Tree partitioning as an alternative to controlled islanding to contain cascading line failures

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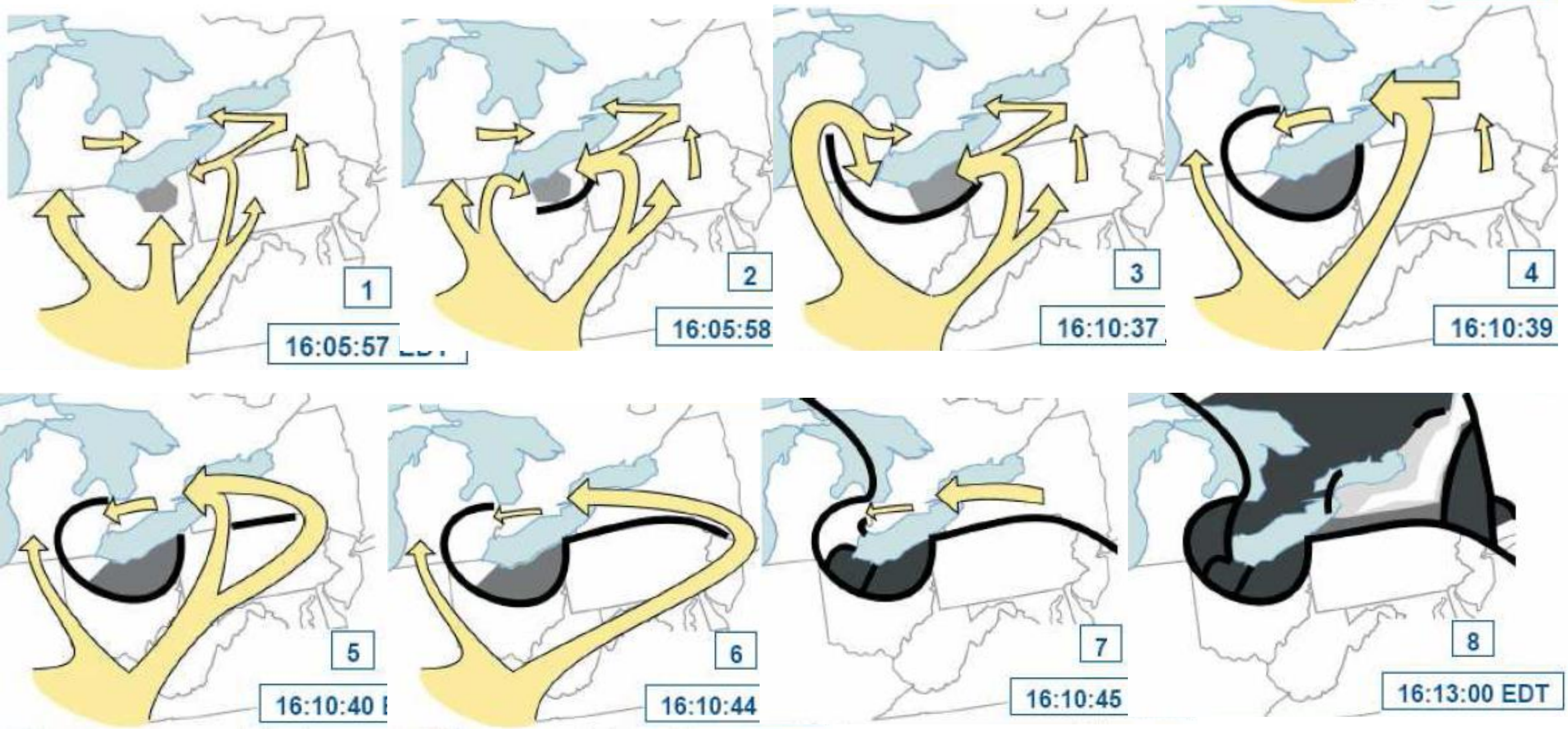
Controlled Islanding (CI)

- Significant research effort over the last two decades
- To stop a cascading blackout, split a network into a number of islands

2003 US/Canada blackout



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Source: US/Canada Power System Outage Force

