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Large-scale Electromagnetic Transient Simulation of the French grid: Challenges and Solutions

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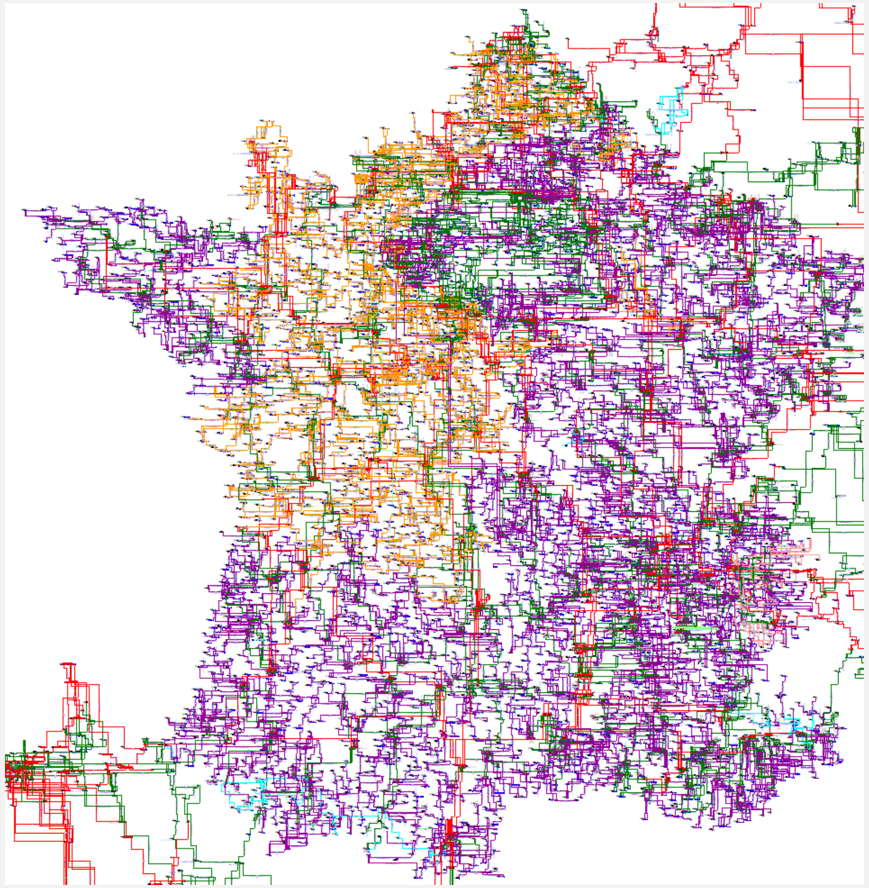
Introduction

- Need to study power electronics interactions
- **Electromagnetic Transient (EMT) simulation of large-scale networks**
- **Challenges**
  - Network modelling fidelity
  - Computation time
- **Solutions**
  - An automatic way to large-scale modelling with a Common Information Model (CIM)/EMT interface
  - Efficient sparse solution techniques

B. Bruned, C. Martin, A. Petit, "Large-scale Electromagnetic Transient Simulation of the French grid: Challenges and Solutions," **Symposium CIGRE Trondheim**, 11 pages, 2025.

Introduction

- Application case: **the entire French grid** with all voltage levels (**400 kV, 225 kV, 90 kV, and 63 kV**)



Entire French grid + transformer saturations + synchronous machine modelling + HVDC links

Items	Numbers
3ph network nodes	25824
Size of the main system of equations	129 185
Saturations (nonlinear inductances, 1ph)	4725
Synchronous machines + Ctrl	40
HVDC links	7

