Employing Graph Traversal Techniques to Simplify Three and Multi-Terminal Line Applications

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Powering A New Direction In System Protection

Presentation Outline

- Misoperation Report Analysis
- Graph Algorithms
- Three-Terminal Line Case Study
- Automation Application
- Conclusion

Grid Complexity

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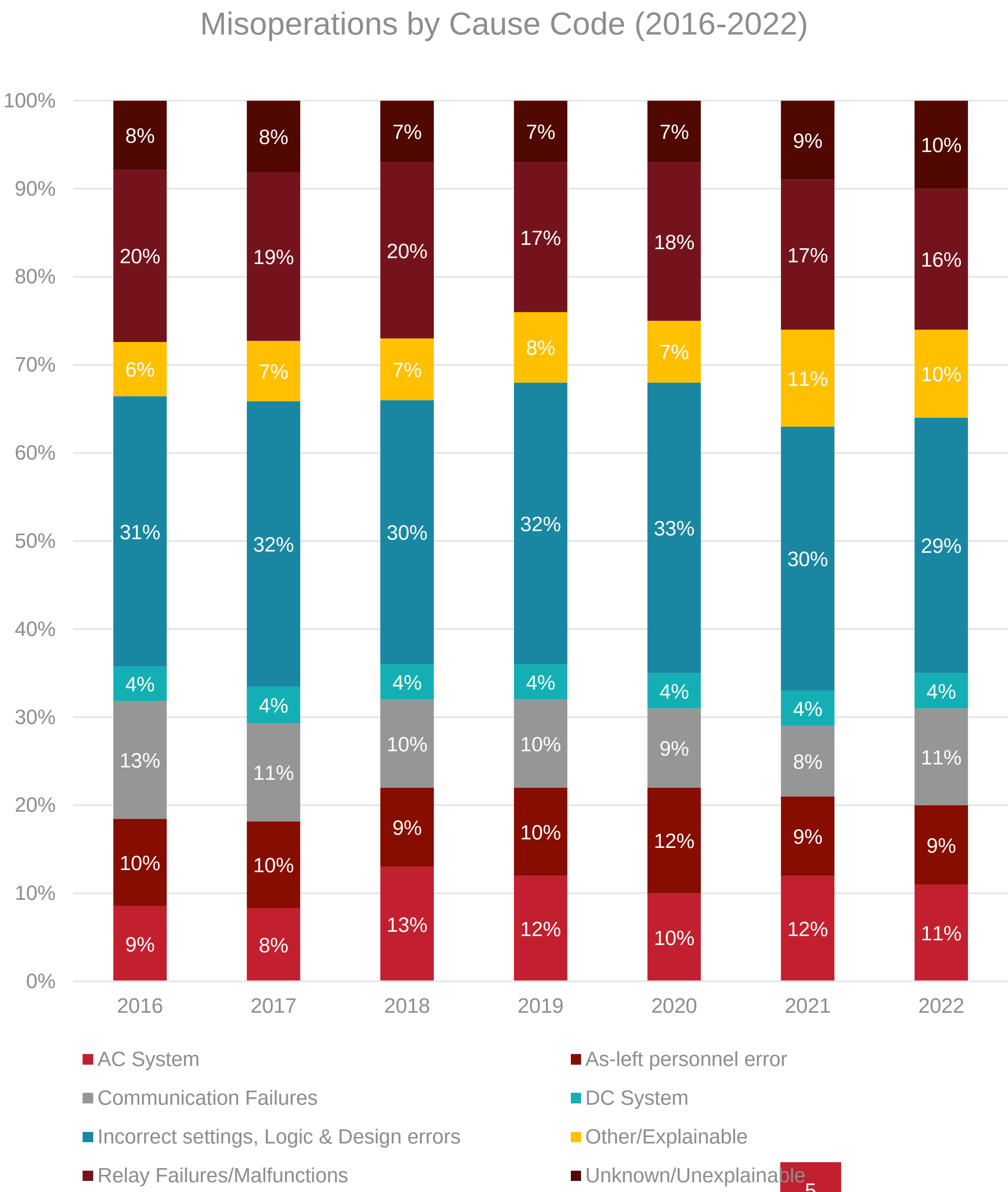
Growing Grid Complexity

- The electric grid is experiencing ever-growing complexities on all fronts due to advances in technology.
- Addressing this growing complexity requires a collective effort from all parties to keep the system reliable and coordinated.
- This growing grid complexity also means that the process of developing relay settings needs to become more meticulous to avoid needless power system operations.

