Robustness measure for power grids with respect to cascading failures

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Outline

- Dynamics on complex networks
- Robustness of complex networks
  - **Cascading failures in power grids**
    - Disturbing events in power grids
    - Motivation and Contribution
    - Single phase circuit diagram
    - DC power flow model
    - Robustness measure
    - Results
    - Conclusions and future work

Dynamics on complex networks

- **Good dynamics**
  - Spread of information
  - Data traffic in the Internet
  - Power flow in power grids
- **Bad dynamics**
  - Spread of rumors
  - Spread of viruses
  - Cascading failures in power grids

Robustness of complex networks

- How robust a complex network is to resist unwanted dynamics

- **Case studies**
  - Viral Conductance: Robustness of networks with respect to spread of viruses
  - **Robustness measure for power grids with respect to cascading failures**

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M. Youssef, R. Kooij, and C. Scoglio "**Viral Conductance: Quantifying the robustness of networks to spread of viruses** "*Journal of Computational Science, Elsevier*, doi:10.1016/j.jocs.2011.03.001, 2011

Disturbing events in power grids

- Many types of triggers can disturb the normal functionality of the electric grid

  - Dips (voltage sags, voltage drop)
  - Brief voltage increases (swells)
  - Transient events
  - Instability of the frequency of generated voltage with large deviation
  - Synchronization of the generators
  - Weather storms and lightening may lead to shutting down some substations and damaging power transmission lines.
  - Human errors

Categories of events by NERC

- Transmission System Standards: Normal and Emergency Conditions

  - Category A: No Contingencies
  - Category B: Event resulting in the loss of a single element
  - Category C: Event(s) resulting in the loss of two or more (multiple) elements
  - Category D: Extreme event resulting in two or more (multiple) elements removed or Cascading out of service

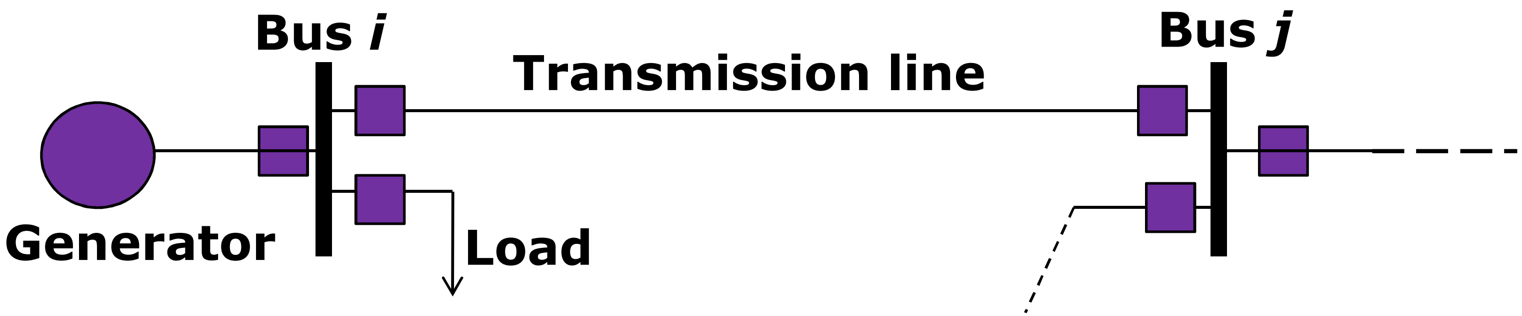
Standard TPL-001-0.1: System Performance Under Normal Conditions, ***Transmission System Standards: Normal and Emergency Conditions,*** **http://www.nerc.com/files/TPL-001-0 1.pdf/**

Contribution and motivation

- The main question:
  - ***How robust is the electric power grid topology to resist cascading failures ?***

- Contribution:
  - Proposing a new metric η to quantify the robustness of the electric power grids
  - Utilizing the power flow model and the electric parameters in assessing the robustness of the grid
  - Outlining the role of the link survival probability and the depth of the cascading failure

