Steady-State Power System Security Analysis with PowerWorld Simulator

S10: Integrated Topology Processing

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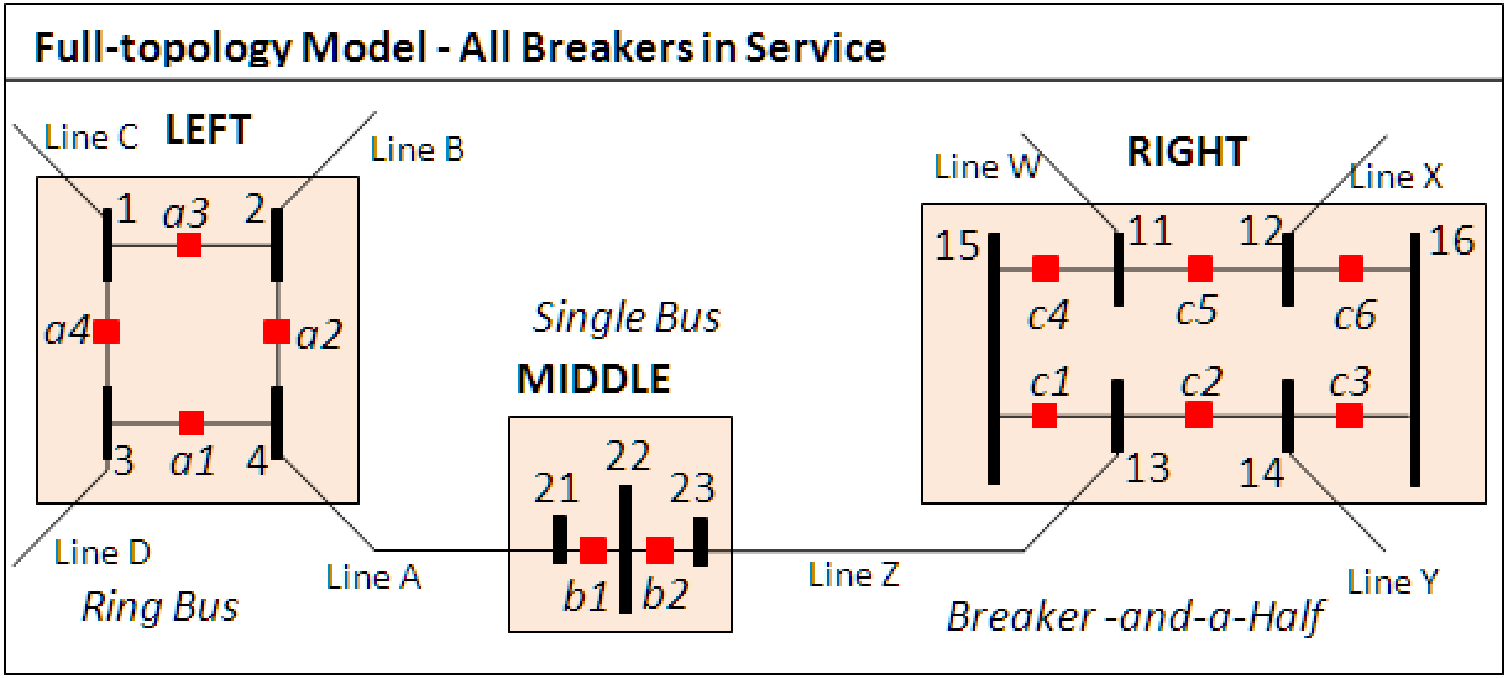
Introduction

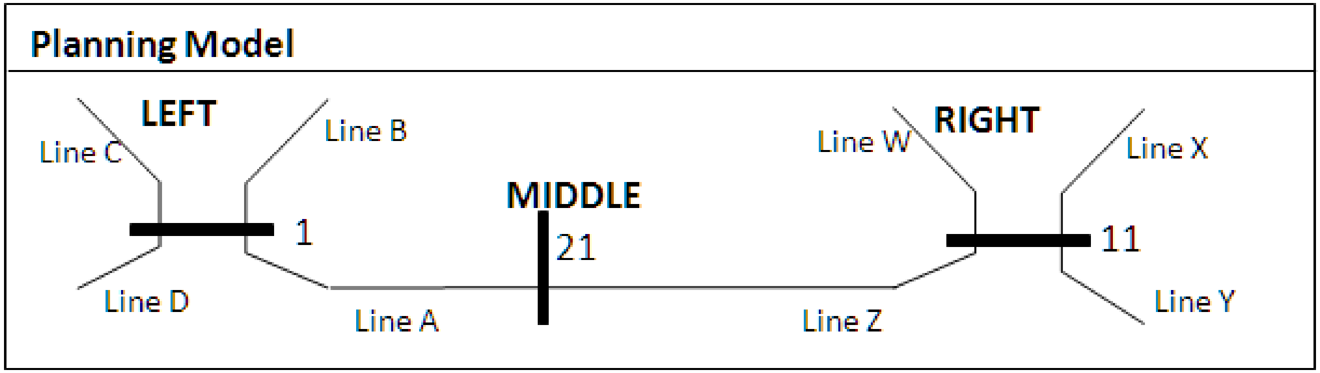
- Integrated Topology Processing (ITP) is a tool that allows Simulator to analyze full-topology cases, by obtaining and solving a smaller, planning-type representation of the network
- ITP consists of two main features:
  - An algorithm that takes place behind the scenes, and that is used internally during numeric solution such as power flow, ATC, etc.
  - A tool to convert the full-topology case to a more traditional planning model which can then be saved as a file that can be consumed software not able to read the full-topology model

Motivation

- Problem
  - Model and Auxiliary Data Maintenance
    - Separate real-time and planning models
    - Topology changes every time that the planning model is exported meaning that a simple bus mapping cannot be used
    - Impossible to maintain auxiliary data such as contingency definitions, interface definitions, cost data, etc. with constantly changing planning model
- Solution
  - PowerWorld's Integrated Topology Processing
    - Utilize the full-topology model directly
    - Only maintain a single model, the full-topology model
    - Update model only when node-breaker topology changes
    - Auxiliary data remains compatible with full-topology model regardless of breaker status and topology

Motivation
Invalid Contingency Simulations

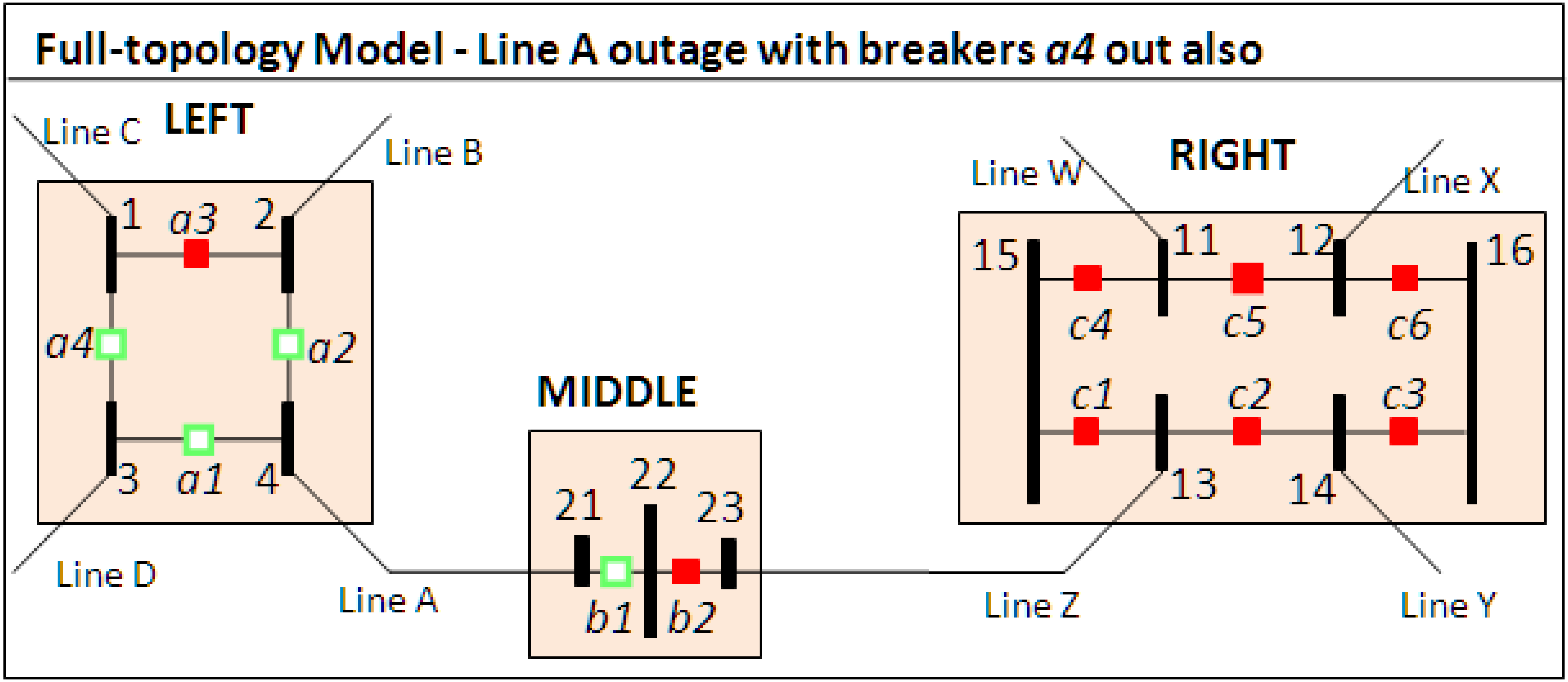




Motivation
Invalid Contingency Simulations

- How is outage of Line A modeled?
  - Planning Model
    - Open Line A
  - Actual System
    - Open breakers *a1*, *a2*, and *b1*
  - Assuming all breakers have same status as original configuration from which planning case was created, then this is a correct simulation in planning case
  - What if a breaker is out for maintenance?