Analysis of Misoperations

- According to NERC, the top causes of misoperations from 2016-2022 have consistently been incorrect settings and relay failures/malfunctions.
- These two reasons have accounted for around 50% of the misoperations in this timeframe.
- The single largest cause of misoperations is human error, accounting for around 40% of the misoperations in this timeframe.
  - The types of human error as-left personnel errors, incorrect settings, logic errors, and design errors.



Types of Human Error

- **As-left Personnel Errors** – Errors due to the as-left condition of the composite protection system following maintenance or constructions procedures.
  - For example, test switches left open, wiring errors, settings placed in the wrong relay, etc.
- **Incorrect Settings** – Errors issued in settings associated with electromechanical or solid-state relays, the protection element settings in microprocessor relays, and errors caused by inaccurate modeling.
- **Logic Errors** – Errors in logic settings and errors associated with programming microprocessor relay inputs, outputs, custom user logic, or protection function mapping to output points.
- **Design Errors** – Errors in physical design.
  - For example, incorrect configuration on ac or dc schematics, wiring drawings, incorrectly applied protective equipment, etc.
- One way to reduce the number of errors due to incorrect settings is to use automated solutions to assist in the settings development process.

Graph Overview

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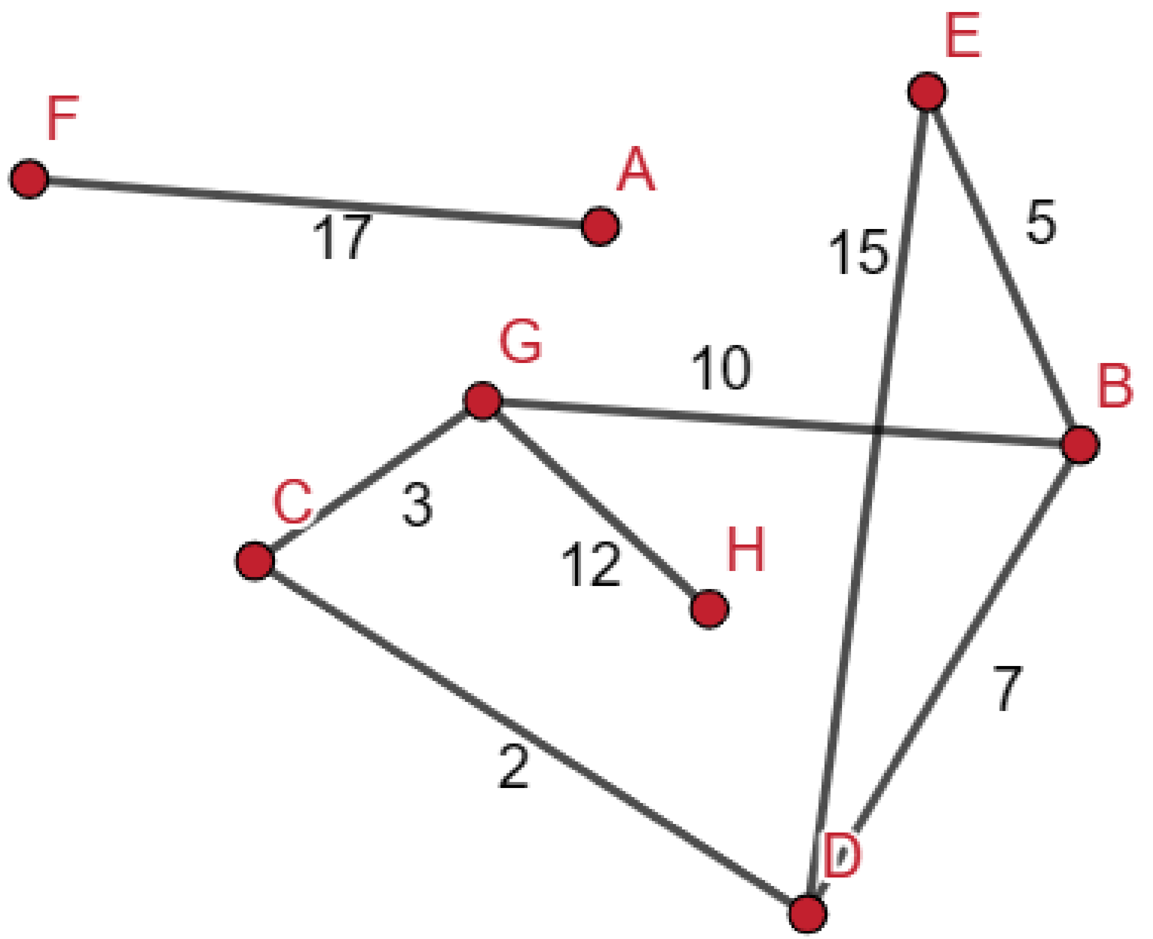
Graph Overview