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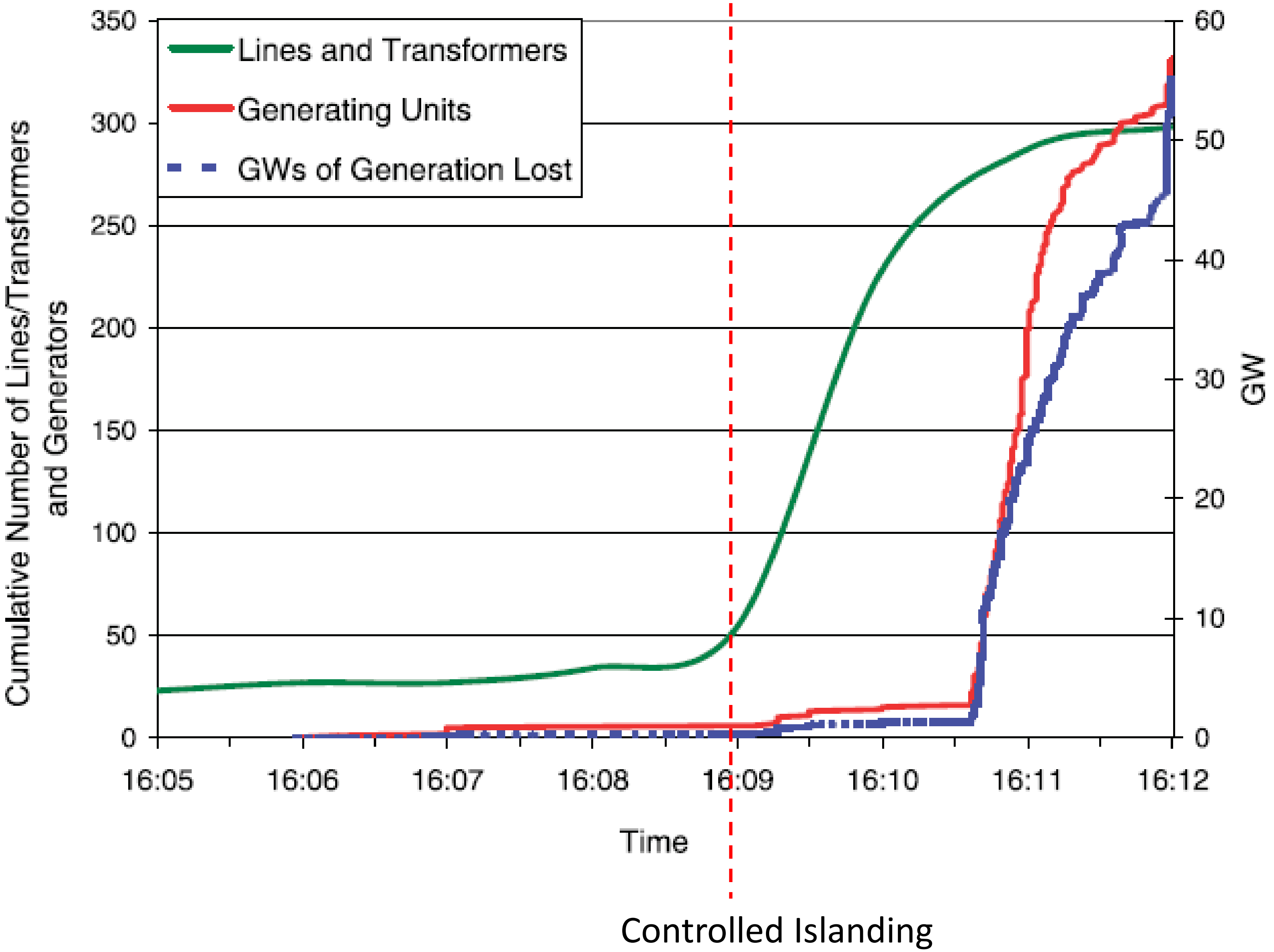
Research questions posed by Controlled Islanding (CI)

- Main problem: optimal clustering
  - how to split a network in a number of clusters that are well-connected internally and with weak external connections
  - Then islanding the clusters (tripping the tie-lines) will not be a big disturbance
- Criteria for clustering
  - Minimise power imbalance of islands
  - Minimise change in power flow patterns
  - Minimise congestion
  - Minimise dynamic stability problems (island should contain only coherent generators)
- Big unresolved question: when to island?

