenomena can vary significantly
  - Some works use a very detailed descriptions of the devices and circuitries involved in the power grid
  - Other works are based on more abstract models, attempting at providing a simplified coarse-grained description of the dynamics of the power grid

- It is of primary importance to reach a trade-off between accuracy of the description and computational efforts for the simulation of the cascades

The structure-preserving model

We consider a network-based, structure-preserving model, explicitly incorporating several protection mechanisms for the line and the bus.

The dynamics of the generators is described by the swing equation

$$\begin{aligned} \dot{\delta}_g &= \omega_g \\ M_g \dot{\omega}_g &= P_{M_g} - \frac{E_g V_g}{x_{d_g}} \sin(\delta_g - \theta_g) - D_g \omega_g \end{aligned}$$

δ_g - generator rotor angle
θ_g - bus angle
M_g - inertia constant
D_g - dumping constant
P_{M_g} - mechanical power
E_g - generator voltage
V_g - bus voltage

The equations for the buses are given by the following algebraic constraints

$$\begin{aligned} 0 &= P_{d_i} - \sum_{j=1}^{N} B_{ij} V_i V_j \sin(\theta_i - \theta_j) \\ 0 &= Q_{d_i} + \sum_{j=1}^{N} B_{ij} V_i V_j \cos(\theta_i - \theta_j) \end{aligned}$$

B_{ij} - coefficient of the admittance matrix
P_{d_i}/Q_{d_i} - active/reactive power

A. R. Bergen and D. J. Hill, "A structure preserving model for power system stability analysis," IEEE transactions on power apparatus and systems, no. 1, pp. 25–35, 1981.

Model of the load

A generic dependence of the terms on the voltage at the node is accounted by the ZIP (or polynomial) model for the load:

$$P_{d_i} = P_{d_i,0}\left(K_Z\left(\frac{V_i}{V_{i,0}}\right)^2 + K_I\frac{V_i}{V_{i,0}} + K_P\right)$$

$$Q_{d_i} = Q_{d_i,0}\left(K_Z\left(\frac{V_i}{V_{i,0}}\right)^2 + K_I\frac{V_i}{V_{i,0}} + K_P\right)$$

$P_{d_i,0}/Q_{d_i,0}/V_{i,0}$ - values at the initial operation conditions

$K_Z/K_I/K_P$ - nonnegative coefficients, weighting constant impedance/current/power terms

Protection mechanisms

- Line tripping
- Load tripping
- Generator tripping

- In case of partial tripping:

$$P_{d_i} = \alpha_k P_{d_i,0}\left(K_Z\left(\frac{V_i}{V_{i,0}}\right)^2 + K_I\frac{V_i}{V_{i,0}} + K_P\right)$$

$$Q_{d_i} = \alpha_k Q_{d_i,0}\left(K_Z\left(\frac{V_i}{V_{i,0}}\right)^2 + K_I\frac{V_i}{V_{i,0}} + K_P\right)$$

Line protection mechanisms

Each line is equipped with:

- *overload protection* (full tripping)

$$|F_{ij}(t)| > \alpha B_{ij,t}\ , \qquad t \in [\bar{t} - \tau_{lo}, \bar{t}]$$

where $F_{ij}(t) = V_i V_j B_{ij} \sin\left(\theta_j(t) - \theta_i(t)\right)$
and $C_{ij} = \alpha B_{ij}$

- *out-of-step protection* (full tripping)

$$|\theta_j - \theta_i| > 2\pi$$

B. Schafer, D. Witthaut, M. Timme, and V. Latora, “Dynamically induced cascading failures in power grids,” Nature communications, vol. 9, no. 1, pp. 1–13, 2018.
Tziouvaras, Demetrios A., and Daqing Hou. "Out-of-step protection fundamentals and advancements." 57th Annual Conference for Protective Relay Engineers, 2004. IEEE, 2004.