Single phase circuit diagram



The power flow between bus *i* and bus *j*

$$P_{ij} = \frac{|V_i||V_j|}{Z_{ij}} \sin(\delta_{ij})$$

V_i : Voltage at bus i

Z_{ij} : Impedance of transmission line between bus i and bus j

δ_{ij} : Voltage angle difference between bus i and bus j

DC power flow model

- Neglect the line resistance

$$Z = R + jX \qquad\qquad R << X$$

- Approximate the voltage angle function

$$\sin(\delta) \approx \delta$$

  - Stability condition: $\delta_{ij} \leq 30^o$
- Flat voltage profile with value *1p.u.*
  - Normal operation: $0.95\,p.u. \leq V \leq 1.05\,p.u.$
- Power flow on link *(i,j)*

$$P_{i,j} = \frac{\delta_{i,j}}{x_{i,j}}$$

$$P = [b]\delta$$

J.A. Casazza, and W.S. Ku, **The co-ordinated use of A-C and D-C network analyzers**, *Proceedings of American Power Conference, Vol.* 16, 1954.

Definition of robustness metric η

$$\eta = \frac{1}{L}\sum_{i=1}^{L} P_i r_i$$

L is total number of links

P_i = Prob(survival of link i)

r_i = Average cascading rank of link i

The higher is the value of η, the higher is the robustness of the grid

Computational algorithm for η

- Probability of link survival P_i
  - Intentionally, remove one link $j \neq i$ (transmission line)
    1. Rank=0, $x_j=0$ ($x_j=1$ if link i fails due to the removal of j)
    2. Compute the power flow on every link
    3. Consider failed and remove the overloaded links
    4. Rank=Rank+1
    5. Repeat the evaluation in step 2 of the power flow until the cascade stops
    6. Compute the size of cascading failures K_j
    7. $x_j=x_j+1$ if link i belongs to K_j
  - Repeat the same procedure for every link $j \neq i$

$$P_i = 1 - \frac{\sum_{j=1}^{L} x_j}{\sum_{j=1}^{L} K_j}$$

Computational algorithm for η

- Depth of cascading failure and link rank:
  - Link rank: The cascading stage at which link *i* fails due to the removal of link *j*

$$r_{i|j \text{ removed}}$$

  - Average rank of link *i*

$$r_i = \frac{1}{L-1} \sum_{j \in L, j \neq i} r_{i|j \text{ removed}}$$

  - Weak links frequently fail at the early stage of cascading failure

Four possible cases

Robustness measure:

$$\eta = \frac{1}{L}\sum_{i=1}^{L} P_i r_i$$

1) The probability of survival is high and the average rank is also high.
2) The probability of survival is high but the average rank is low.
3) The probability of survival is low but the average rank is high.
4) The probability of survival is low and the average rank is also low.

