

GRID EMT

SIMULATION INITIATIVE

BTD Detection and Re-ordering

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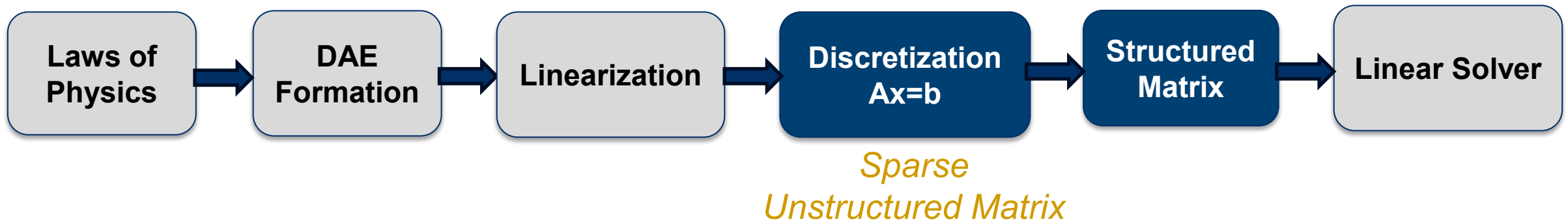
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Motivation

- **Slow Nature of EMT Simulation**

- Although EMT simulations involve sparse system matrices, arbitrary sparsity alone does not guarantee computational efficiency, as the underlying matrix structure may not be exploited during the solution process.
- **Reordering sparse matrices can reveal structure that enables the use of optimized solvers and parallel computation, thereby reducing computational cost and improving scalability.** e.g., reordering may expose **Block Diagonal (BD)** or **Block Tri-Diagonal (BTD)** structures that can be solved much more efficiently than a general sparse matrix.

Overall EMT Solver Workflow



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Approach

- **Matrix Structure Detection**

- **Input Matrices:** Sparse matrices with BD, BBD, BTD, or general sparse structures are provided to the detection model.
- **Matrix-to-Graph Conversion:** Each matrix row and column index is represented as a graph node, while nonzero off-diagonal entries define connections between nodes.
- **Graph Convolutional Network:** The GCN analyzes the connectivity pattern of the graph and learns the structural characteristics of the matrix.
- **Predicted Matrix Class:** The trained GCN classifies the matrix as BD, BBD, BTD, or General Sparse, and the predicted structure guides the selection of a suitable linear solver.

1. Sparse Matrix Input

BD, BBD, BTD & Normal Matrices

2. Graph Conversion

Nodes = Variables, Edges = Nonzeros

3. GCN Model

Topology-Aware Deep Neural Network

4. Predicted Class

Routes to Custom Parallel Solver



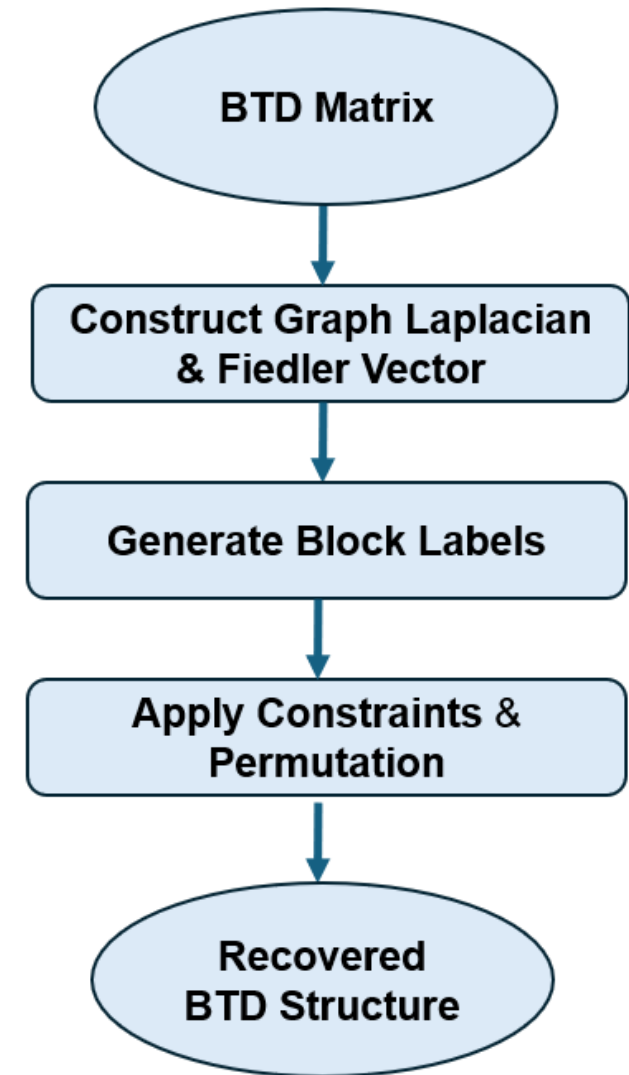
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Approach