Split the system when the cascade is inevitable



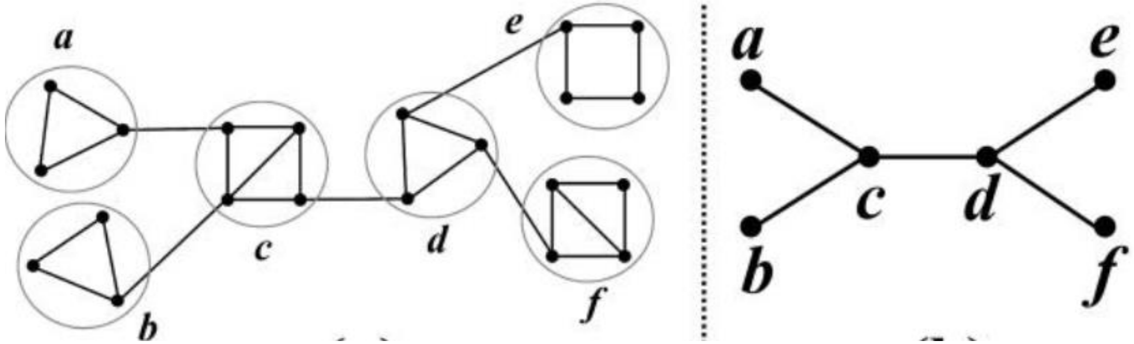
Source: US/Canada Power System Outage Force

Problems with CI

- Why, despite a significant research effort over the last 20 years, there has been no reported practical implementation?
    - Islanding goes against fundamental instincts of System Operators who always try to keep the system together
    - The islands will generally have power imbalance requiring load/generation shedding meaning more customers would be disconnected
    - A large number of tie-lines linking clusters have to be cut: a big shock to the system which may cause stability problems
    - Resynchronisation needed
    - The risk of unnecessary islanding
- The cure could be worse than the disease
- Research question: can we isolate cascading line trips without islanding?

Tree-partitioning (TP)

- Tree-partitioned network: cluster-level graph forms a tree (no cycles)



- Spectral analysis, using linear DC network model, of the Laplacian matrix
    - Kirchhoff’s Matrix Tree Theorem
    - Power Transfer Distribution Factors (PTDFs) and Generalised Line Outage Distribution Factors (GLODFs)
    - Proved that for non-cut set outages (i.e. inside a cluster), GLODF is block-diagonal and therefore the faults are localized
    - line trips inside one cluster (non-cut set outages) do not affect power flows in other clusters

L. Guo, C. Liang, A. Zocca, S. H. Low and A. Wierman, "Line Failure Localization of Power Networks Part I: Non-Cut Outages," in *IEEE Transactions on Power Systems*, Sept. 2021

Theorem 10 (Failure localization: non-cut set outage): Suppose a non-cut set F of lines trip simultaneously so that the surviving graph $(\mathcal{N}, \mathcal{E} \setminus F)$ remains connected. For any surviving line $l = (i, j)$:

1) GLODF $K^F_{l\hat{l}} = 0$ if l and $\hat{l}$ are in different blocks of $\mathcal{G}$.
2) $K^F := K^F_{-FF}$ has a block diagonal structure:

$$K^F =: \begin{bmatrix} K^F_1 & 0 & \dots & 0 \\ 0 & K^F_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & K^F_b \end{bmatrix}, \quad (11a)$$

where for $k = 1, \dots, b$ each K^F_k is $|F_{-k}| \times |F_k|$ and involves lines only in block $\mathcal{E}_k$ of $\mathcal{G}$, given by:

$$K^F_k := D_{-k}(I - D_k)^{-1} \quad (11b)$$

$$= K_k \left(I - \text{diag}(D_k)\right) (I - D_k)^{-1}, \quad (11c)$$

or in terms of B, C and A:

$$K^F_k = B_{-k} C^T_{-k} A C_k \left(I - B_k C^T_k A C_k\right)^{-1}. \quad (11d)$$

Again, since a bridge is a block, a non-cut outage does not impact the branch flow on any bridge. The invertibility of $I - D_k$ follows from Corollary 5 and the block-diagonal structure of D_{FF}. Theorem 10 subsumes Corollary 9 which corresponds to the special case where $F = \{\hat{l}\}$. In that case $K^F = K^{\hat{l}}$ is a size $m - 1$ column vector. If $\hat{l} \in \mathcal{E}_1$ then $D_{FF} = D_{\hat{l}\hat{l}}$ and