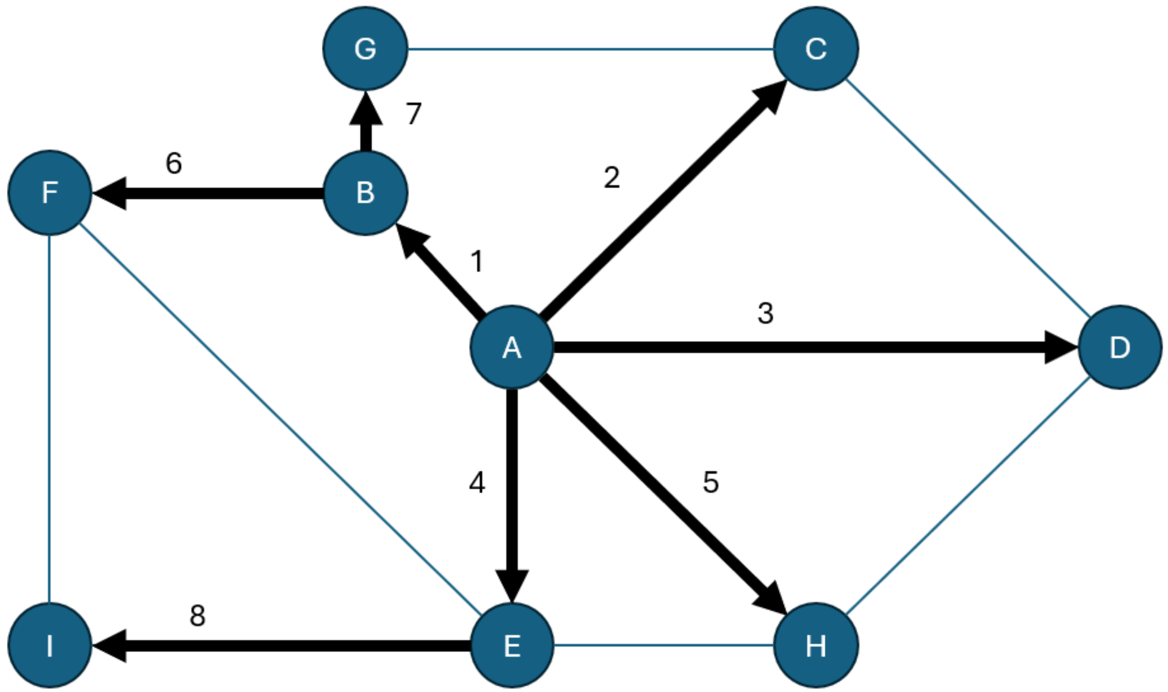
- **Definition** – In computer science, a graph data structure is a non-linear data structure consisting of vertices and edges.
  - Vertex – A vertex is one of the data points in the graph.
  - Edges – An edge connects two data points in the graph.
- Edges can have numerical quantities associated with them, called weights. A graph that has weighted edges is called a weighted graph.
- Edges can also have direction, meaning that they are one-way connections. A graph with directed edges is called a directed graph.
- **Example** – Google Maps. The edges represent segments of road and vertices represent travel locations and points where roads meet.



Common Graph Traversal Algorithms

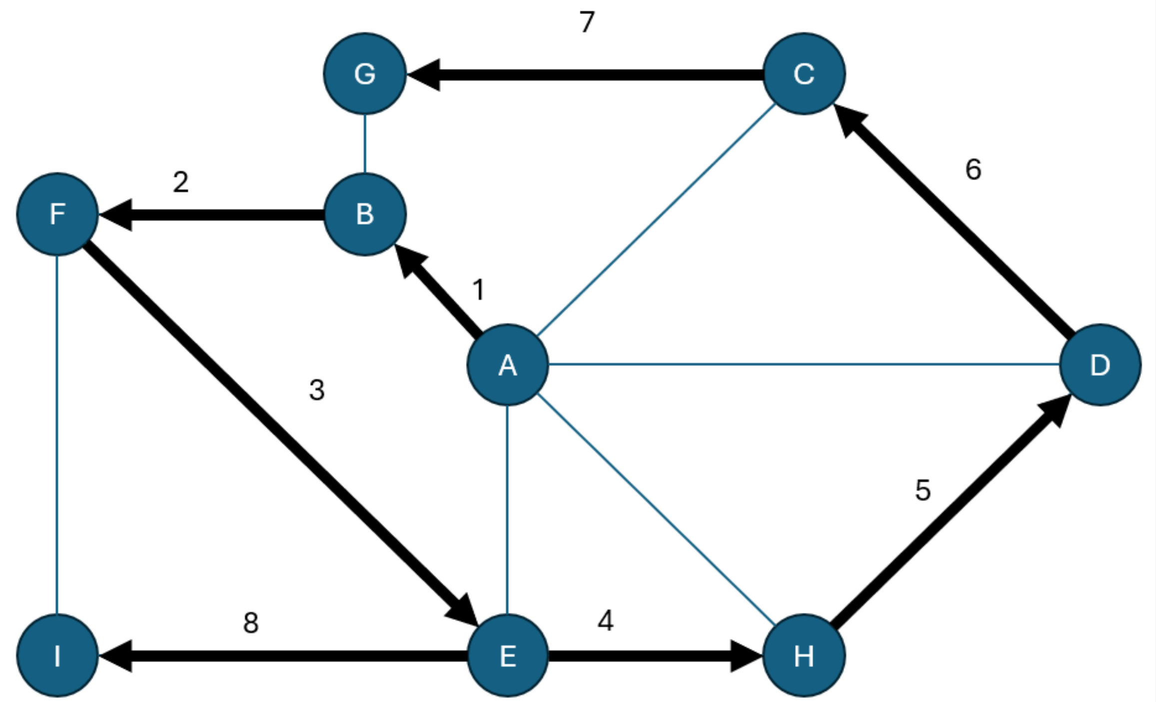
Breadth-First Search (BFS)