Load protection mechanisms

Overvoltage protection

- first condition

(partial tripping)

$$V_i(t) > r^L_{hv,1} V_i(0), \qquad t \in [\bar{t} - \tau^L_{hv,1} \bar{t}]$$

- second condition

(full tripping)

$$V_i(t) > r^L_{hv,2} V_i(0), \;\; t \in [\bar{t} - \tau^L_{hv,2} \bar{t}],$$

where $r^L_{hv,2} > r^L_{hv,1}$ and $\tau^L_{hv,2} < \tau^L_{hv,1}$

Undervoltage protection

(partial tripping)

$$V_i(t) < r^L_{lv} V_i(0), \qquad t \in [\bar{t} - \tau^L_{lv} \bar{t}]$$

Load protection mechanisms

Frequency protection

High frequency protection
(partial tripping)

$$\widetilde{\omega}_i(t) > \omega_{hf}^L, \qquad t \in [\bar{t} - \tau_{hf}, \bar{t}]$$

Low frequency protection
(partial tripping)

$$\widetilde{\omega}_i(t) < \omega_{lf}^L, \qquad t \in [\bar{t} - \tau_{lf}, \bar{t}]$$

Generator protection mechanisms

Overvoltage protection

- first condition
(full tripping)

$$V_i(t) > r^G_{hv,1} V_i(0), \qquad t \in [\bar{t} - \tau^G_{hv,1} \bar{t}]$$

- second condition
(full tripping)

$$V_i(t) > r^G_{hv,2} V_i(0), \ t \in [\bar{t} - \tau^G_{hv,2} \bar{t}],$$

where $r^G_{hv,2} > r^G_{hv,1}$ and $\tau^G_{hv,2} < \tau^G_{hv,1}$

Generator protection mechanisms

Over frequency

- first condition

(partial tripping)

$$\omega_i(t) > \omega^G_{hf,1}, \qquad t \in \left[\bar{t} - \tau^G_{hf,1}, \bar{t}\right]$$

- second condition

(full tripping)

$$\omega_i(t) > \omega^G_{hf,2}, \qquad t \in [\bar{t} - \tau^G_{hf,2}, \bar{t}]$$

Under frequency

(full tripping)

$$\omega_i(t) < \omega^G_{lf}, \qquad t \in [\bar{t} - \tau^G_{lf}, \bar{t}]$$

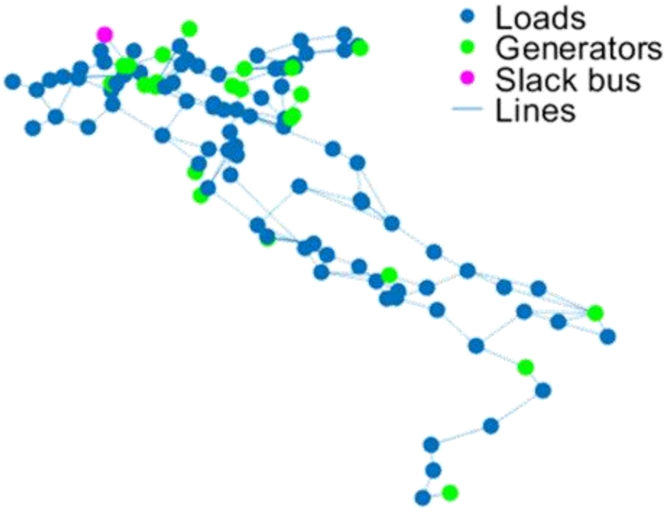
Case study

- Italian high-voltage (380kV) power grid, whit N=127 nodes (34 generators and 93 loads) connected by 171 edges