- **Matrix Reordering**

- **BTD Matrix:** Input sparse matrix to be reordered.
- **Construct Graph Laplacian & Fiedler Vector:** Compute the graph Laplacian and extract the Fiedler vector to capture the matrix connectivity.
- **Generate Block Labels:** Partition the Fiedler vector into the desired number of diagonal blocks.

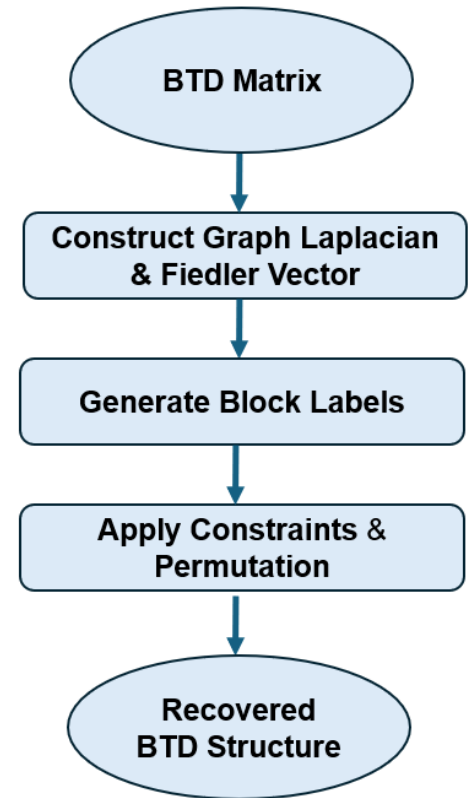


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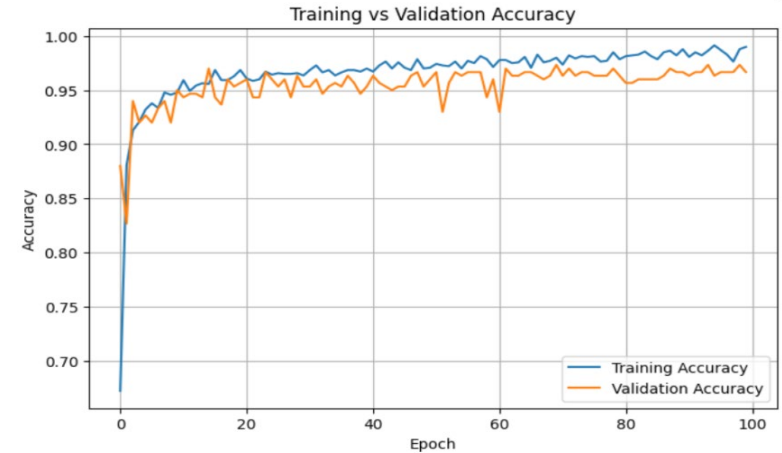
Approach (Cont.)

- **Apply Constraints & Permutation during Matrix Reordering**
 - **Constraint 1: Balanced Block Sizes**
Keep all diagonal blocks approximately equal in size.
Allow less than about 10% size difference.
 - **Constraint 2: Compact Off-Diagonal Blocks**
Keep off-diagonal non-zeros grouped close to the main diagonal.
 - **Constraint 3: Limited Spike Bandwidth**
Keep each left spike below half the size of the previous block.
Keep each right spike below half the size of the next block.
The first block has no left spike, and the last block has no right spike.
 - Constraints are generated based on solver's performance.
- **Recovered BTD Structure:** Obtain a solver-ready BTD matrix with preserved dimensions and non-zero entries.