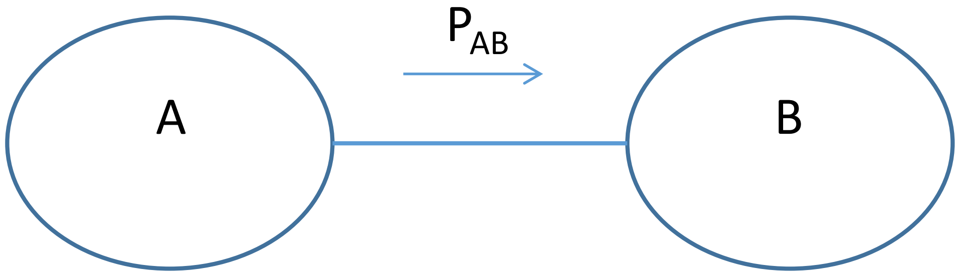
$$K^{\hat{l}} = \begin{bmatrix} K_1 \\ 0 \\ \vdots \\ 0 \end{bmatrix},$$

with $K_1 := D_{-1}(1 - D_{\hat{l}\hat{l}})^{-1}$ and $D_{-1} := (D_{l\hat{l}}, l \neq \hat{l}, l \in \mathcal{E}_1)$.

The ability to characterize in terms of the GLODF K^F the localization of the impact of line outages within each block where outages occur is illustrated in the next example.

Physical explanation of the fault localisation property of tree-partitioned networks

- S. Low et al proved it using spectral analysis of the network Laplacian – quite mathematical
- A simpler proof here based on physics: consider first two clusters connected by a single tie-line (a bridge)



- The only way one cluster can influence the other is via tie-line flows: if they stay constant, a fault is isolated
- Power transfer P_{AB} depends <u>only</u> on the power imbalance in each cluster: export of A = import by B
- If the power imbalances stay constant (i.e. no generation trips), a line trip in one cluster does not affect power flows in the other cluster

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J. W. Bialek and V. Vahidinasab, "Tree-Partitioning as an Emergency Measure to Contain Cascading Line Failures," in *IEEE Transactions on Power Systems*, Early Access

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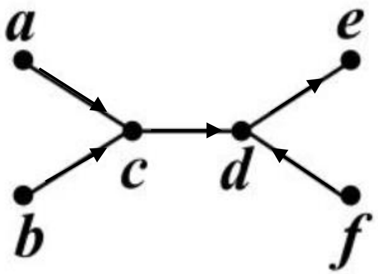
Generalisation to a tree-partitioned network



- There are no cycles in a tree so bridge flows depend <u>only</u> on the tree topology and cluster power imbalances, but not on the internal topology of each cluster
- Proof: KCL $p = C\ f$

Vector of (*N*-1) bridge flows

Vector of *N* cluster imbalances (injections at tree nodes)

Cluster-level *N*x(*N*-1) incidence matrix

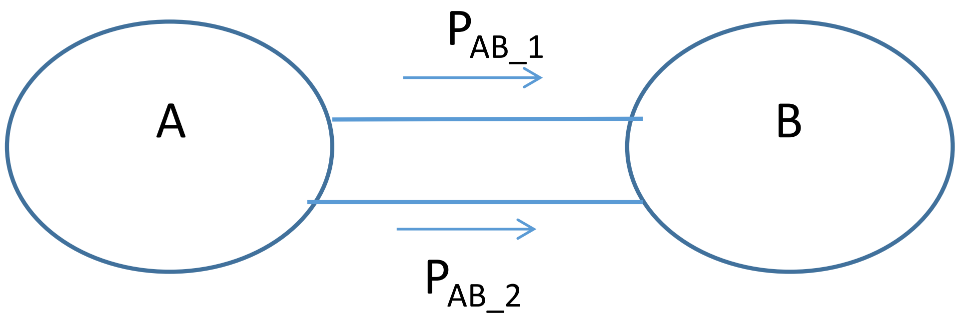
- As the graph is a tree, *C* has full rank equal to (*N*-1), (C^TC) is invertible, bridge flows *f* are unique and equal to

$$f = (C^TC)^{-1} C^T p \qquad \text{(Moore-Penrose pseudoinverse)}$$

- No dependence on internal cluster topology

J. W. Bialek and V. Vahidinasab, "Tree-Partitioning as an Emergency Measure to Contain Cascading Line Failures," in *IEEE Transactions on Power Systems*, Early Access

Why not leave in two tie-lines linking clusters?