- **Challenges**
  - Network modelling
  - Computation time

Presentation Outlines

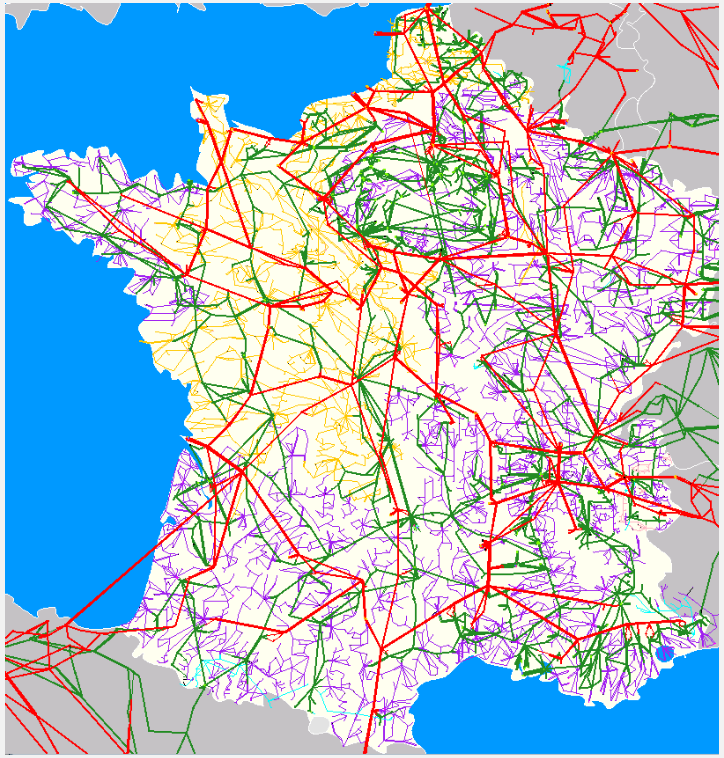
- **CIM/EMT interface Enhancements**
  - Automatic CIM/EMT Interface
  - Visualization of the modelling

- **Sparse EMT solution techniques**
  - Sparse EMT solution method
  - Parallelization through BTF
  - Partial refactorization