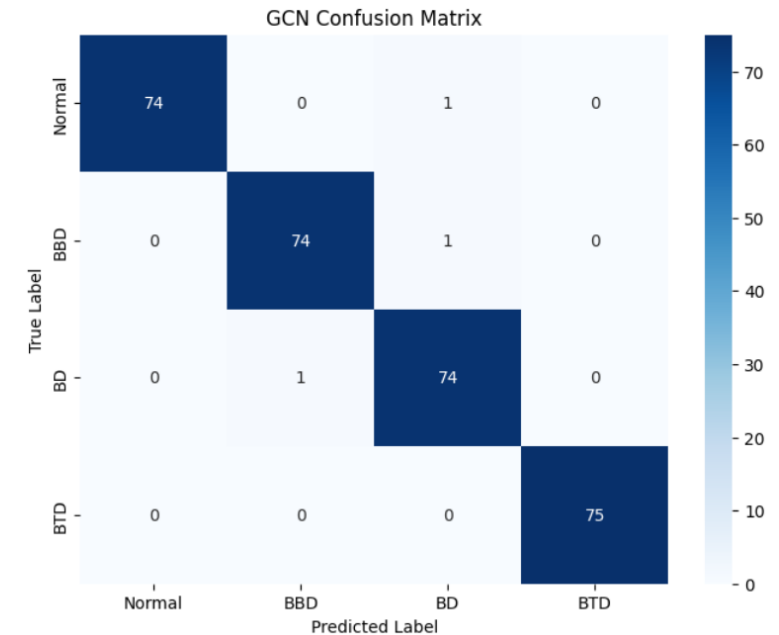
Results/Observations

- **Matrix Structure Detection using GCN**
 - Excellent convergence, reaching over 95% validation accuracy within the first 10–15 epochs.
 - High classification accuracy, with final training accuracy $\approx 99\%$ and validation accuracy $\approx 97\%$.
 - Stable learning behavior, as both training and validation accuracies plateau after convergence.
 - Minimal overfitting, with only a small ($\sim 2\%$) gap between training and validation accuracy.
 - Demonstrates strong generalization for accurately identifying matrix structures (BD, BBD, BTD, and General Sparse).
 - GCN inference time: 0.32s for 300 matrices (Google Colab)
Average inference time: 1.079 ms/matrix (Google Colab)
Time from graph preparation through test evaluation: 41.20 s (Google Colab)