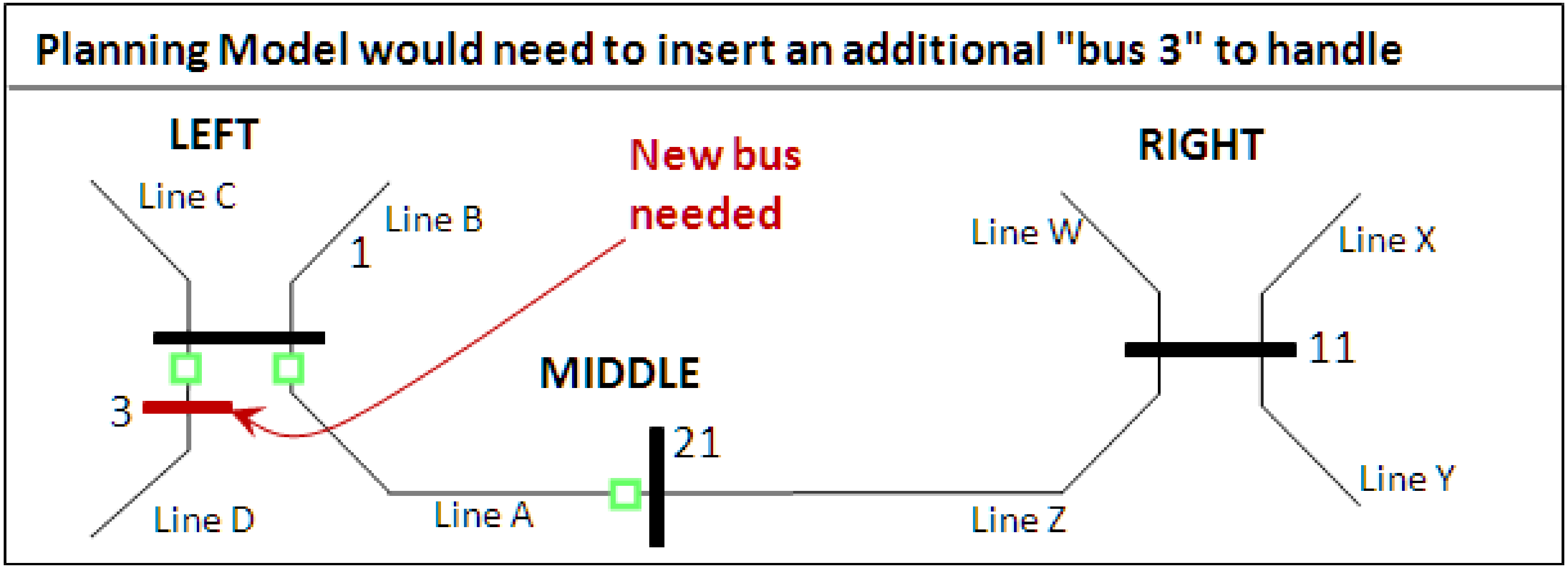
Motivation
Invalid Contingency Simulations



Motivation
Invalid Contingency Simulations

- How is outage of Line A modeled along with open breaker *a4*?
  - Planning Model
    - Open Line A
    - No other lines are isolated
    - Bus split not captured
  - Actual System
    - Open breakers *a1*, *a2*, and *b1*
    - Line D isolated from Line B and Line C
  - Modification of planning model is required to correctly model this condition

Motivation
Invalid Contingency Simulations



Motivation
Invalid Contingency Simulations

- Problem
  - Certain breaker outages in the real-time model require modifications of the planning model
    - New buses needed
    - New contingency list to match bus numbers
    - Modification of supporting data such as injection groups or interfaces
    - Effects could also be ignored creating incorrect contingency results

Motivation
Invalid Contingency Simulations

- Solution
  - Simulator Integrated Topology Processing handles these situations automatically
    - Full-topology model is maintained with appropriate breaker statuses incorporated in the solution algorithm
    - No need to modify contingency list and other supporting data

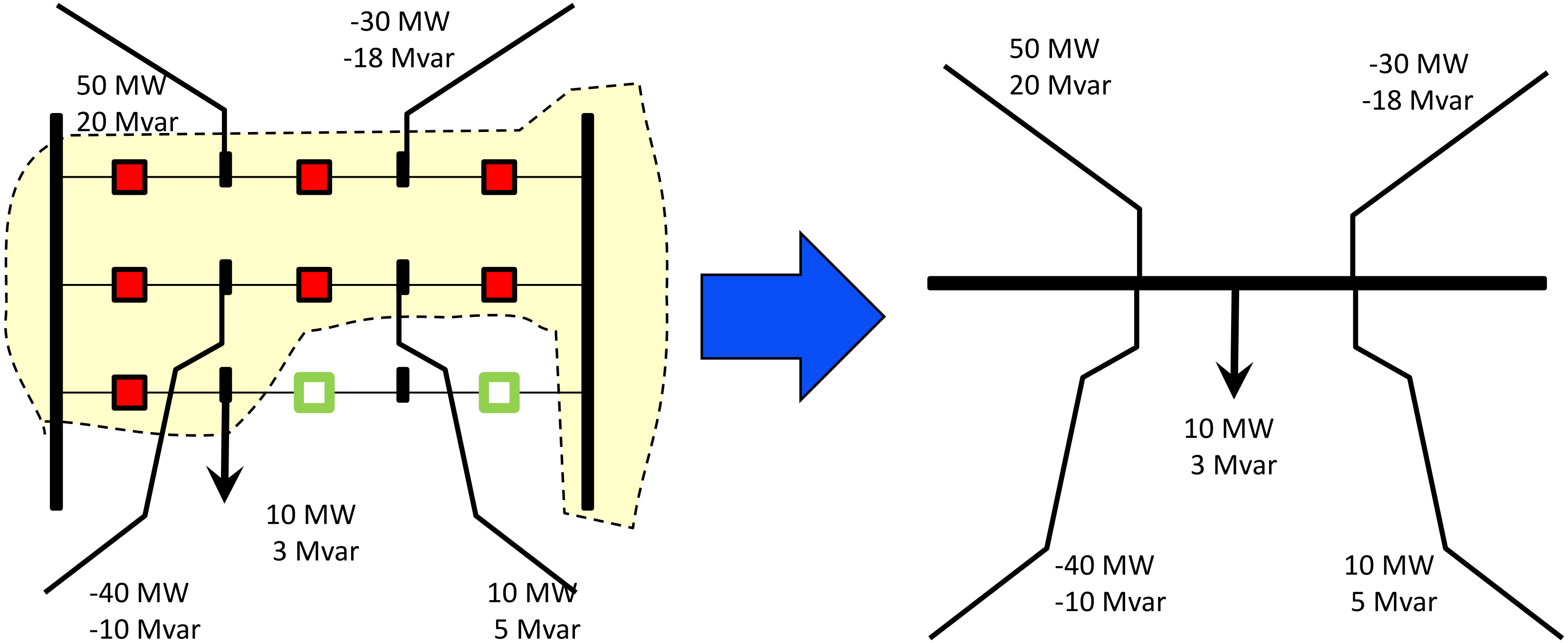
EMS and Planning Models

EMS Model

- Used for real-time operations
- Call this ***Full-Topology*** model
- Has *node-breaker* detail

Planning Model

- Traditionally for off-line analysis
- We call this ***Consolidated*** model
- Has *bus-branch* detail



Modeling

- A *SuperBus* in the full topology model is a group of buses connected through **closed** breakers
  - These buses correspond to the same electric point
- During Topology Processing, the buses in a superbus are merged resulting in a single bus. We call this process *Consolidation*.
- The consolidated case, as any case used in planning, consists only of these merged buses
  - Consolidation removes the breakers (zero impedance branches) from the model, which is necessary to avoid numerical solution problems