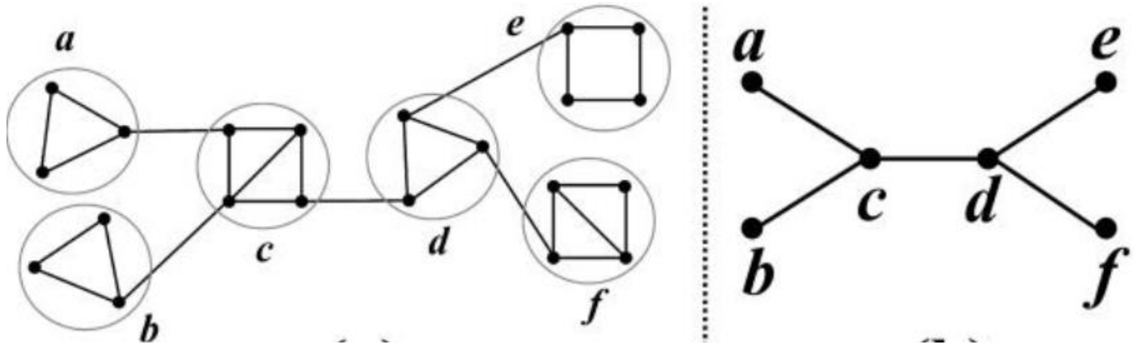
- Fewer lines would have to be disconnected and it would increase robustness: the system would be (N-1) secure
- An internal cluster fault does not affect the <u>total</u> power transfer $P_{AB} = (P_{AB\_1} + P_{AB\_2})$ as it depends only on cluster imbalances
- However a fault could result in a different distribution of P_{AB} between P_{AB_1} and P_{AB_2}
- Changed tie-line flows would affect power flows in the other cluster
- The fault generally would not be localised
- Working with Steven Low on deriving conditions when a fault would not change significantly tie-line flows

Application of tree-partitioning for emergency control

- S. Low et al suggested that networks should be permanently tree-partitioned to prevent any future cascading blackouts
- This would permanently weaken a network (as it would require switching off some tie-lines) so unlikely to be adopted by utilities
- Instead, use TP as an *emergency* measure, similarly as Controlled Islanding, when a cascading blackout is imminent
- An emergency measure, rather than a permanent one, is more likely to be adopted by utilities

J. W. Bialek and V. Vahidinasab, "Tree-Partitioning as an Emergency Measure to Contain Cascading Line Failures," in *IEEE Transactions on Power Systems*, Early Access, doi: 10.1109/TPWRS.2021.3087601