- The network is undirected and unweighted

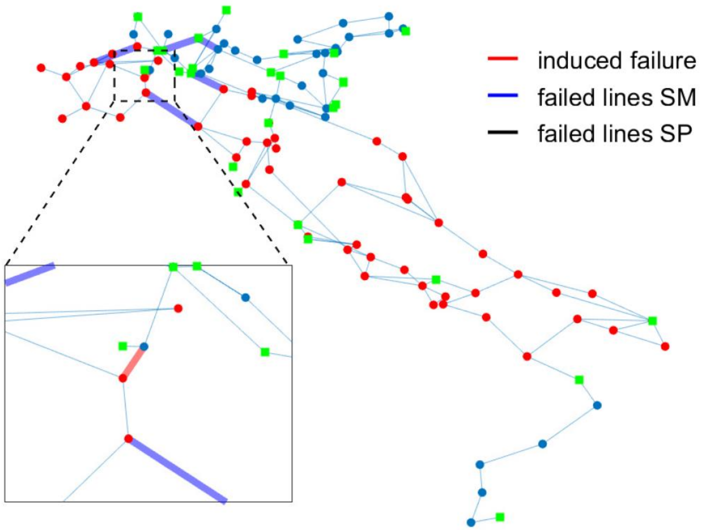
- We set B=0.04 (k=25) such that, in the absence of faults, the network is synchronized

- α=0.6

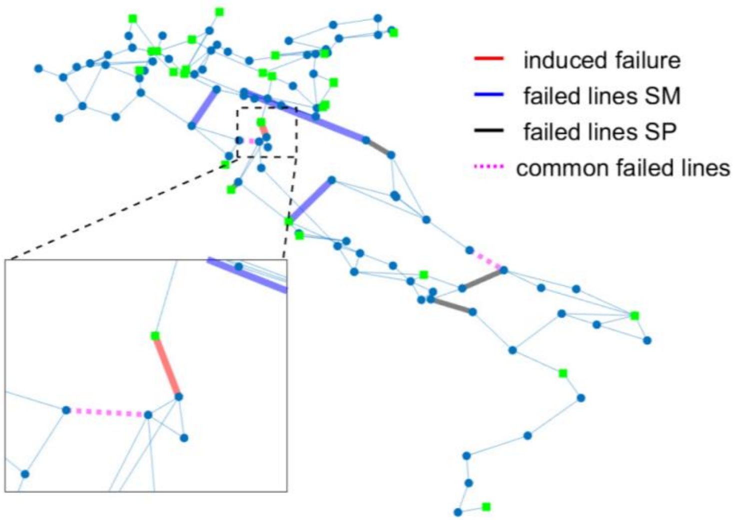


Failures induced by an initial fault in line 107

With protection mechanisms



Without protection mechanisms



The synchronous-machine dynamical model

Each node of the grid is modeled as a rotating machine with state variables given by the rotor angle $\theta_i(t)$ and its angular velocity $\omega_i(t)$ and dynamics described by a swing equation:

$$\frac{d\theta_i}{dt} = \omega_i$$

$$I_i \frac{d\omega_i}{dt} = P_i - \gamma_i \omega_i + \sum_{j=1}^{N} K_{ij} \sin(\theta_j - \theta_i)$$

with

$$K_{ij} = B_{ij} V_i V_j$$

Ref: [B. Schafer et al., Dynamically induced cascading failures in power grids, *Nat. Comm.* 9:1975 (2018)]

The synchronous-machine dynamical model 2/2

Only line failures are considered in the model, a failure triggers when the line power flow overcomes its capacity:

$$|F_{ij}(t)| > \alpha B_{ij}, \forall t \in [\bar{t} - \tau_{lo}, \bar{t}].$$

where $\alpha \in [0,1]$ is a tunable parameter.