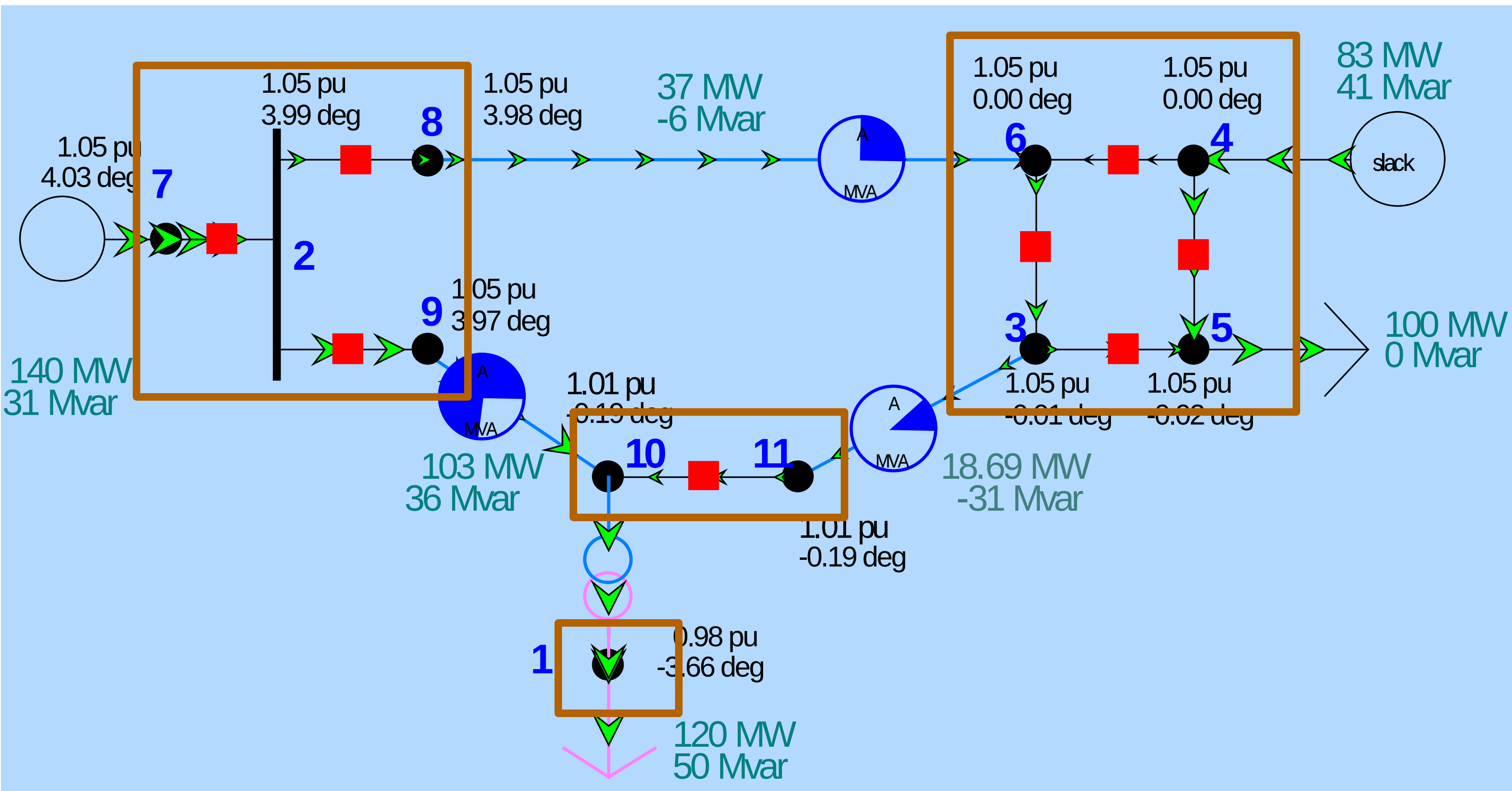
Modeling

- Note that since information about the breaker topology is lost during the bus merging, **it is not possible** to obtain a full model from the consolidated model.

- EMS systems do internally a type of consolidation that use separate objects and data structures for buses and superbuses
- We'll describe later on how Simulator uses a single object (a bus) to model both a bus and a superbus