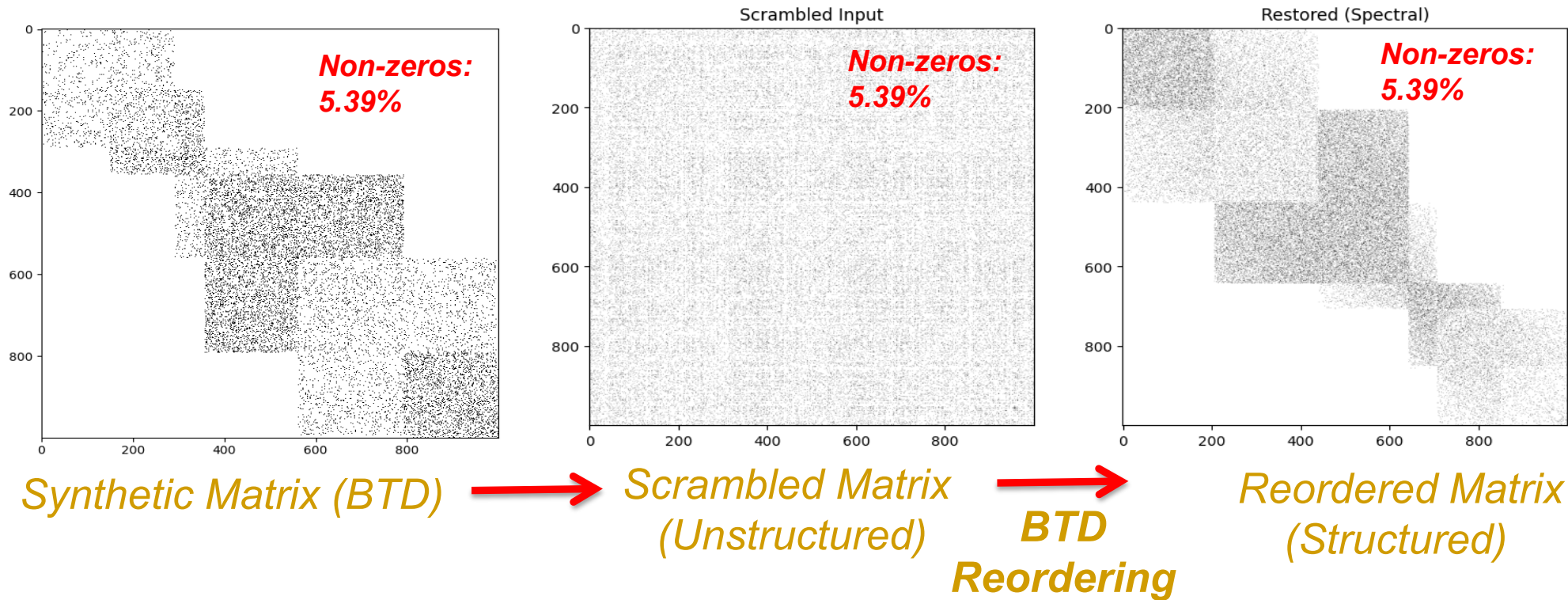
Results/Observations

- **Matrix Structure Detection using GCN**
 - One Normal matrix was misclassified as BD.
 - One BBD matrix was misclassified as BD.
 - One BD matrix was misclassified as BBD.
 - All 75 BTD matrices were classified correctly.
 - Only three misclassifications occurred: one Normal and one BBD matrix were classified as BD, while one BD matrix was classified as BBD.
 - BTD achieved 100% classification accuracy with no misclassifications.
 - Each class contains 75 test samples (300 total test)



Results/Observations

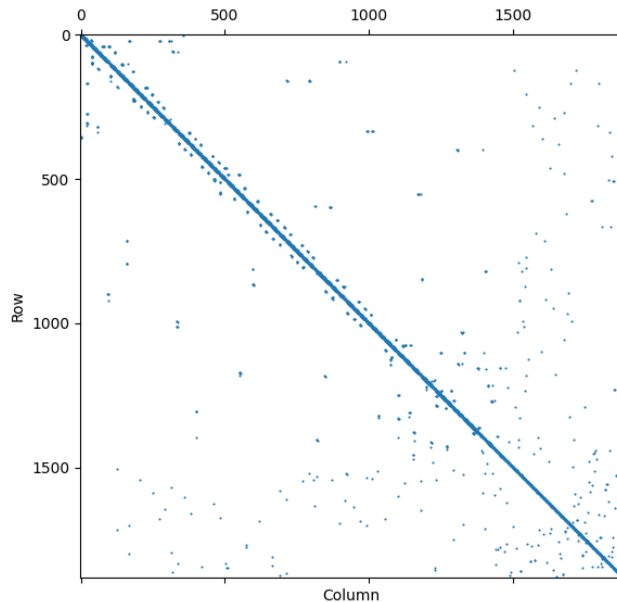
- Matrix Reordering



Results/Observations

- Matrix Reordering for IEEE 123 Node Test System**

Matrix representation of IEEE 123 Nodes System

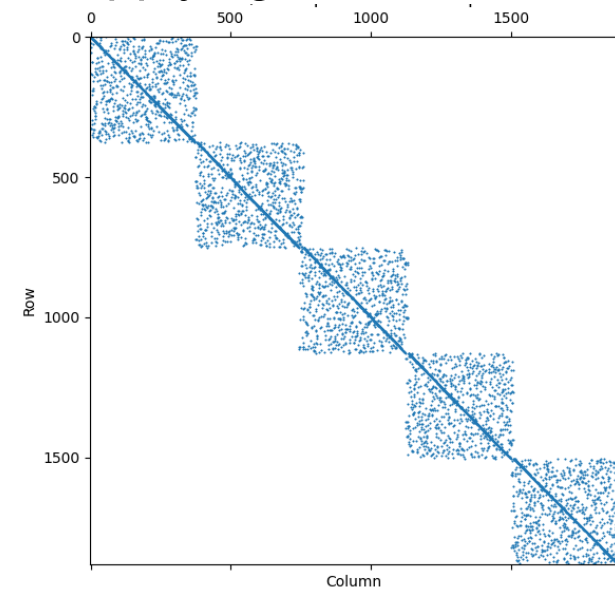


Matrix Shape: 1880 x1880
Number of non-zeros: 5645

BTD Reordering



Reordered IEEE 123-Node Test System
After Applying All Constraints



Matrix Shape: 1880 x1880
Number of non-zeros: 5645



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Conclusions

- Successfully classified Normal, BD, BBD, and BTD sparse matrices with high accuracy using a Graph Convolutional Network (GCN).
- Recovered BTD structures from synthetic sparse matrices and the IEEE 123-node test system through spectral graph-based reordering with solver-specific constraints.
- Demonstrated the feasibility of combining graph learning and constraint-based spectral reordering for automated matrix analysis and solver selection.
- Lessons learned from LLM Utilization:
 - **BTD reordering:** Accelerated Python-to-C++ conversion and debugging.
 - **GCN detection:** Supported GCN implementation and debugging.



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Next Steps

- Expand the training dataset and improve model robustness using enhanced computational resources.
- Extend the evaluation to larger power system test cases and investigate additional sparse matrix structures and solver-specific reordering strategies.
- Integrate the matrix classification and reordering modules into a complete end-to-end workflow within the RE-INTEGRATE framework.



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