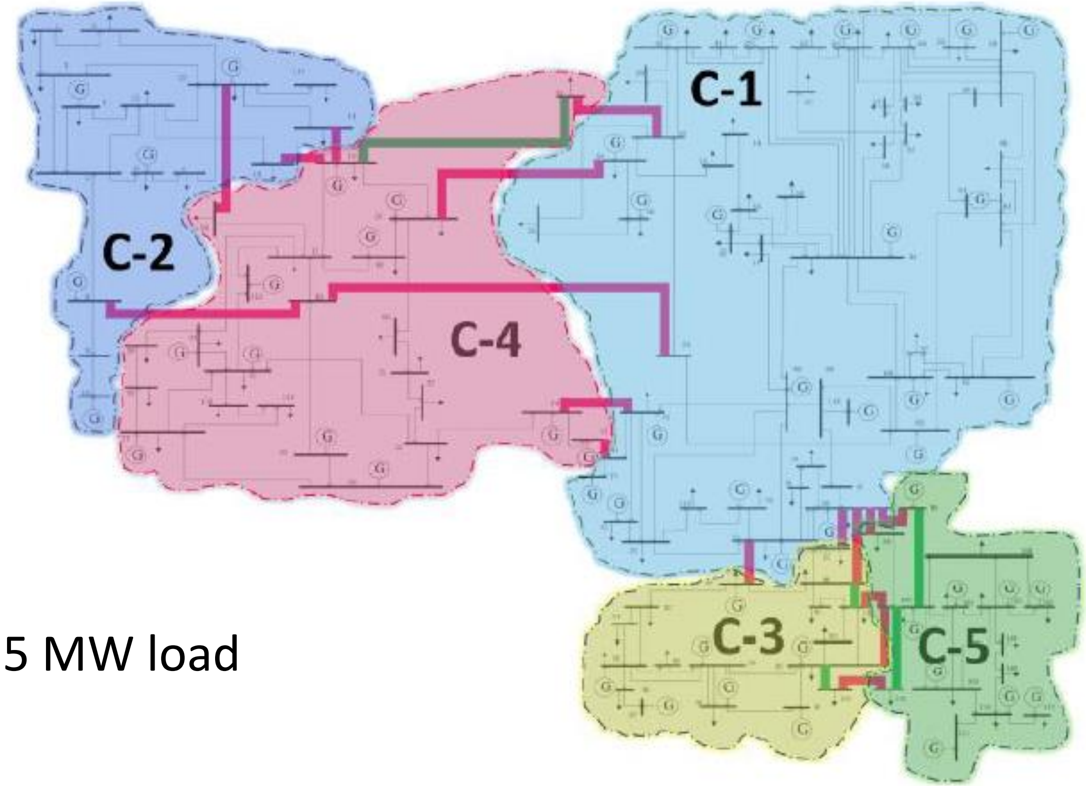
Advantages of TP over CI

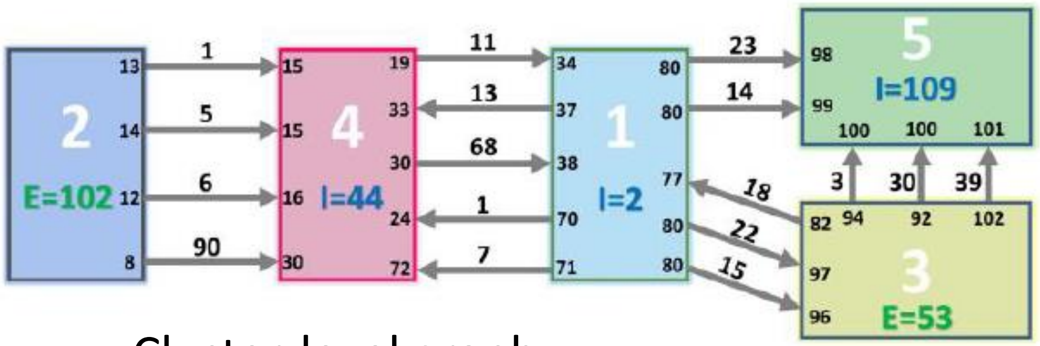


- Both TP and CI achieve localisation of line trips but for TP the bridges stay on so the network graph is still connected
- Power transfers between clusters can still take place (subject to the capacity of the bridges)
  - Reduced need for power balancing actions (load shedding)
- Fewer tie-lines are cut so smaller shock to the system
- No need for resynchronisation
- More likely to be accepted by the industry

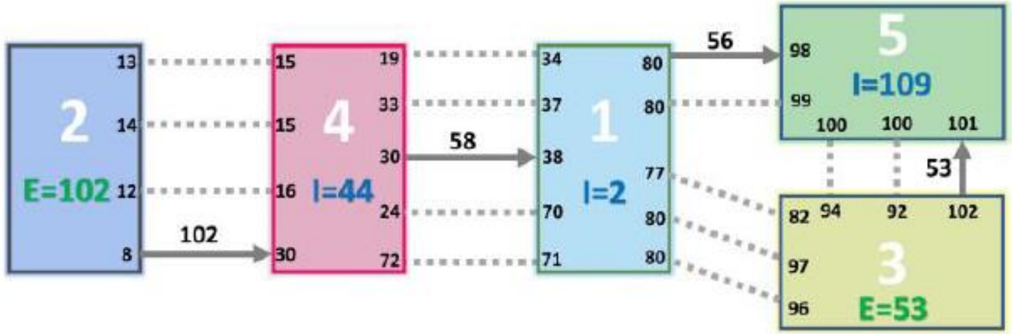
Example: IEEE 118 node network divided into 5 clusters