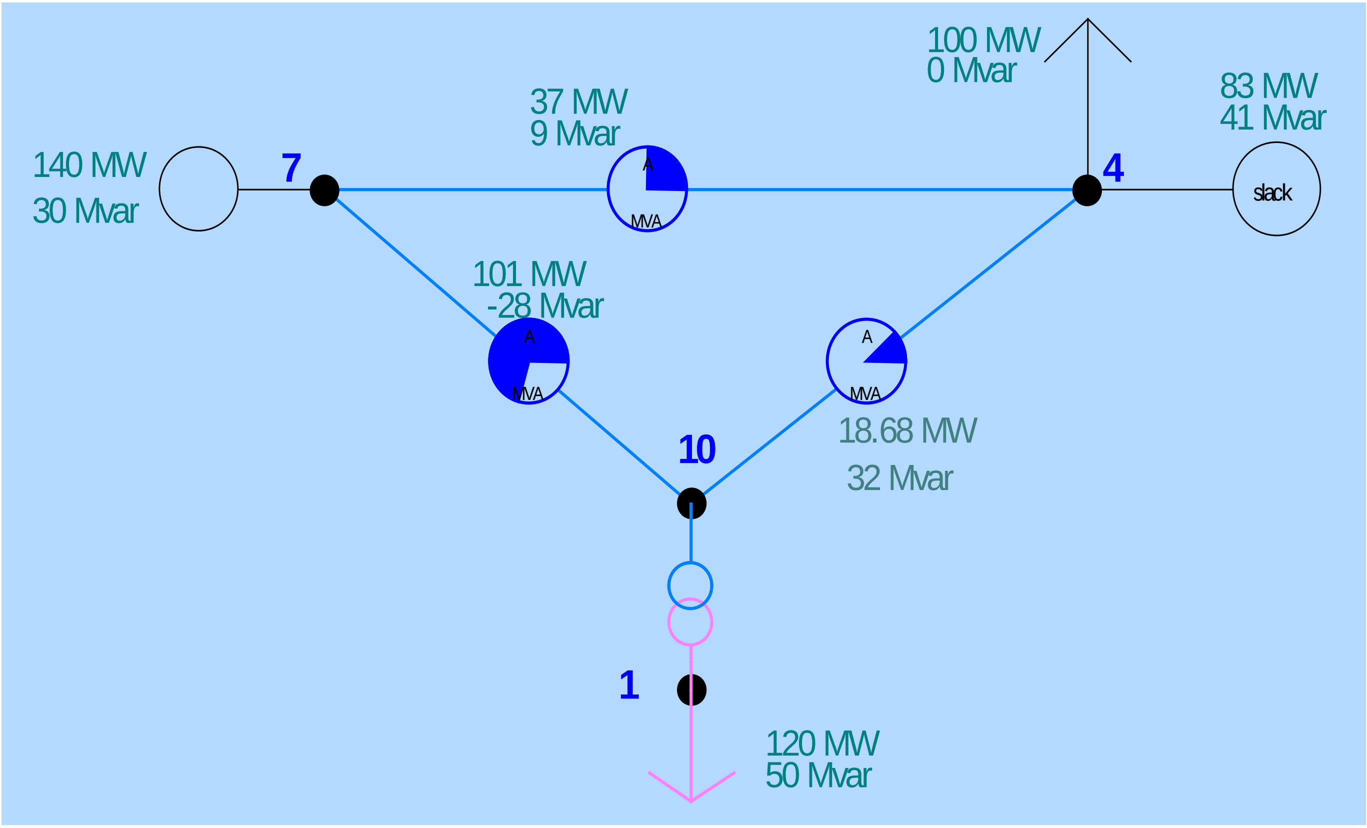
Modeling

- Example: Full-Topology, 11-Bus Model with 4 Superbuses



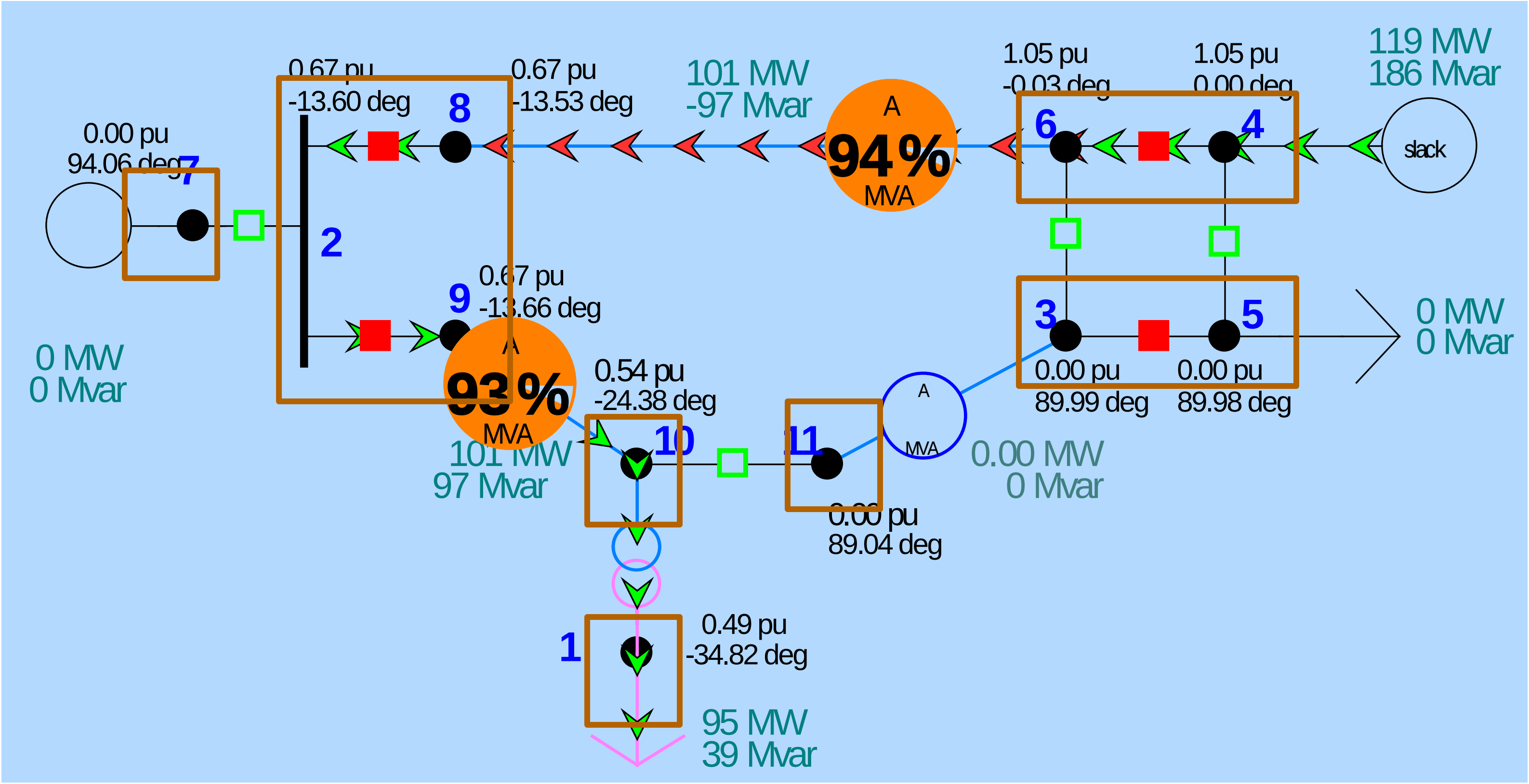
Modeling

- Planning Equivalent with 4 Buses



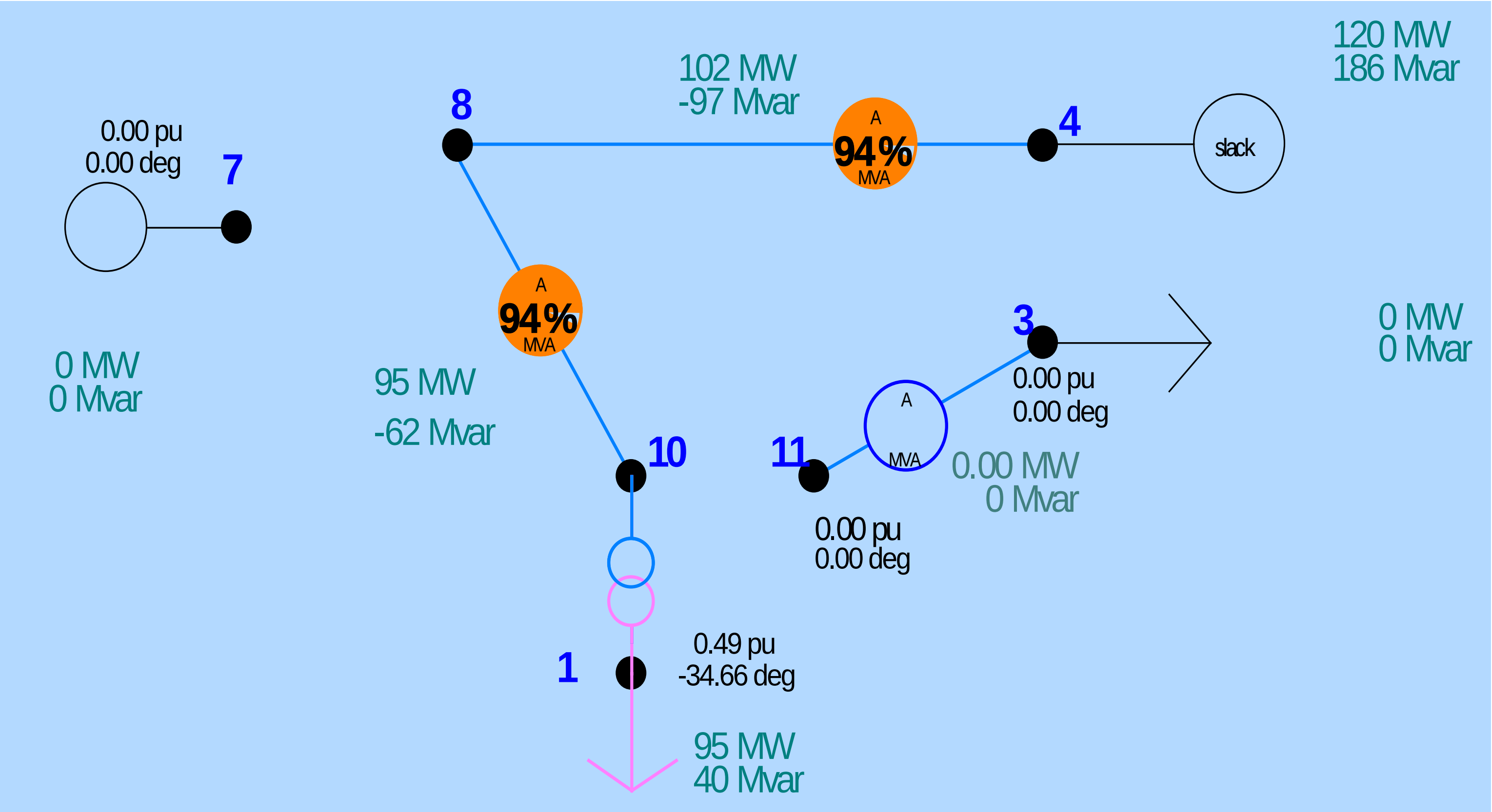
Modeling

- Same 11-Bus Model with 7 Superbuses



Modeling

- Planning Equivalent with 7 Buses



Modeling

- Simulator models EMS systems and planning cases using the same (planning) format
- In the planning format every two-terminal device is modeled using a branch record
- Full model breakers are also modeled in Simulator using the branch records. Therefore, Simulator needs to know:
  - The type of each branch: xfrmr, line, CB, etc.
  - The branches that can be treated as zero impedance and that can be consolidated

Modeling

Branch Records

Line and Transformer Records | Buses

Records ▾ Geo ▾ Set ▾ Columns ▾ Options ▾

	Branch Device Type	Allow Consolidation	From Number	To Number	Circuit	Status	Xfrmr	R	X	B	Lim A MVA
1	Transformer		10	1	1	Closed	YES	0.00000	0.05000	0.00000	0.0
2	Line		3	11	1	Closed	NO	0.05000	0.10000	0.00000	300.0
3	Line		6	8	1	Closed	NO	0.04000	0.20000	0.00000	150.0
4	Line		9	10	1	Closed	NO	0.01500	0.08000	0.00000	150.0
5	Breaker	YES	6	3	1	Closed	NO	0.00000	0.00050	0.00000	0.0
6	Breaker	YES	2	8	1	Closed	NO	0.00000	0.00050	0.00000	0.0
7	Breaker	YES	3	5	1	Closed	NO	0.00000	0.00050	0.00000	0.0
8	Breaker	YES	6	4	1	Closed	NO	0.00000	0.00050	0.00000	0.0
9	Breaker	YES	4	5	1	Closed	NO	0.00000	0.00050	0.00000	0.0
10	Breaker	YES	2	9	1	Closed	NO	0.00000	0.00050	0.00000	0.0
11	Breaker	YES	10	11	1	Closed	NO	0.00000	0.00050	0.00000	0.0
12	Breaker	YES	7	2	1	Closed	NO	0.00000	0.00050	0.00000	0.0

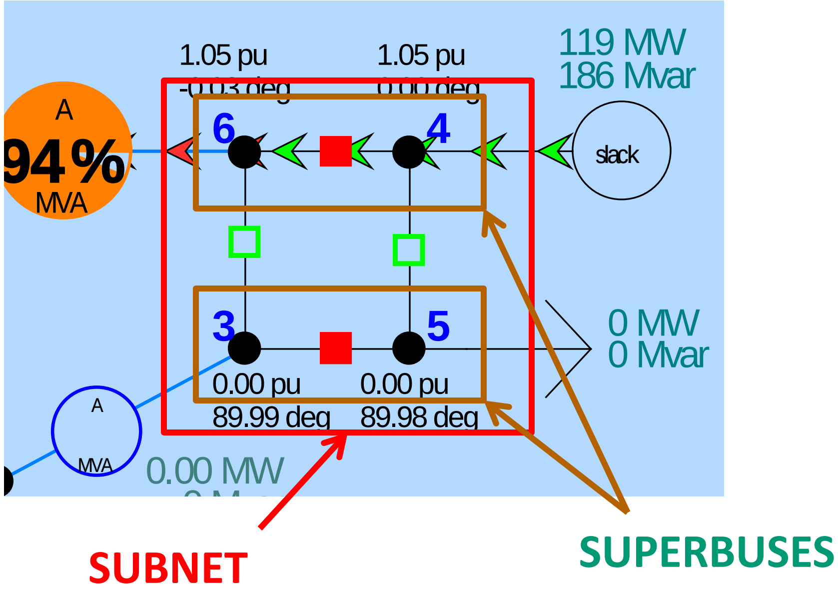
Branch Device Type:
Transformer, Line
Breaker, Series Cap,
Phase Shifter

Allow Consolidation:
If YES, then this branch is treated as a zero impedance branch.