- **Simulation Performance**

Automatic CIM/EMT Interface

Planning tool data



Models used for planning and post event analysis

Export

CIM CGMES files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    <cim:ACLineSegment.bch>9.6e-05</cim:ACLineSegment.bch>
    <cim:ACLineSegment.gch>0</cim:ACLineSegment.gch>
    <cim:ACLineSegment.r>0.03</cim:ACLineSegment.r>
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</cim:ACLineSegment>
<cim:CurrentLimit rdf:ID="_AGASSL71ARAMO_ACLS_CL00">
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    <cim:OperationalLimit.OperationalLimitSet rdf:resource="#_AGASSL71ARAMO_ACLS_T0_OLS"/>
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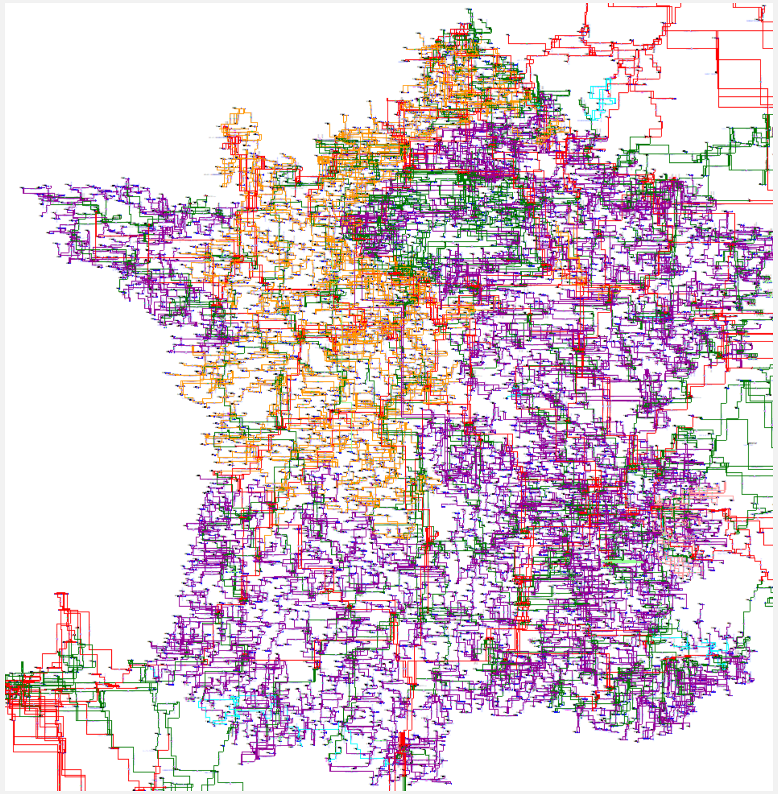
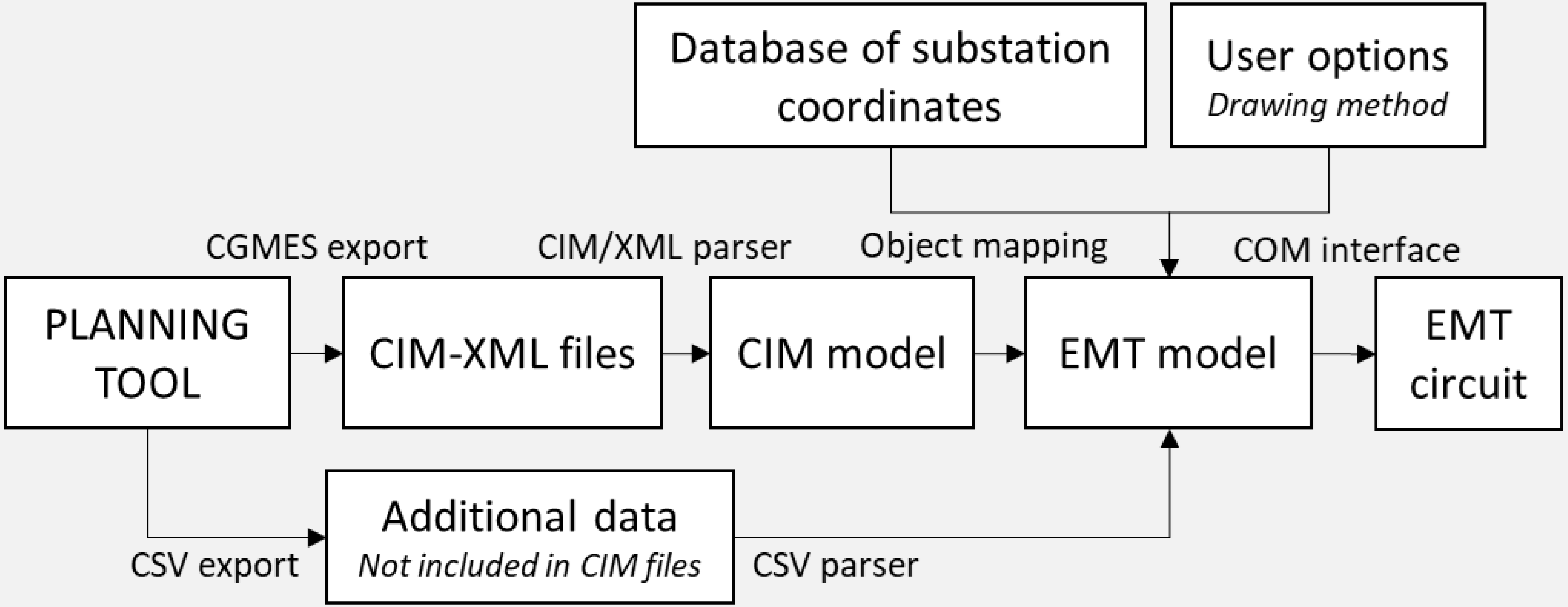
    <cim:IdentifiedObject.name>_AGASSL71ARAMO_ACLS</cim:IdentifiedObject.name>
</cim:CurrentLimit>
```


Import

EMT Modelling



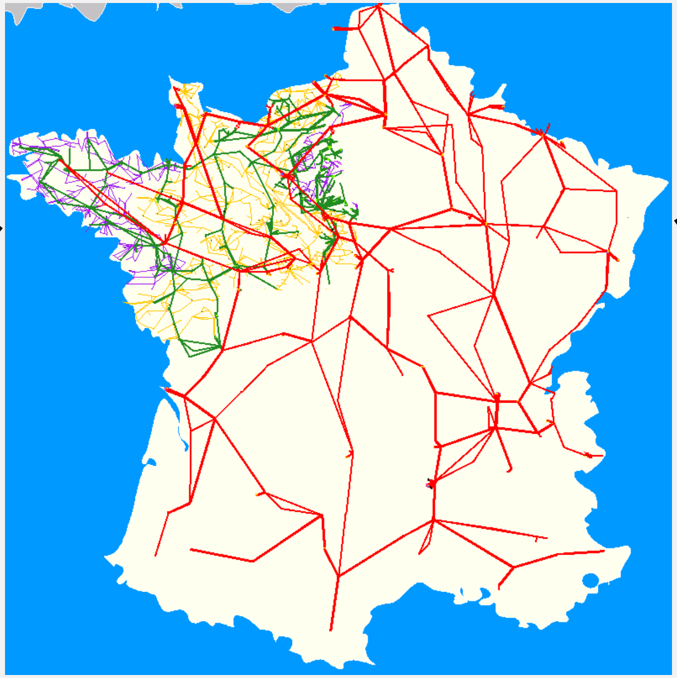
Automatic CIM/EMT Interface



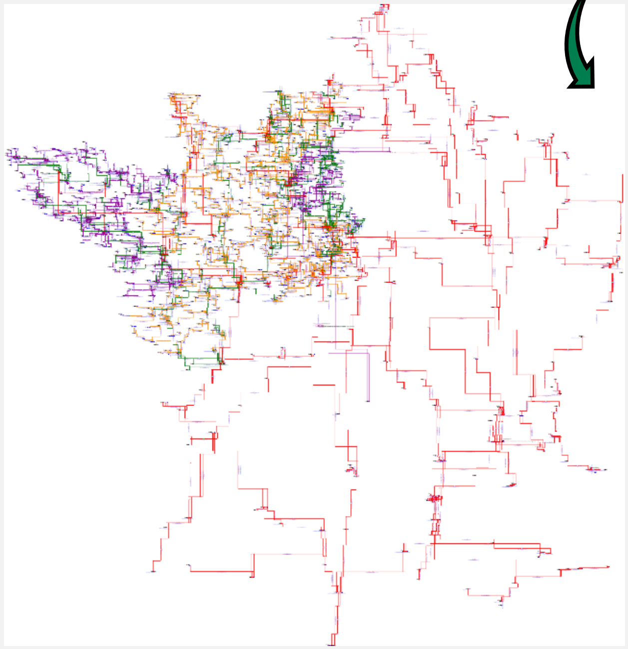
- Export CIM CGMES (bus-branch model)
- Additional data not exported (CSV)