A graph traversal algorithm that explores all the vertices in a graph at the current depth before moving onto the vertices at the next depth level.



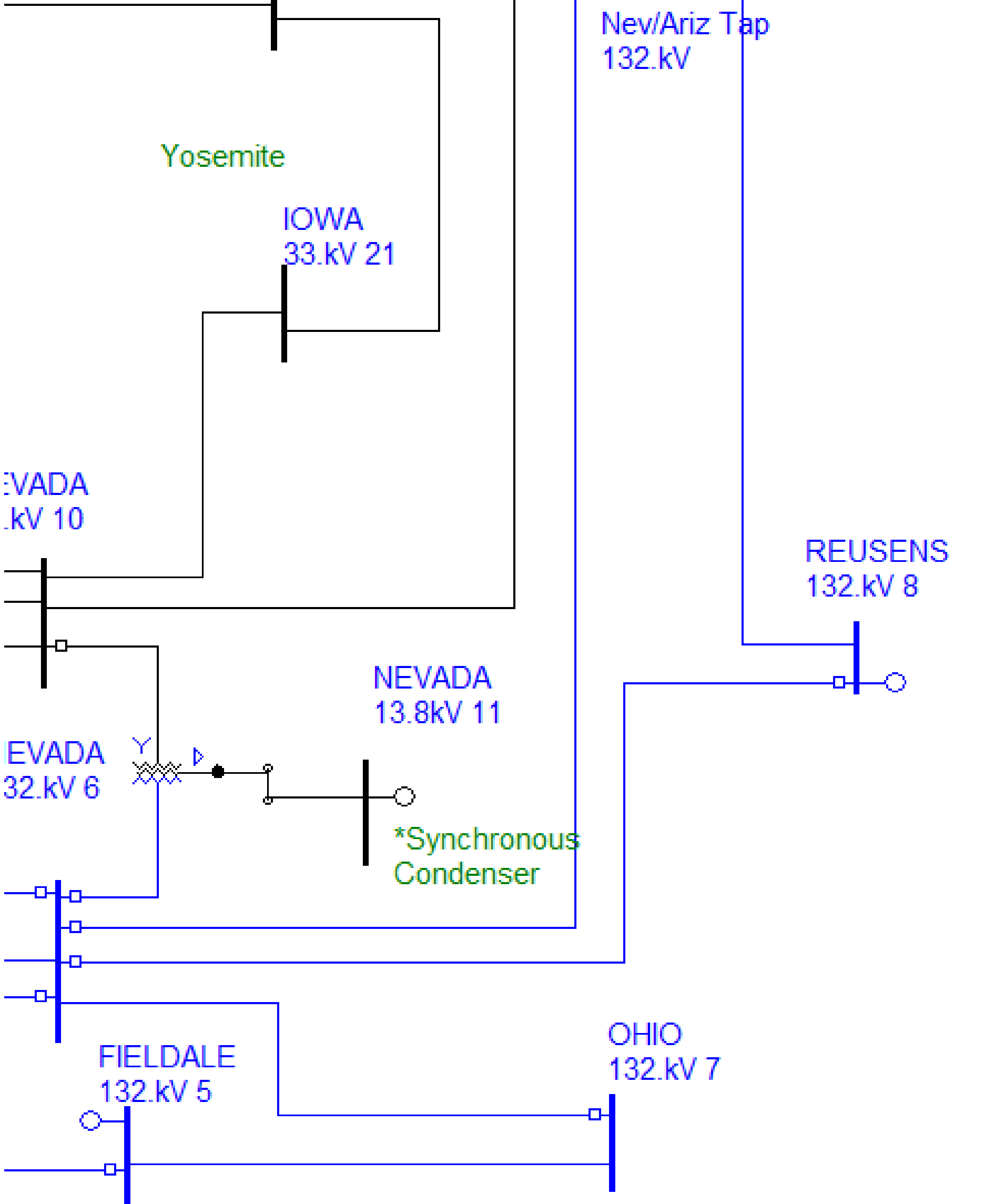
Depth-First Search (DFS)