Breakers used default values, including a very low reactance

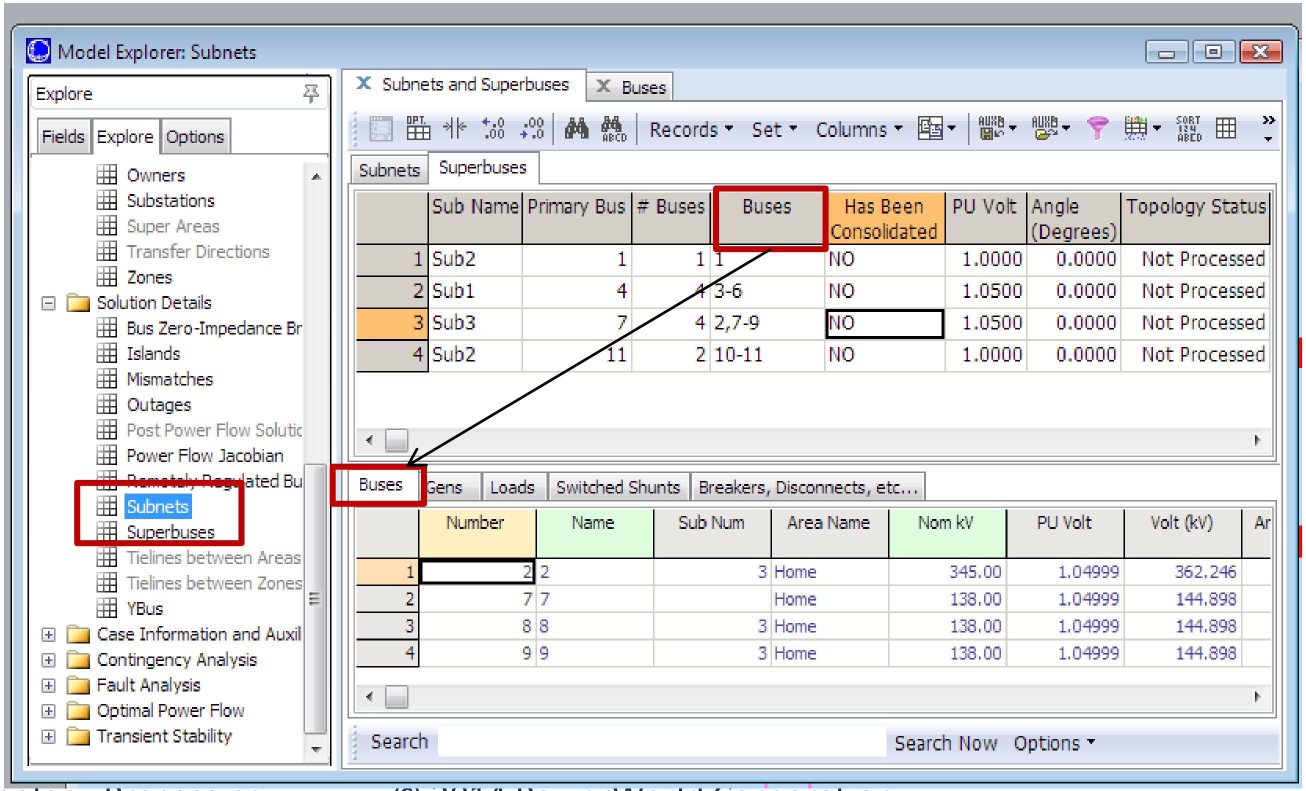
Modeling

- A *Subnet* is a group of buses connected through breakers regardless of the breakers' status
- Subnets are bounded by transmission line and transformer terminals
- Subnets contain one or more superbuses
- A superbus can be in only one subnet



Exploring the Case

- Subnets and Superbuses are set automatically when the case is read from the binary or aux file
- Open **Model Explorer, Solution Details, SuperBuses**



Exploring the Case

Superbus Records

Substation Name
Superbuses 1 and 4
Are in the Substation 2

Aggregate quantities for
each superbus

Subnets | Superbuses

	Sub Name	Primary Bus	# Buses	Buses	Has Been Consolidated	PU Volt	Angle (Degrees)	Topology Status	Gen MW	Gen Mvar	Load Mvar	Load MW	Switched Shunts Mvar
1	Sub2	1	1	1	NO	1.0000	0.0000	Not Processed			50.00	120.00	0.00
2	Sub1	4	4	3-6	NO	1.0500	0.0000	Not Processed	82.76	40.82	0.00	100.00	0.00
3	Sub3	7	4	2,7-9	NO	1.0500	0.0000	Not Processed	140.00	30.37			0.00
4	Sub2	11	2	10-11	NO	1.0000	0.0000	Not Processed					0.00

This bus would
be preserved in the
consolidated model

All the buses in *each*
superbus will have exactly
the same voltage phasor

Topology Processing

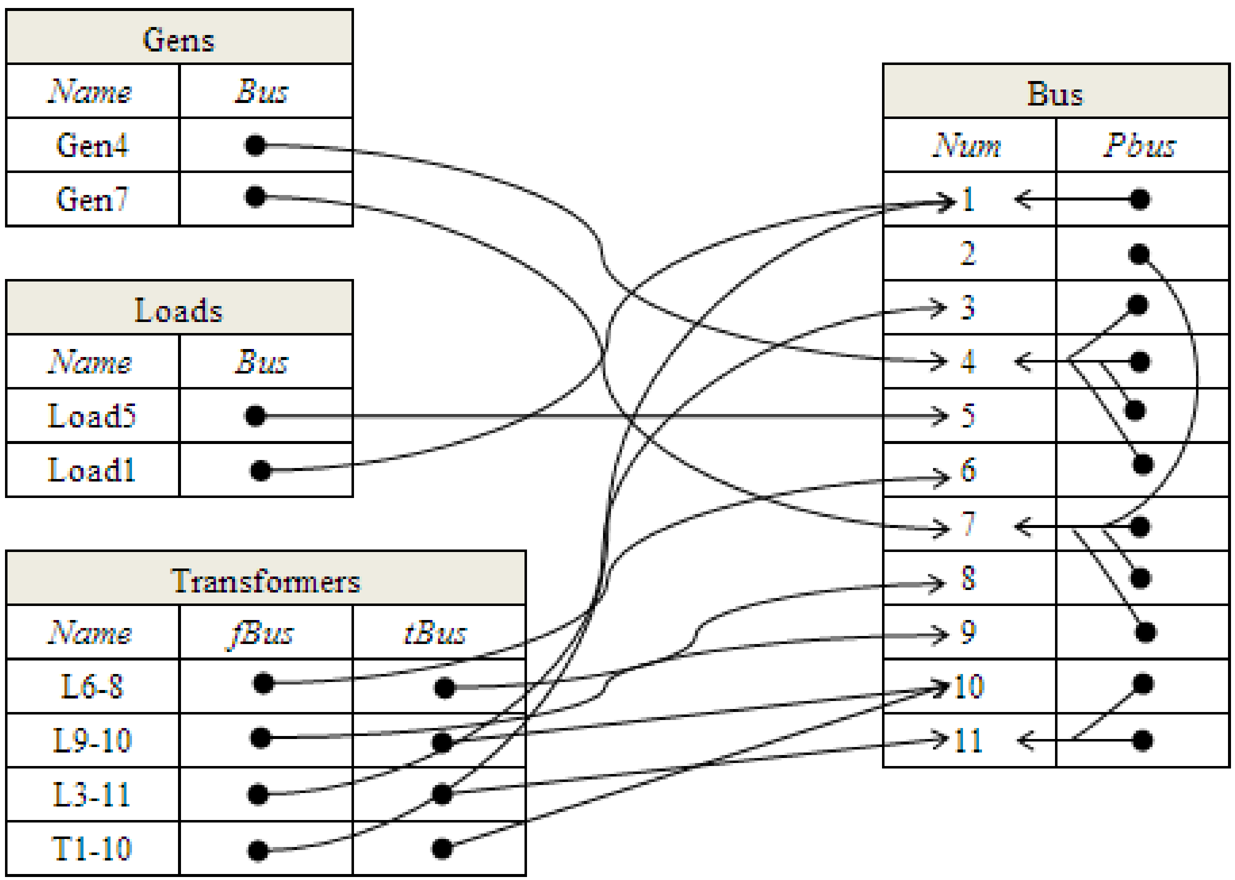
- The buses of a superbus will be merge into a the *Primary Bus* (also called the *pBus*)
- The primary bus is selected base on a priority scheme:
    - Slack bus (highest priority)
    - Multi-Terminal DC Line Terminals
    - Generator Regulated Bus
    - Switched Shunt Regulated Bus
    - LTC Regulated Bus
    - DC Line Terminal
    - Generator Terminal
    - Switched Shunt Terminal
    - Load Terminal
    - Series Capacitor Terminal
    - Transformer Terminal
    - AC Transmission Line Terminal
    - ZBR, Breaker, and Disconnect Terminals (lowest priority)
- In case of ties, the minimum bus number is selected as primary bus