  - Zero sequence, coordinates of electrical substations, machine reactance's

Visualization of the modelling

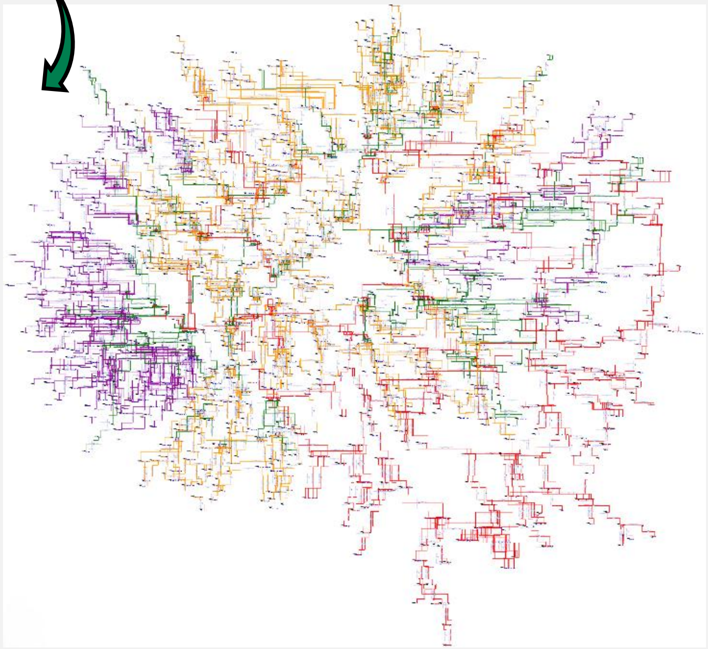
Network data



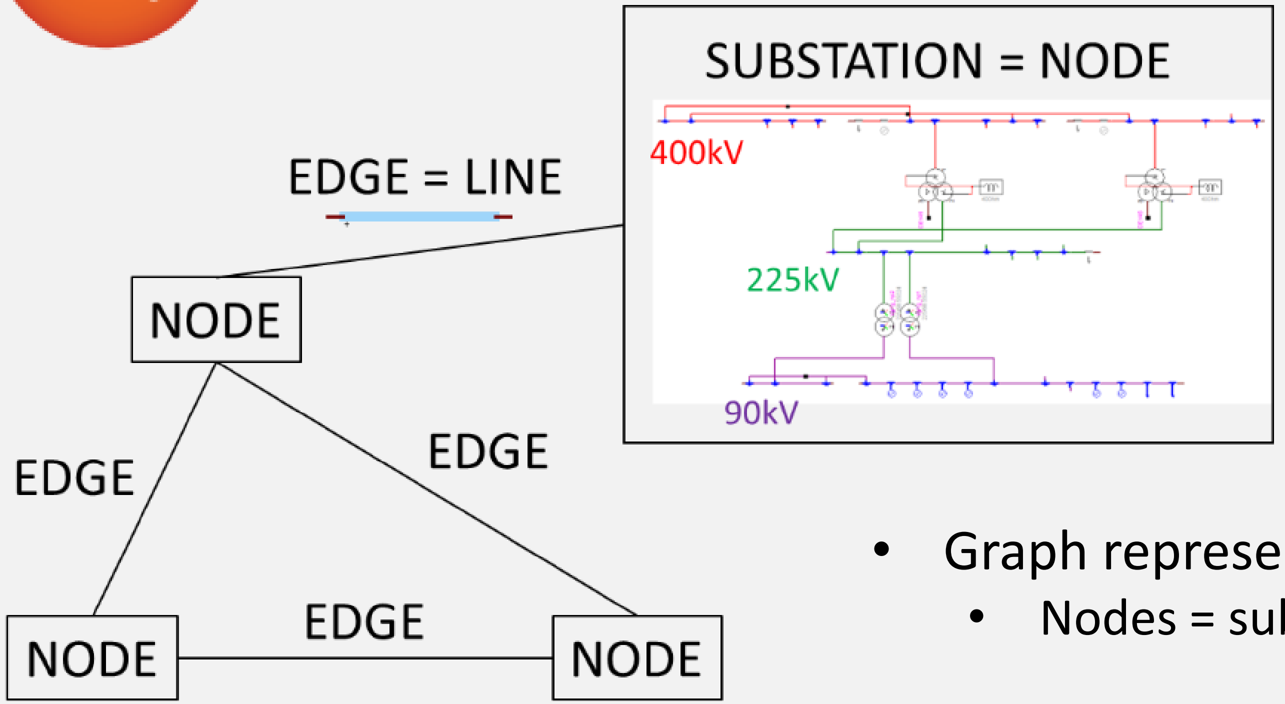
French Database Layout



Automatic Layout

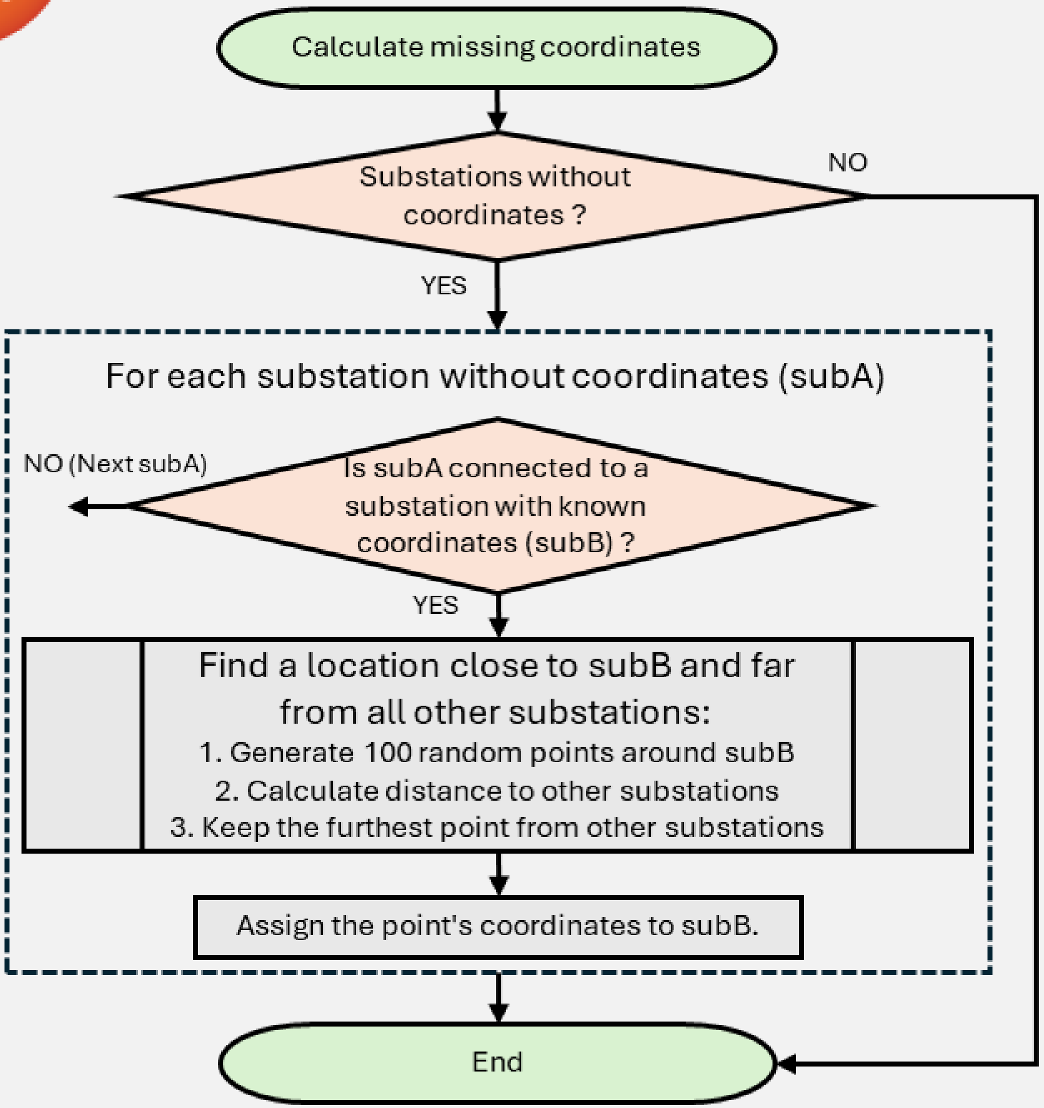


Automatic Layout



- Graph representation of the network modelling
  - Nodes = substations, Edges = lines
- Apply graph automatic positioning
  - Microsoft Automatic Graph Layout (MSAGL)
  - Put directly connected nodes in proximity
  - Minimize the crossing of edges over nodes

French Database Layout



- Database containing coordinates of French substations
- Unknown futures substations coordinates not yet represented in this database
- An algorithm to compute coordinates of substations absent from the database
  - Positioning unknown substations near the closest known coordinates

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- **Sparse EMT solution techniques**
  - Sparse EMT solution method
  - Parallelization through BTF
  - Partial refactorization
- **Simulation Performance**

Sparse EMT solution method