A graph traversal algorithm that starts at one vertex in a graph and explores as far as possible along each branch before backtracking.



Application to Power Systems

- The power grid can be represented as a weighted, undirected graph.
  - The vertices represent buses.
  - The edges represent any pieces of equipment that connect buses.
    - Lines, switches, transformers, etc.
- By representing the power grid as a graph, we can take advantage of pre-existing graph algorithms and specialize them for use in settings development.



Three and Multi Terminal Lines

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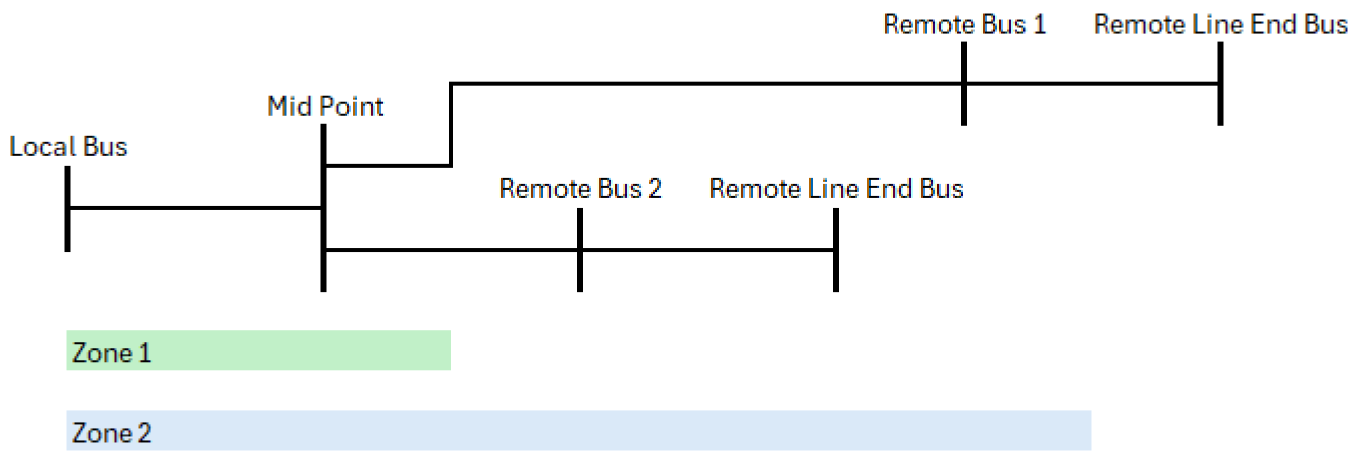
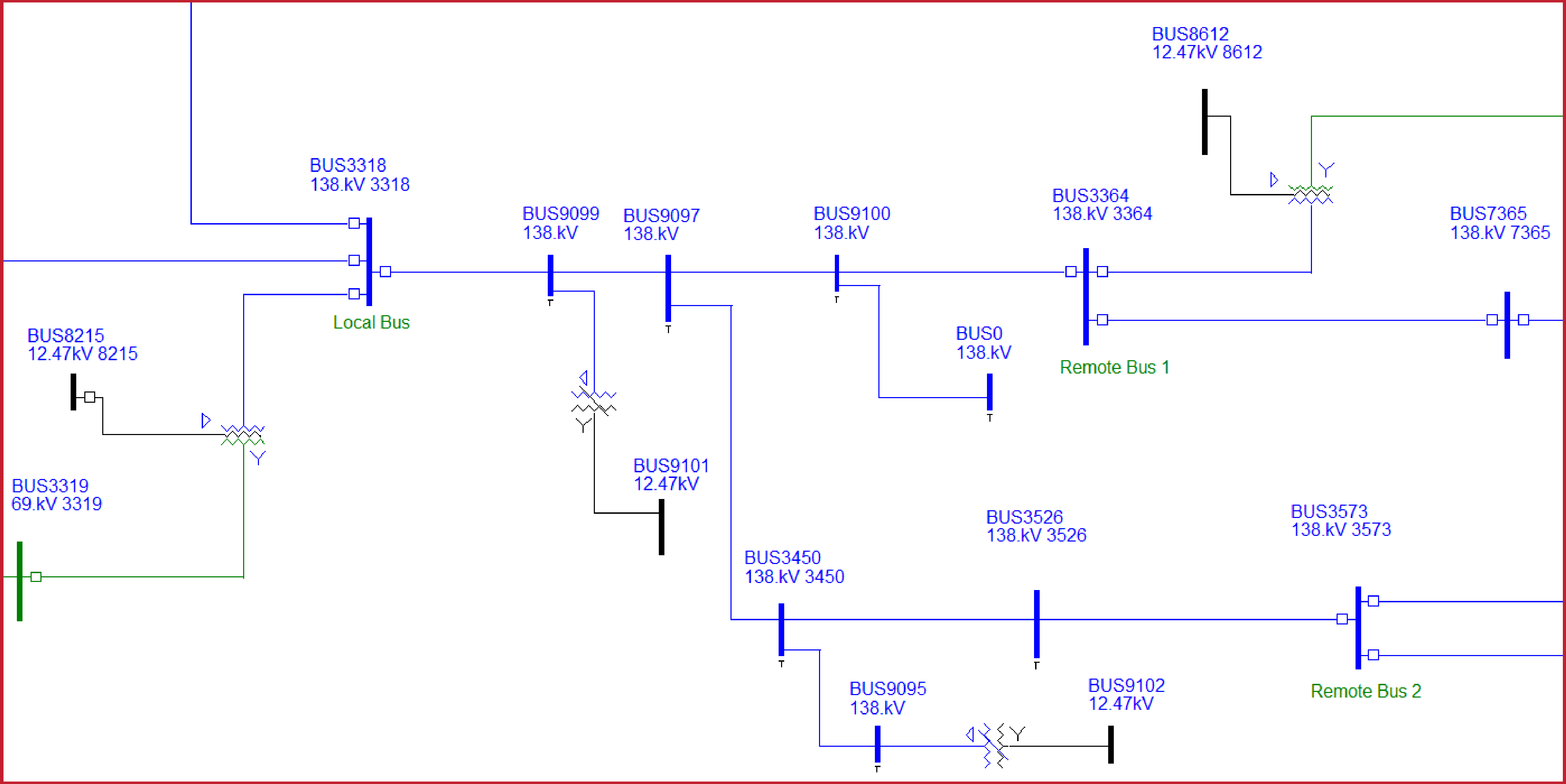
Developing Settings for Multi Terminal Lines