The flow along the line connecting bus *i* and bus *j* is given by

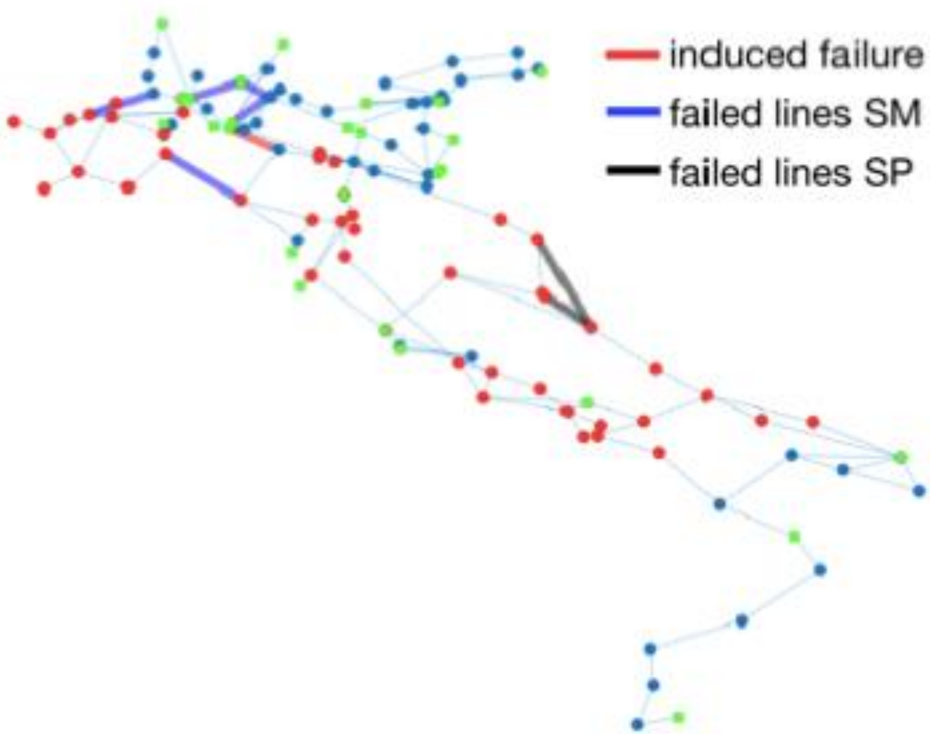
$$F_{ij}(t) = V_i V_j B_{ij} \sin(\theta_j(t) - \theta_i(t))$$

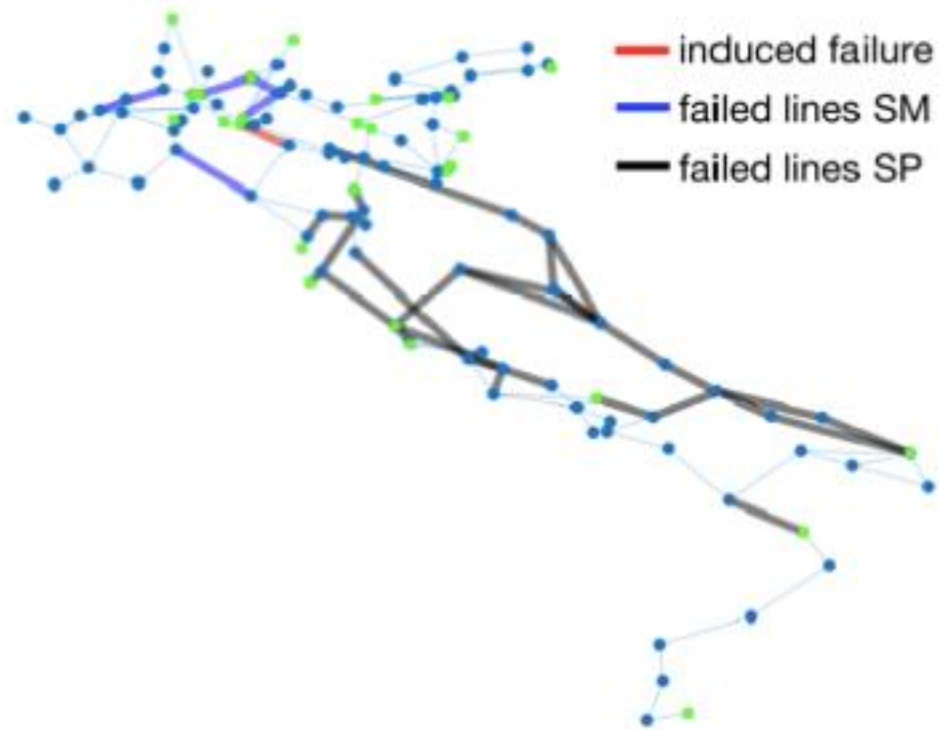
The capacity of a line, as a fraction of the maximum flow is