- Clusters determined using spectral clustering with line flows as weights: tie-lines shown in red
- Maximum-weight spanning tree (Prim's algorithm) to determine which tie-lines should be kept as bridges
- CI: all 17 tie-lines are cut, 366 MW total power interruption, 155 MW load shedding needed to balance the resulting islands
- TP: 13 tie-lines are cut, 146 MW total power interruption, no load shedding needed (assuming TP does not cause congestion)





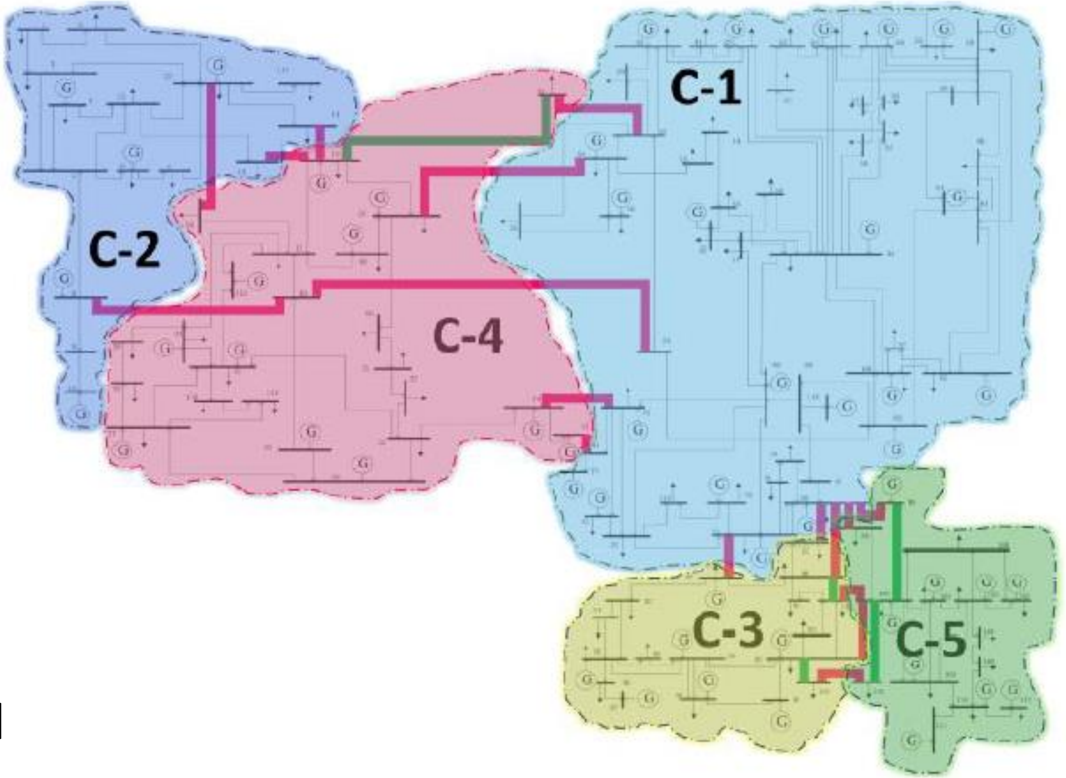
Cluster-level graph

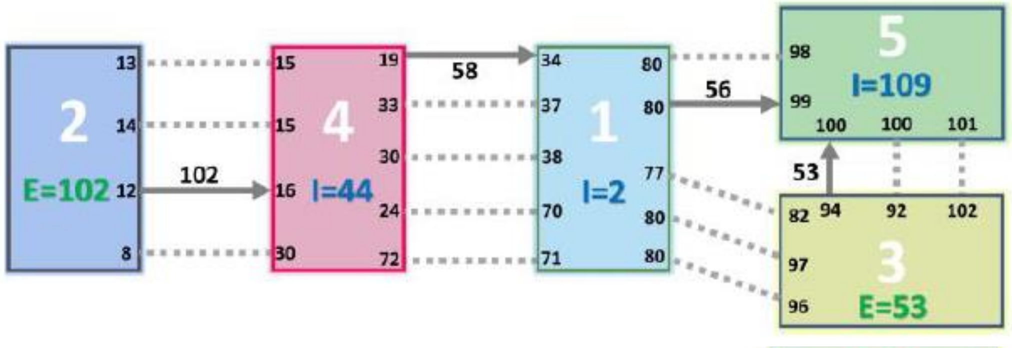


Maximum-weight spanning tree

Minimising load shedding to relieve congestion

- Now let us consider a more realistic case: TP does cause congestion (green lines)
- How to select an optimal spanning tree that minimises load shedding required to relieve congestion?
- Brute force: calculate overloads for all 420 possible spanning trees (Kirchhoff's Matrix Tree theorem)
- Linear Line Outage Distribution Factors (LODF) cannot be used to calculate changes in line flows due to the non-linear effect of multiple outages considered (checked using AC model)
- Using full AC model to calculate overloads is still viable due to a limited number of cases - and tricks possible to speed-up the calculations
- The resulting optimal spanning tree is slightly different than the maximum-weight tree (different tie-lines retained as bridges)



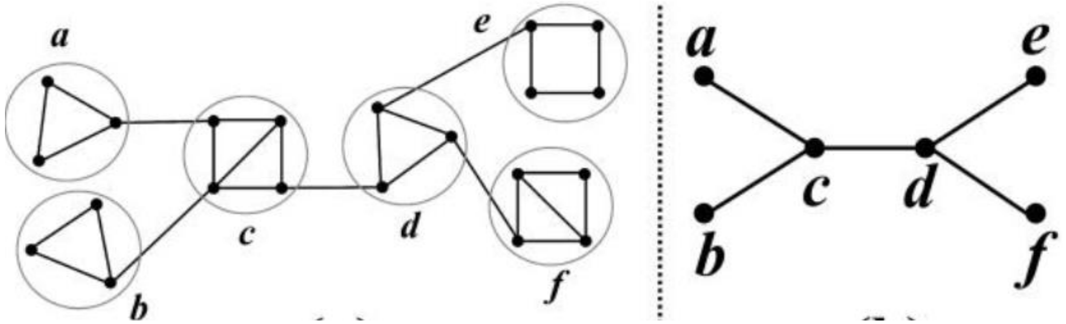


Optimal spanning tree minimising the sum of overloads

Discussion

- The effects of using AC network model
  - Transmission losses: not important
  - Reactive power flows: possible use as line weights for spectral clustering, influence on congestion
  - Voltage effects: line trips in one cluster could cause voltage collapse in the whole network => CI might be needed to separate the "sick" cluster
- Dynamic effects:
  - If clusters are chosen such that they contain only coherent generators, power swings between the clusters could cause the bridges to trip => effectively CI
  - Generator failures often accompany line trips