- A three terminal line is characterized by a line with a fork in the middle that leads to three separate buses with their own sources and loads. Three sets of settings need to be calculated, one from each end.
- Both paths from each bus need to be considered and their impedances calculated separately.
- The settings must be generalized to work for both as much as possible, though perfect solutions may be impossible in some cases.
- A simple example of this is shown below, where the impedance of one of the paths overreaches the remote line of the other path.



Case Study



BUS8612
12.47kV 8612
BUS3318
138.kV 3318
BUS9099
138.kV
BUS9097
138.kV
BUS9100
138.kV
BUS3364
138.kV 3364
BUS7365
138.kV 7365
Local Bus
BUS8215
12.47kV 8215
BUS0
138.kV
Remote Bus 1
BUS3319
69.kV 3319
BUS9101
12.47kV
BUS3526
138.kV 3526
BUS3573
138.kV 3573
BUS3450
138.kV 3450
BUS9095
138.kV
BUS9102
12.47kV
Remote Bus 2

Case Study Considerations

- There are many tap buses, which necessitates the retrieval of many R and X values to get the full impedance values of each line.
- There are two tapped lines and two distribution transformers.
- Line settings will need to be made to operate on each main path of the line and each tap line but not on the other side of the distribution transformers.
- There are many lines and transformers connected to the three ends.
- All of these as well as any mutually coupled lines must be taken out to ensure correct behavior in alternate grid conditions.
- This would be a significant amount of issues to consider, but using a graph to represent this system with the surrounding lines opens the door to a very streamlined process.
- This will guarantee that nothing gets missed.

Application

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Gathering Information

- By representing the grid using a graph, we can use various grid traversal algorithms to automatically analyze and record data for a relay settings project.
- Both sections of the primary line are identified and their respective impedances are calculated.
- All other equipment is found in the same way: source lines, remote lines, distribution transformers, tap lines, and mutually coupled lines.
- All of these values are displayed and stored for use in any future calculations.
- This greatly reduces the chances for error from manual calculations and copying and pasting.