Modified-Augmented-Nodal Analysis (MANA) formulation + discretized companion models

Solve at each time-point $\boldsymbol{Ax{=}b}$ (Iterations for nonlinear elements)

Sparse direct LU decomposition $\boldsymbol{A = LU}$ **(1)**

Forward substitution $\boldsymbol{Lx' = b}$

Backward substitution $\boldsymbol{Ux = x'}$

(1) Most computationally intensive step for nonlinear elements

Modified version of KLU solver (MKLU)
parallelization + partial refactorization

Parallelization through BTF

Apply Block Triangular Factorization (BTF) to $\boldsymbol{A}$ to get a block-diagonal form (transmission line decoupling)

$$\boldsymbol{A_{BTF}} = \boldsymbol{P_{BTF}AQ_{BTF}}$$

$$\boldsymbol{A_{BTF}} = \begin{bmatrix} \boldsymbol{A_1} & & & \\ & \boldsymbol{A_2} & & \\ & & \ddots & \\ & & & \boldsymbol{A_n} \end{bmatrix}$$

Solve each subsystem/BTF block i in parallel

$$\boldsymbol{A}_i\boldsymbol{x}_i = \boldsymbol{b}_i$$

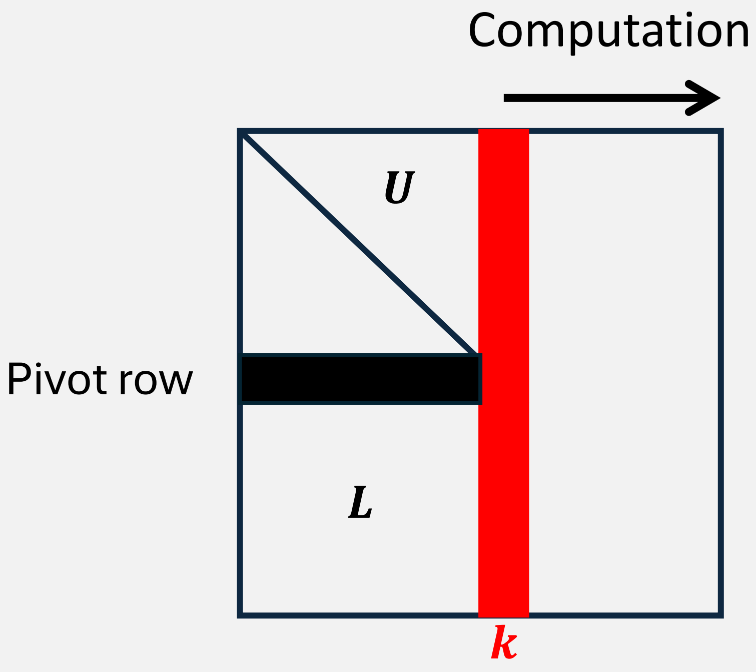
LU Factorization

Apply fill-in reduction (minimize the non-zeros of LU factors)

$$\boldsymbol{A'} = \boldsymbol{PAQ}$$

Where $\boldsymbol{P}$ and $\boldsymbol{Q}$, row and column permutation matrices