Topology Processing

- Electrically, merging a bus is equivalent to move all the devices to the primary bus
  - Programmatically, each bus contains a pointer to the primary bus. For the primary bus, this pointer points to itself.
- By accessing not the actual bus pointer, but the pointer to the primary bus, Simulator makes the application *believe* that all the devices are connected to the primary bus
- We call this method *Device Relocation* and is the basis for consolidation

Topology Processing

Device Relocation to the Primary Bus

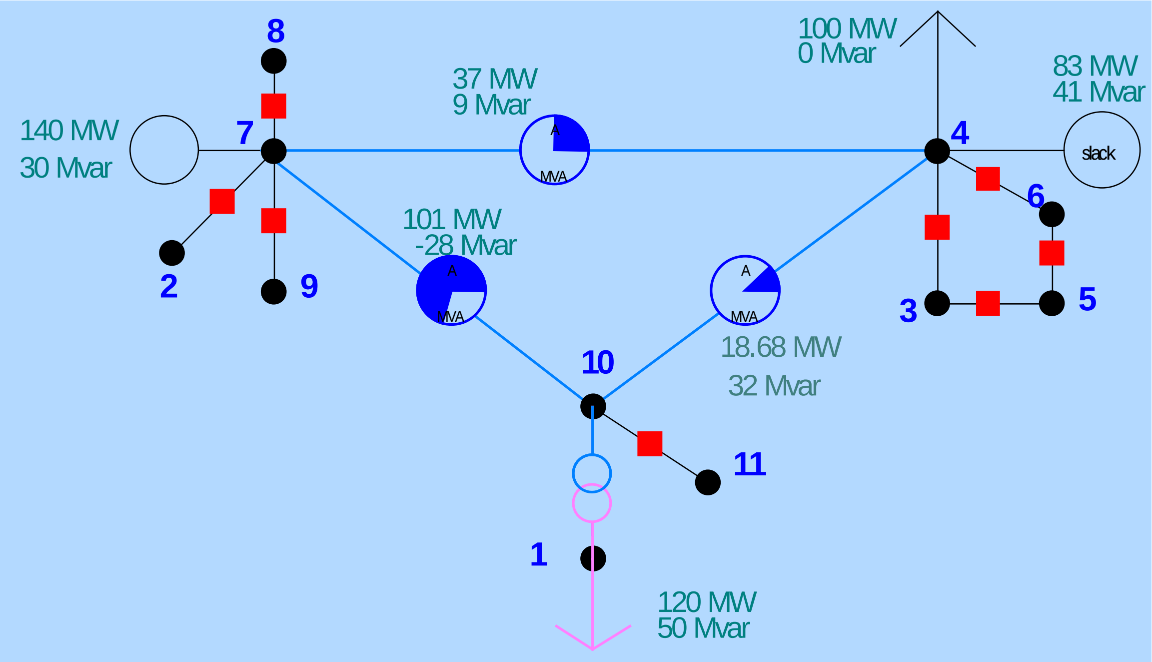


Topology Processing

- Device relocation allows every Simulator application to see a consolidated, smaller, planning-like representation of the full system
  - In this representation all the devices appear as connected to the primary buses
- Working with a smaller representation will allow for faster calculations and more numerically stable solutions

Topology Processing

- Example: Assuming all the CBs are closed, device relocation would result in the following system



- Note that after relocation, the breakers could be removed without affecting the power flow solution!

Topology Processing

Full-Topology Jacobian

Name	Jacobian Equation	Angle Bus 1	Angle Bus 2	Angle Bus 3	Angle Bus 5	Angle Bus 6	Angle Bus 7	Angle Bus 8	Angle Bus 9	Angle Bus 10	Angle Bus 11	Volt Mag Bus 1	Volt Mag Bus 2	Volt Mag Bus 3	Volt Mag Bus 5	Volt Mag Bus 6	Volt Mag Bus 7	Volt Mag Bus 8	Volt Mag Bus 9	Volt Mag Bus 10	Volt Mag Bus 11
1	Real Power	19.81								-19.81		-1.22								-1.19	
2	Real Power		6613.06				-2204.66	-2204.42	-2203.99				1.26				-1.75	-0.07	0.56		
3	Real Power			4417.36	-2204.45	-2204.41					-8.50			5.04	-0.19	-0.84					-4.17
5	Real Power			-2204.45	4409.27									-0.65	-0.11						
6	Real Power			-2204.41		4414.40		-5.21						0.00		1.85		-1.36			
7	Real Power		-2204.66				2204.66						0.91				1.75				
8	Real Power		-2204.42			-5.36		2209.78					-0.77			-0.66		1.43			
9	Real Power		-2203.99						2216.93	-12.94			-1.40						2.80	-1.45	
10	Real Power	-19.81							-12.59	2072.23	-2039.83	1.22							-3.16	2.69	-0.59
11	Real Power			-8.47						-2039.83	2048.30			-4.06						-0.22	4.44
1	Reactive power	-1.20								1.20		19.14								-19.62	
2	Reactive power		-1.32				1.84	0.07	-0.59				6299.08				-2099.69	-2099.69	-2099.69		
3	Reactive power			-5.29	0.20	0.88					4.22			4207.70	-2099.65	-2099.65					-8.41
5	Reactive power			0.69	-1.88									-2099.83	4199.65						
6	Reactive power			0.00		-1.94		1.43						-2099.78		4204.62		-4.97			
7	Voltage Magnitude																1.00				
8	Reactive power		0.81			0.69		-1.50					-2099.75			-5.11		2104.80			
9	Reactive power		1.47						-2.94	1.47			-2099.34						2112.02	-12.81	
10	Reactive power	-1.20							3.32	-2.72	0.59	-20.16							-12.00	2052.06	-2019.66
11	Reactive power			4.27						0.22	-4.49			-8.07						-2019.97	2028.05