PRIMARY LINE

3573 BUS3573 (LONGEST SEGMENT)	
Positive Sequence Magnitude (pu)	0.13719
Positive Sequence Angle (°)	77.20941
Zero Sequence Magnitude (pu)	0.45084
Zero Sequence Angle (°)	77.88022
Length (mi)	34.0089
3364 BUS3364 (SHORTEST SEGMENT)	
Positive Sequence Magnitude (pu)	0.08419
Positive Sequence Angle (°)	67.58063
Zero Sequence Magnitude (pu)	0.25558
Zero Sequence Angle (°)	73.94344
Length (mi)	18.703

Running Calculations

- All the calculated values are stored and able to be viewed symbolically.
- All the symbolic equations are created in the template and then filled in automatically during the project.
- For example, $SPLS_{Z1MAG}$ represents the shortest primary line segment's positive sequence impedance and $LPLS_{Z1MAG}$ represents the longest primary line segment's positive sequence impedance.
- We can use $SPLS_{Z1MAG}$ to calculate the zone 1 phase setting to ensure that it under-reaches the nearest remote bus.
- Likewise, we can use $LPLS_{Z1MAG}$ to calculate the zone 2 setting to ensure that it overreaches the farthest remote bus.
- Apparent impedance results from specific faults can also be used in these calculations if they are specified in the template beforehand.

Z1P (Ω, SEC) ··· **1.64**

Zone 1 Phase Reach

$$Z1P = SPLS_{Z1Mag} \cdot BaseOhms \cdot \left(\frac{CTR}{PTR}\right) \cdot 0.85$$ 1.64

Z2P (Ω, SEC) ··· **3.76**

Zone 2 Phase Reach

$$\mathrm{A} = LPLS_{Z1Mag} \cdot BaseOhms \cdot \left(\frac{CTR}{PTR}\right) \cdot 1.2$$ 3.76

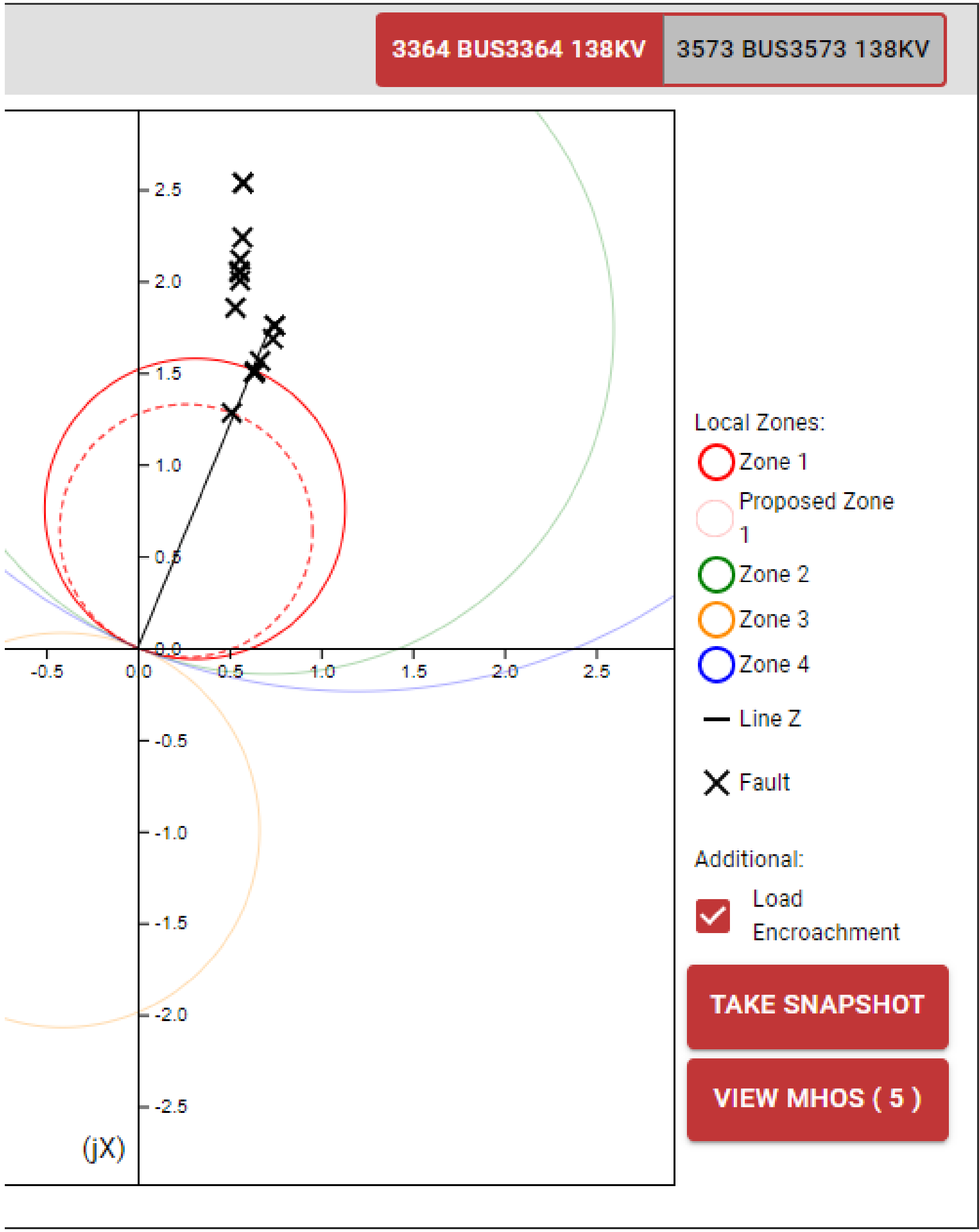
$$\mathrm{B} = \mathrm{mag}\left(LPLS_{Z1} + 0.5 \cdot SRL_{Z1}\right) \cdot BaseOhms \cdot \left(\frac{CTR}{PTR}\right)$$ 3.25