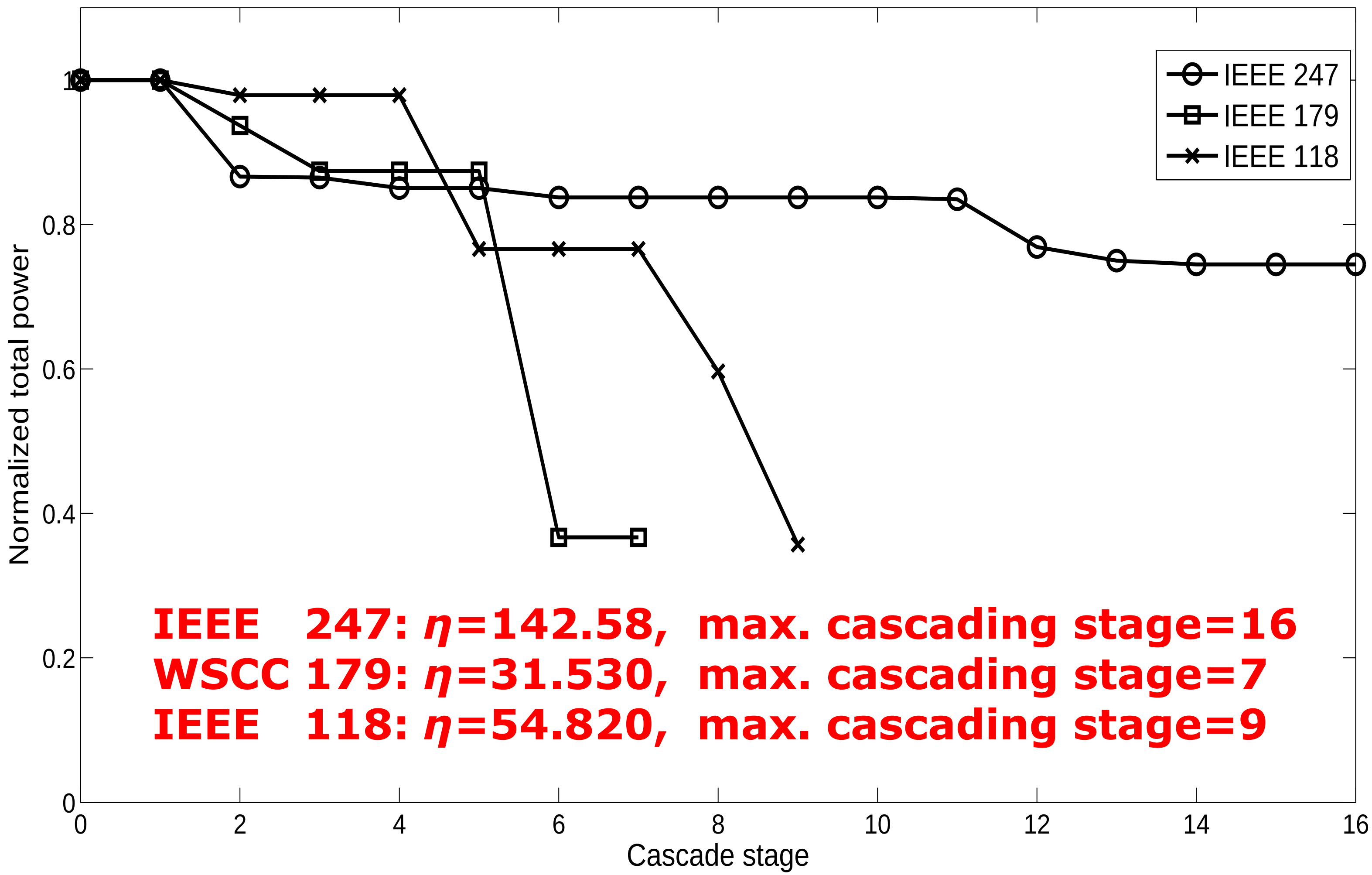
Power grid topologies and data

- Real topologies
  - IEEE 247 bus test system with 355 links
  - IEEE 118 bus test system with 179 links
  - WSCC 179 bus equivalent system with 222 links
- Synthetic topologies
  - Number of available power grid topologies are very limited
  - Generate synthetic power grids having the same number of nodes, the same number of links, and the same maximum node degree.

Numerical results

Network	η	Max. cascade stage
IEEE 247		
Real network	142.58	16
Synthetic network 1	160.03	21
Synthetic network 2	133.66	23
WSCC 179		
Real network	31.53	7
Synthetic network 1	114.71	15
Synthetic network 2	71.16	12
IEEE 118		
Real network	54.82	9
Synthetic network 1	75.42	11
Synthetic network 2	132.98	16

Numerical results



IEEE 247: η=142.58, max. cascading stage=16
WSCC 179: η=31.530, max. cascading stage=7
IEEE 118: η=54.820, max. cascading stage=9

Conclusions and future work

- **Conclusions**
  - Proposing a new robustness measure
  - Utilizing the power flow model
  - Outlining the role of survival probability and the depth of failure
- **Future work**
  - Applying the new metric to different types of grids
  - Analyzing the impact of a single failed link on the size of the cascading
  - Proposing islanding as mitigation strategies for cascading failures

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Questions


Thank You!