Factorization: Left-looking algorithm with partial pivoting to compute LU factors



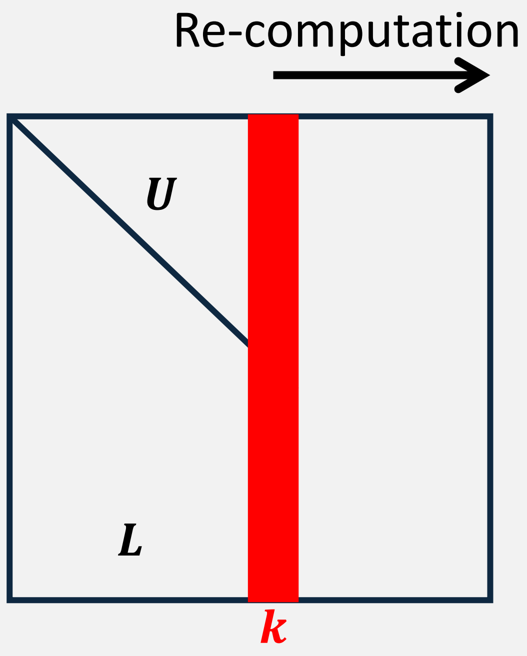
Algorithm 1 Factorization with partial pivoting

$\boldsymbol{L} \leftarrow \boldsymbol{I}$
for $\boldsymbol{k} = 1$ *to* n **do**
  solve $\boldsymbol{Lx} = \boldsymbol{A'}(:, \boldsymbol{k})$
  partial pivoting on $\boldsymbol{x}$
  $\boldsymbol{U}(1:k, \boldsymbol{k}) \leftarrow \boldsymbol{x}(1:k)$
  $\boldsymbol{L}(k:n, \boldsymbol{k}) \leftarrow \boldsymbol{x}(k:n)/\boldsymbol{U}(k,k)$
end for

Partial Refactorization

Refactorization : without pivoting, keep pivots ($\boldsymbol{P_p}$ pivot row permutation matrices)

$$\boldsymbol{A''} = \boldsymbol{P_p}\boldsymbol{A'}$$



Algorithm 2 Partial Refactorization without pivoting

$\boldsymbol{L} \leftarrow \boldsymbol{I}$
for $\boldsymbol{k} \in \boldsymbol{C}$ **do**
  solve $\boldsymbol{Lx} = \boldsymbol{A''}(:, \boldsymbol{k})$
  $\boldsymbol{U}(1:k, \boldsymbol{k}) \leftarrow \boldsymbol{x}(1:k)$
  $\boldsymbol{L}(k:n, \boldsymbol{k}) \leftarrow \boldsymbol{x}(k:n)/\boldsymbol{U}(k,k)$
end for