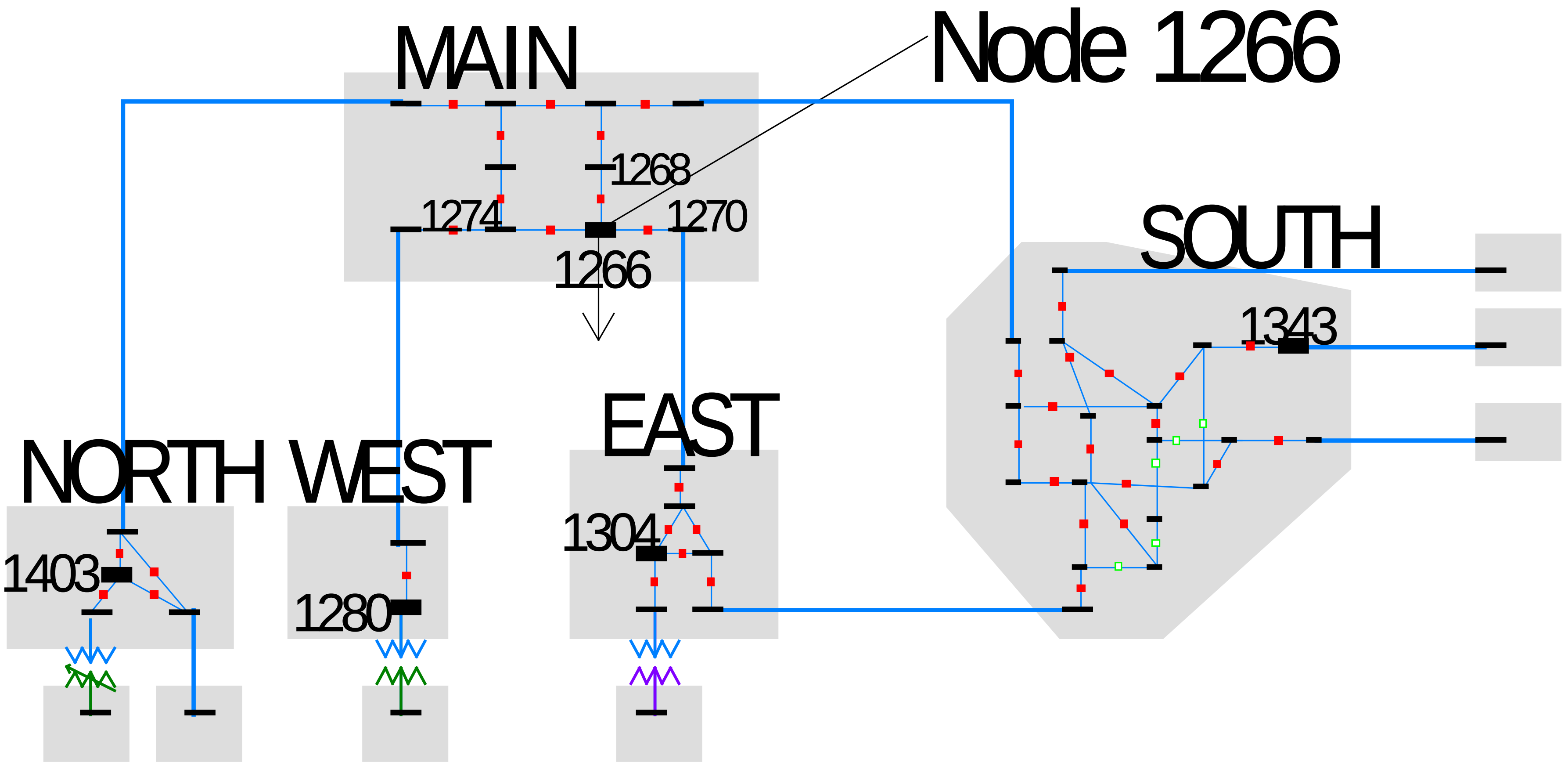
Consolidated Jacobian

Name	Jacobian Equation	Angle Bus 1	Angle Bus 7	Angle Bus 10	Volt Mag Bus 1	Volt Mag Bus 7	Volt Mag Bus 10
1	Real Power	19.82		-19.82	-1.22		-1.19
7	Real Power		18.31	-12.95		4.72	-1.45
10	Real Power	-19.82	-12.60	40.89	1.22	-3.17	6.33
1	Reactive power	-1.20		1.20	19.15		-19.62
7	Voltage Magnitude					1.00	
10	Reactive power	-1.20	3.32	-6.39	-20.17	-12.00	40.48

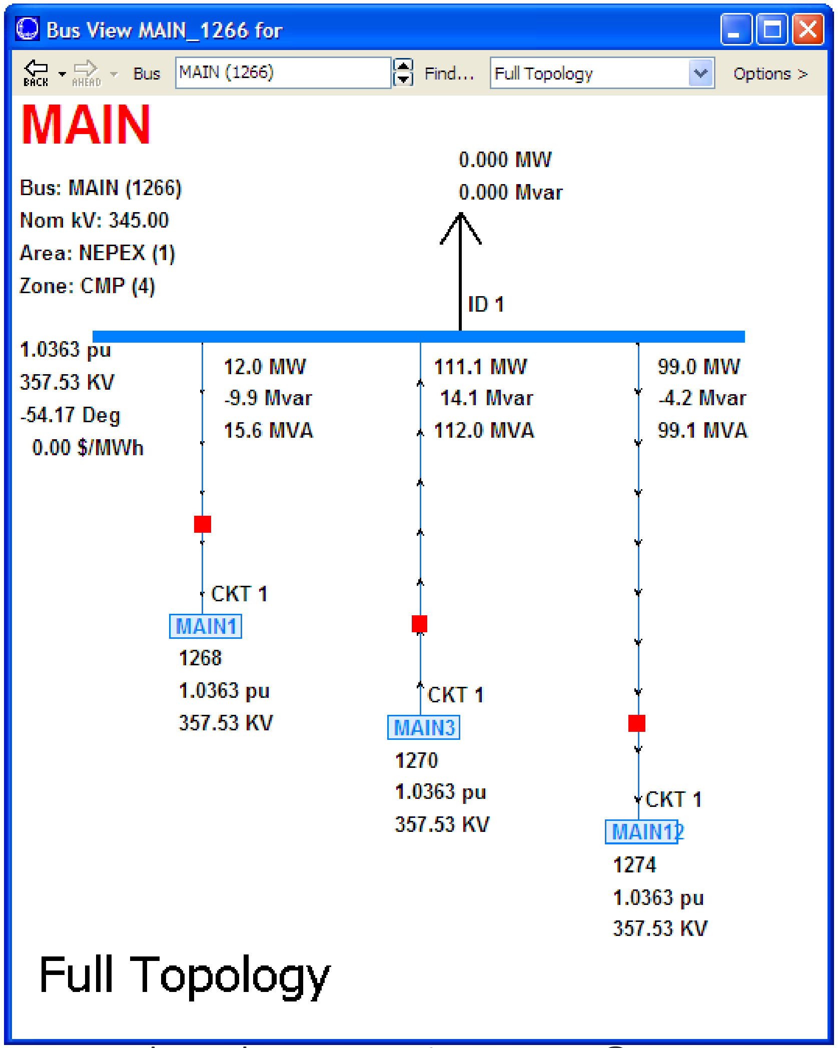
Bus View

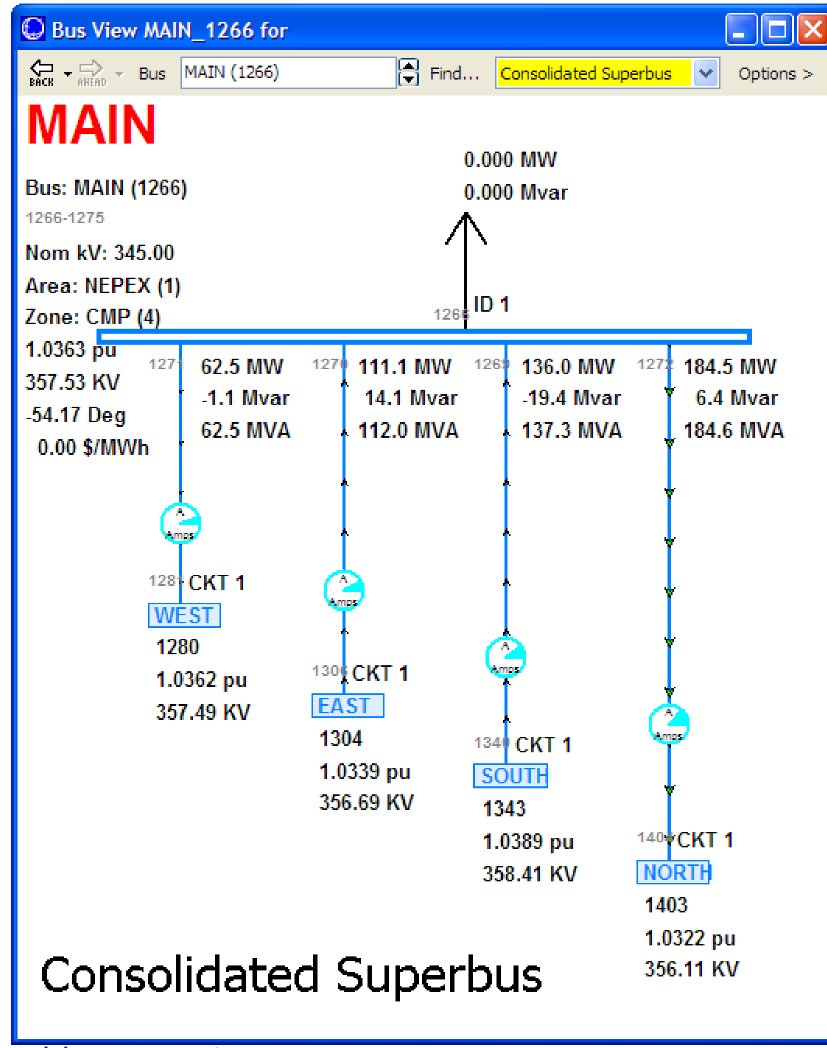
- Visualization of the Full Topology Model is also important
- For users of traditionally consolidated planning models all the new information must be brought to them in a familiar environment
- To meet this, several new enhancements and features have been added to Simulator's Bus View

Full-Topology Example



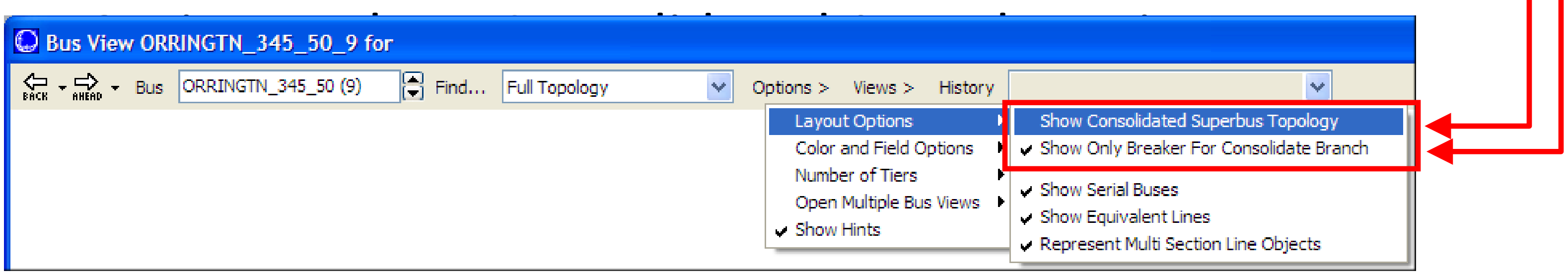
Full Topology vs. Consolidated Superbuses