$$C_{ij} = \alpha B_{ij}.$$

Results

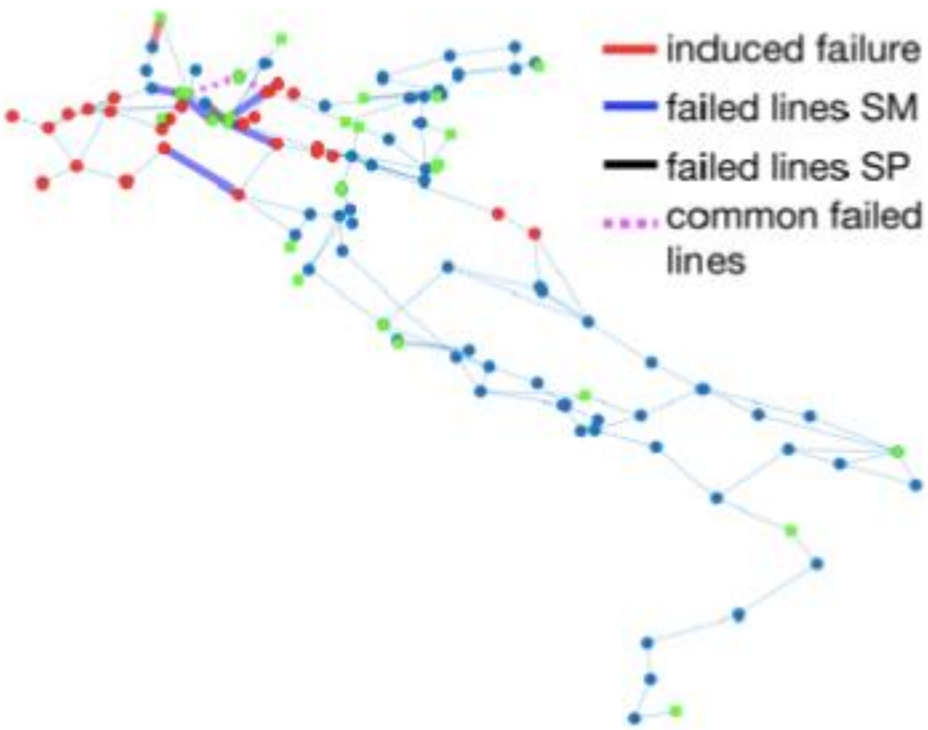
Cascading failures induced in the Italian PG by an initial fault in link 82