$$Z2P = \max\left(\mathrm{A}, \mathrm{B}\right)$$ 3.76

Comments

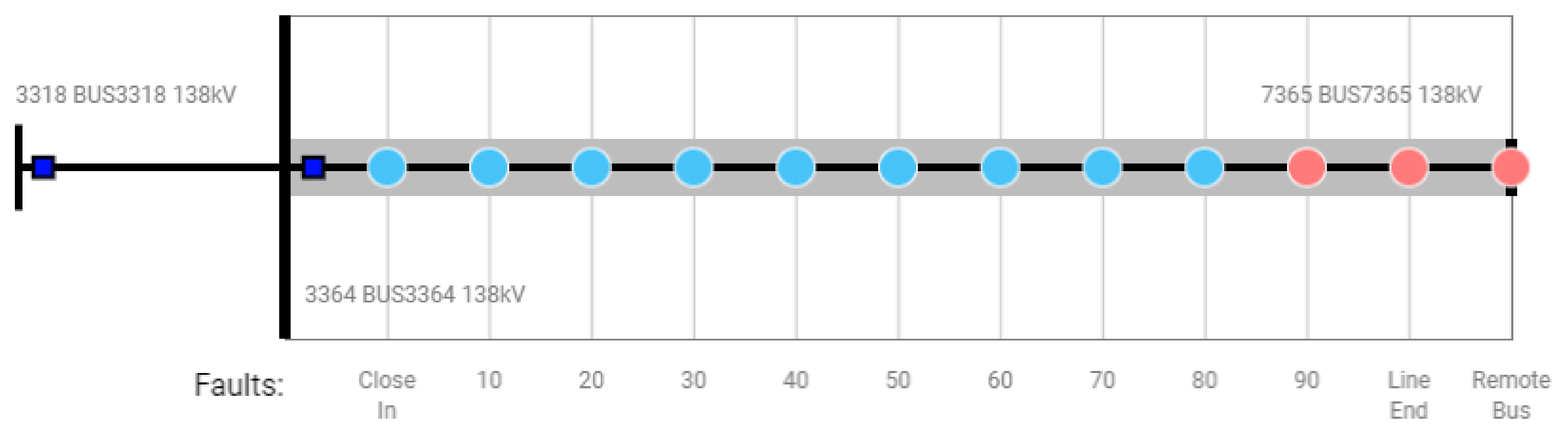
Calibrating Settings

- After all the settings have been calculated, a significant portion of the testing can be done using many of the same automation techniques.
- In this example, a reach check is being done to detect under or over reaching zone settings.
- In this case, faults are placed at the desired reach (80% for each line end) under n-1 contingencies.
- The fault with the lowest apparent impedance should be used to ensure the setting doesn't over reach.
- A similar testing process can be done for the other settings as well.



Coordination Time Interval Checks

- A coordination check can also be done with existing relays.
- This ensures that the timings of newly calculated settings will properly coordinate with existing neighboring relays.
- The example shows results when faults are placed on the remote line of the shortest primary path.
- The results indicated that the zone 2 of the primary relay was calculated to be very high and so the engineer should increase the time delay to achieve coordination.



Conclusion

- The plurality of relay misoperation have been and continue to be human error.
- The increased size of the grid has necessitated a higher number of multi-terminal lines and difficulty in system protection.
- Turning to methods of automation will reduce the number of human errors and make for a more sustainable process.