Partial Refactorization : minimize $\boldsymbol{C}$

$$\boldsymbol{C_{KLU}} = [\![1, n]\!]$$

$$\boldsymbol{C_{MKLU}} = [\![n_{chg}, n]\!]$$

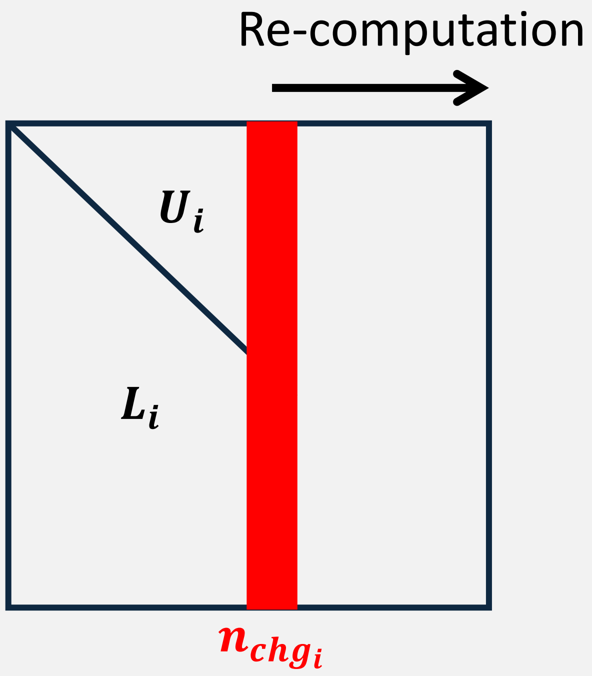
n_{chg} : minimum indices of changed columns in $\boldsymbol{A''}$

Partial Refactorization through BTF

Per BTF block refactorization : recompute $L_i U_i$ factors (changed submatrix A_i)

$$A_{BTF} = \begin{bmatrix} A_1 & & & \\ & A_i & & \\ & & \ddots & \\ & & & A_n \end{bmatrix}$$

Recompute $L_i U_i$ columns from the minimum indices n_{chg_i} of changed columns in A_i



Algorithm 3 Partial Refactorization BTF

$L_i \leftarrow I$
for $k = n_{chg_i}$ *to* n **do**
  solve $L_i x_i = A_i(:, k)$
  $U_i(1:k, k) \leftarrow x_i(1:k)$
  $L_i(k:n, k) \leftarrow x_i(k:n)/U_i(k, k)$
end for

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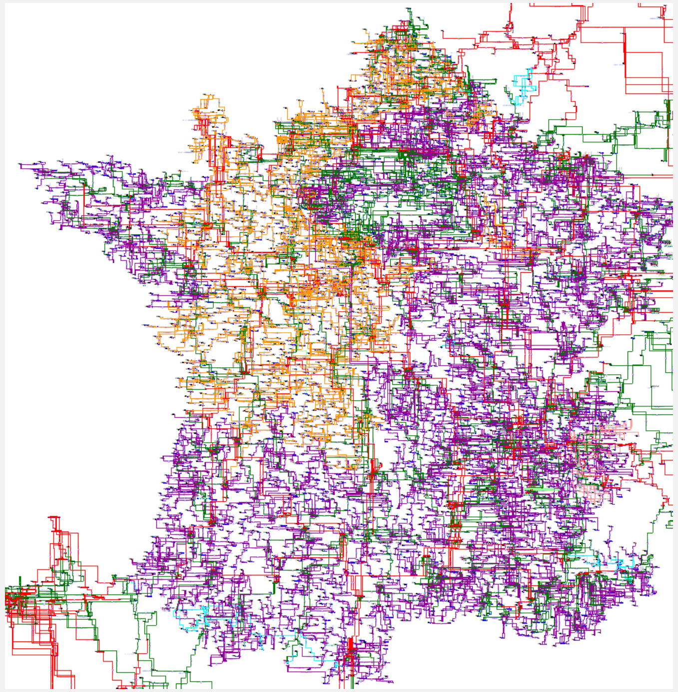
- **Simulation Performance**

Simulation Performance

Solutions Methods	Execution Times	Iterations
Load-Flow	36 s	7
Time Domain (1 s, 50 μs)	2822 s (**47 min**)	2.64



47 min to simulate 1 s of the entire French grid

Solution Steps	Ax=b	Control
% of the Time Domain Execution Time	**93.1%**	2.1%

Solving Ax=b takes most of the computation time

Simulation Performance

Legacy : current sparse linear solver (no parallelization)
MKLU : modified KLU solver (partial refactorization + parallelization)
MKLU+RefactBTF : modified KLU solver (BTF-based partial refactorization + parallelization)

Simulation speedups

Solution methods/Number of Cores	1 core	2 cores	3 cores	4 cores	5 cores
Legacy	1	-	-	-	-
MKLU	2.48	3.65	4.27	4.72	5.02
MKLU+RefactBTF	3.78	4.80	5.27	5.37	**5.71**

- **Most of the acceleration on one core (speedup of 3.8)**
- **Until 5.7 speedup, 1 s simulated in 8 mins**

Conclusions

- Demonstrated feasibility of EMT simulation of a large-scale network (the French Grid)
- An enhanced CIM/EMT interface
- Sparse linear solution + Partial Factorization + Parallelization to accelerate the simulation
- For the French grid, 1 s simulated in 8 min.

- Further works
  - Integration in EMTP
  - Add offshore wind parks and manufacturers models to the French grid modelling
  - Use of a parallel co-simulation platform

Thank you!
Q&A

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