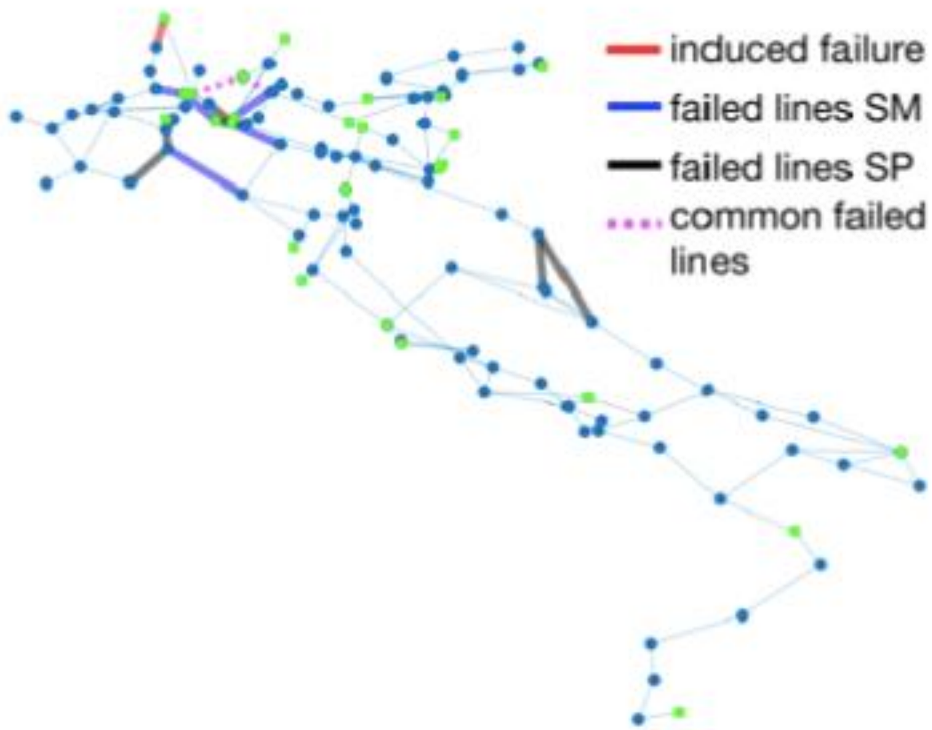




Results

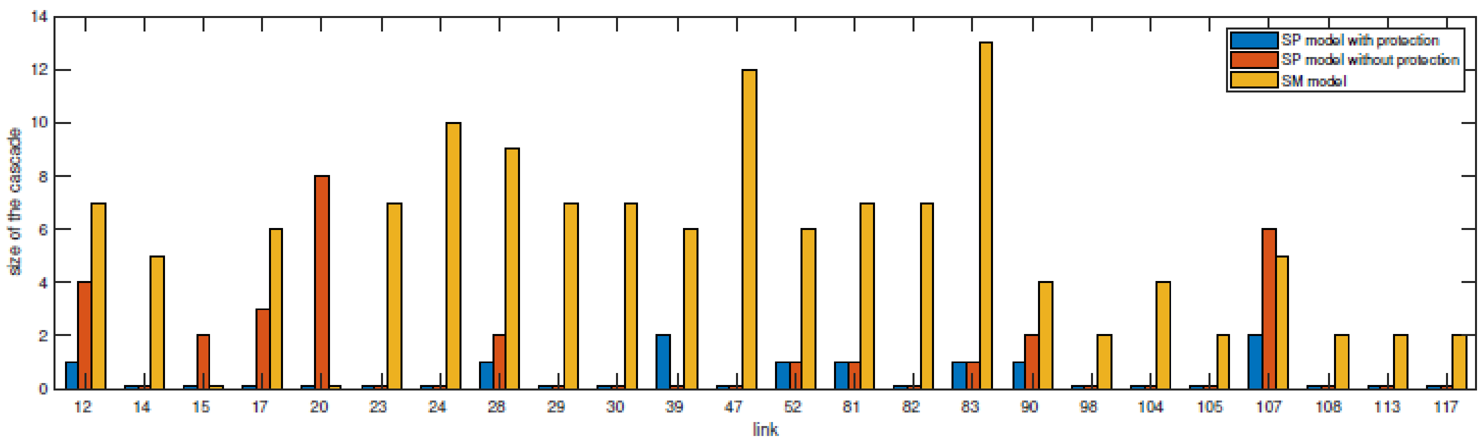
Cascading failures induced in the Italian PG by an initial fault in link 24





Comparison between SM and SP model with/without protection mechanisms

(a) (b) (c)



(a) SP model with protection mechanism

(b) SP model without protection mechanism

(c) SM model

Conclusions?

- The dynamics used to model the load is quite important to determine cascading failures (size & composition)
- The presence of protection mechanisms is also a key factor to take into account
- There is always a way to make the model more realistic, e.g., incorporating the peculiar characteristics of the devices at each station/substation of the grid
- Can still have a model that can analytically tractable?

and apologies

- La Sardegna!