    - Cluster power imbalances affected => violates the fundamental assumption of TP
    - Frequency response of the whole system - it may, or not, be better than CI
- Generally, *two-step defense*: first try TP as less drastic but, if TP does not manage to localise failures (voltage effects, transient stability, frequency stability), use CI

J. Quiro's-Tortos, R. Sanchez-Garcia, J. Brodzki, J. Bialek, and V. Terzija, "Constrained spectral clustering-based methodology for intentional controlled islanding of large-scale power systems," *IET Generation, Transmission & Distribution*, vol. 9, no. 1, 2014



- The effect of bridge trips (cut set outages)
  - Any bridge trip splits the network - islanding
    - one part has a deficit and the other a surplus of power
    - Power flows in all clusters may be affected
- Include tree-partitioning into a network clustering procedure
  - All known clustering procedures assume that the clusters will be islanded (all tie-lines cut): the tie-lines should be lightly-loaded
  - But for TP one tie-line is kept as a bridge
  - This may change the optimal clustering results: it may make sense to select a heavy-loaded line as a tie-line
  - The subject of current research undertaken with graph theorists – difficult!

L. Guo, C. Liang, A. Zocca, S. H. Low and A. Wierman, "Line Failure Localization of Power Networks Part II: Cut Set Outages," in *IEEE Transactions on Power Systems*, Sept. 2021

Summary

- Controlled Islanding (CI) prevents spreading of cascading line trips but it is a drastic action and therefore unlikely to be accepted by utilities
- A similar effect of localising line failures is achieved when the cluster-level graph is still connected and forms a tree
- Tree Partitioning (TP) is less drastic than CI as the clusters are still connected
  - Smaller shock to the system
  - Less load shedding required
  - No need for resynchronisation
  - More likely to be accepted by the industry
- Further research is needed: AC network model, dynamic effects, generator trips, optimal clustering
- Two-step defense mechanism:
  - First try TP
  - If TP fails to stop a cascade, use CI