Bus View

- The large number of buses in the full model makes the bus view much more difficult to use and navigate
- Hence, two new options have been added to the bus view to make it more useful when viewing full-topology models
  - Option to show the breaker symbol only for branches marked as **Allow Consolidation** = *YES*



Bus View

- In addition, other features have been added to enhance the bus view look:
  - Show radial-connected generator, load and switched shunt buses above the main bus
  - For series-connections of buses, the main branch shown will be the first branch that is marked as NOT available for consolidation (i.e. **Allow Consolidation** = *NO*)

Bus View: Show Consolidated Superbus View

- The behavior of the bus view changes so that ONLY the primary buses are shown
- All generator, load, and switched shunt devices will appear connected to their Superbus instead of the actual bus
- Only branches that connect between different superbuses will be shown:
  - This means that closed circuit breakers will not appear on the Consolidated Superbus view because they connect two buses that are in the same Superbus

Sample Superbus View

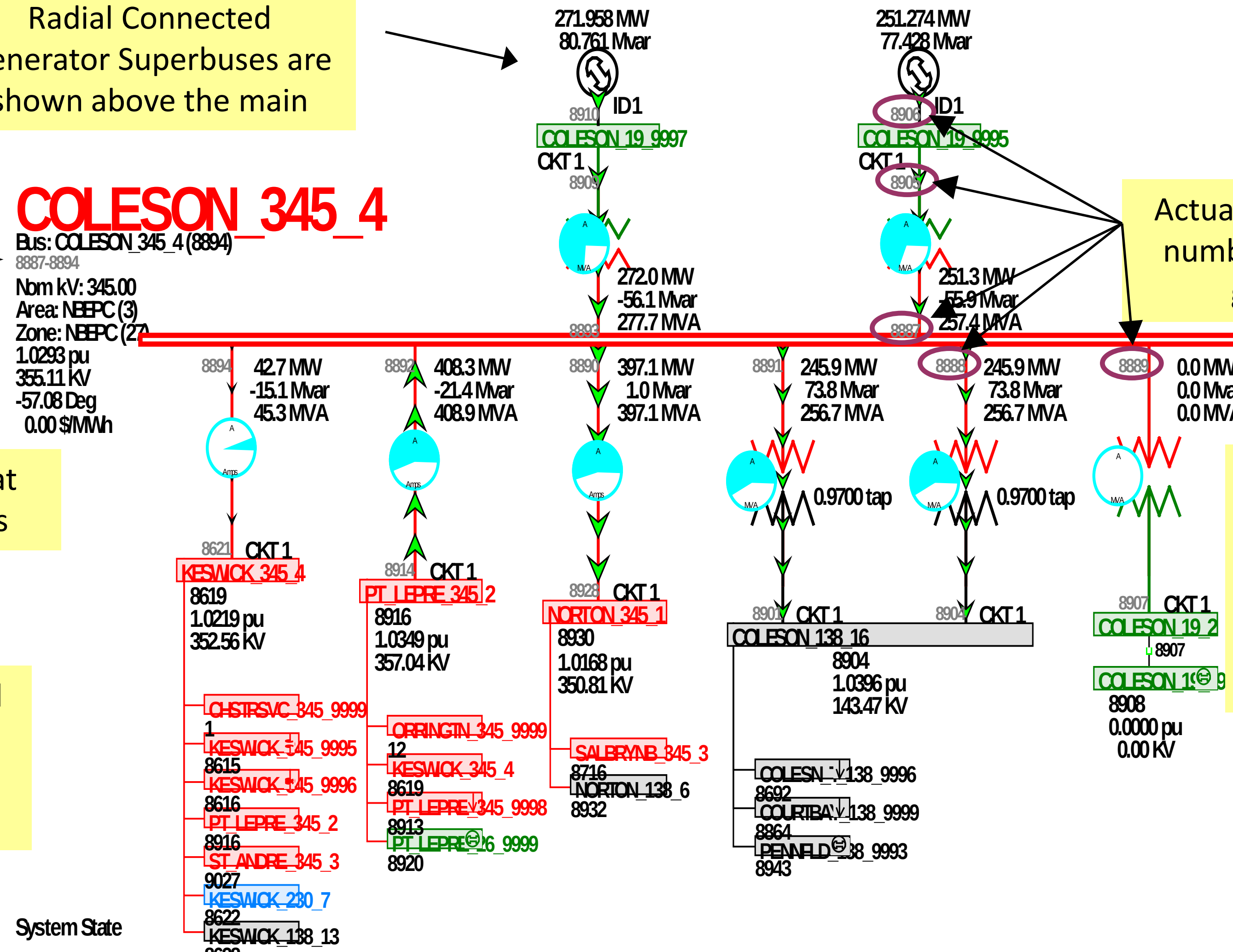
Radial Connected Generator Superbuses are shown above the main

Actual Terminal bus numbers shown in gray text

List of buses at this Superbus

All buses listed as bus links represent a Superbus

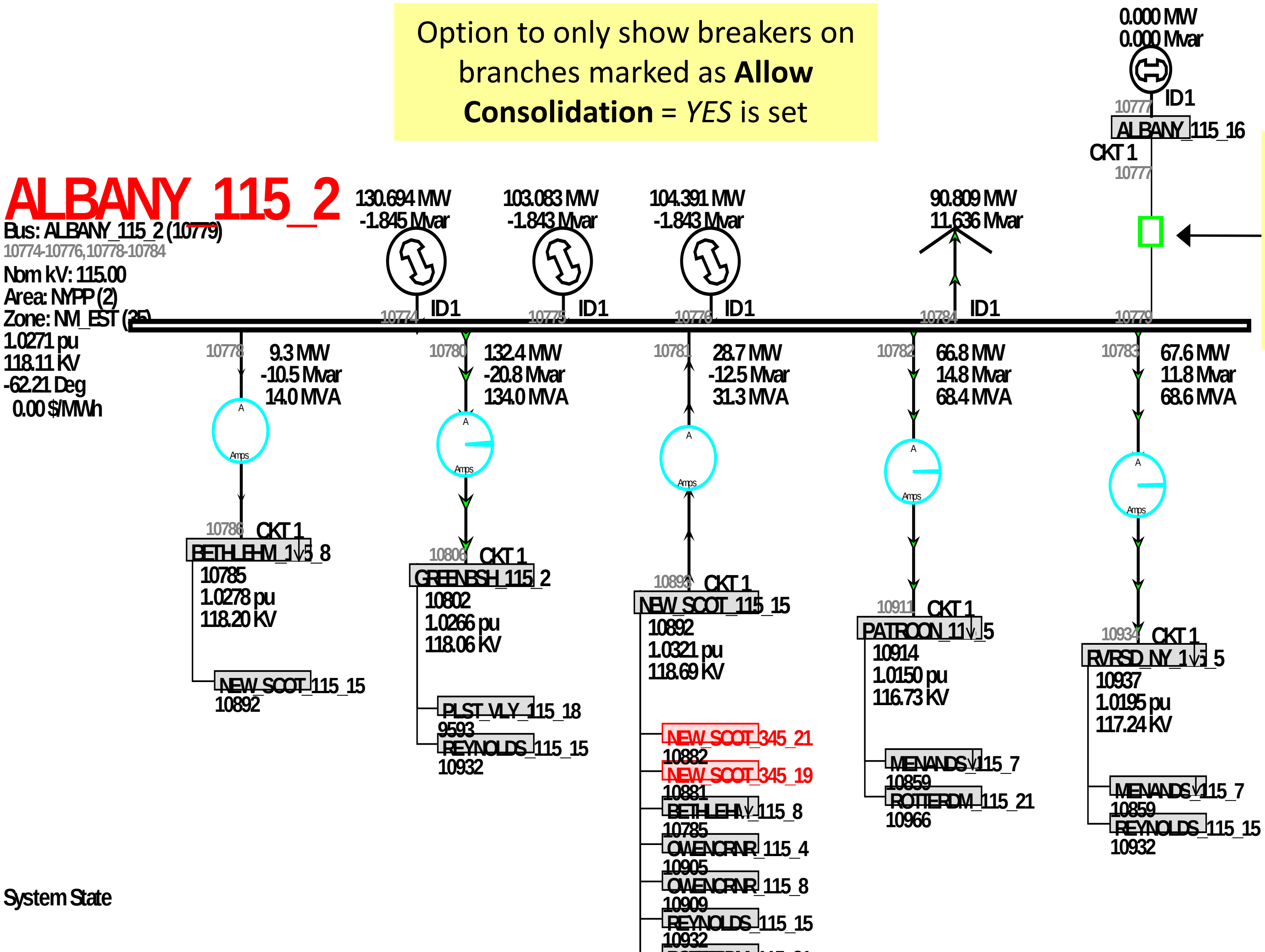
Superbus is shown as an unfilled rectangle instead of filled to provide visual clue



Another Sample Superbus View

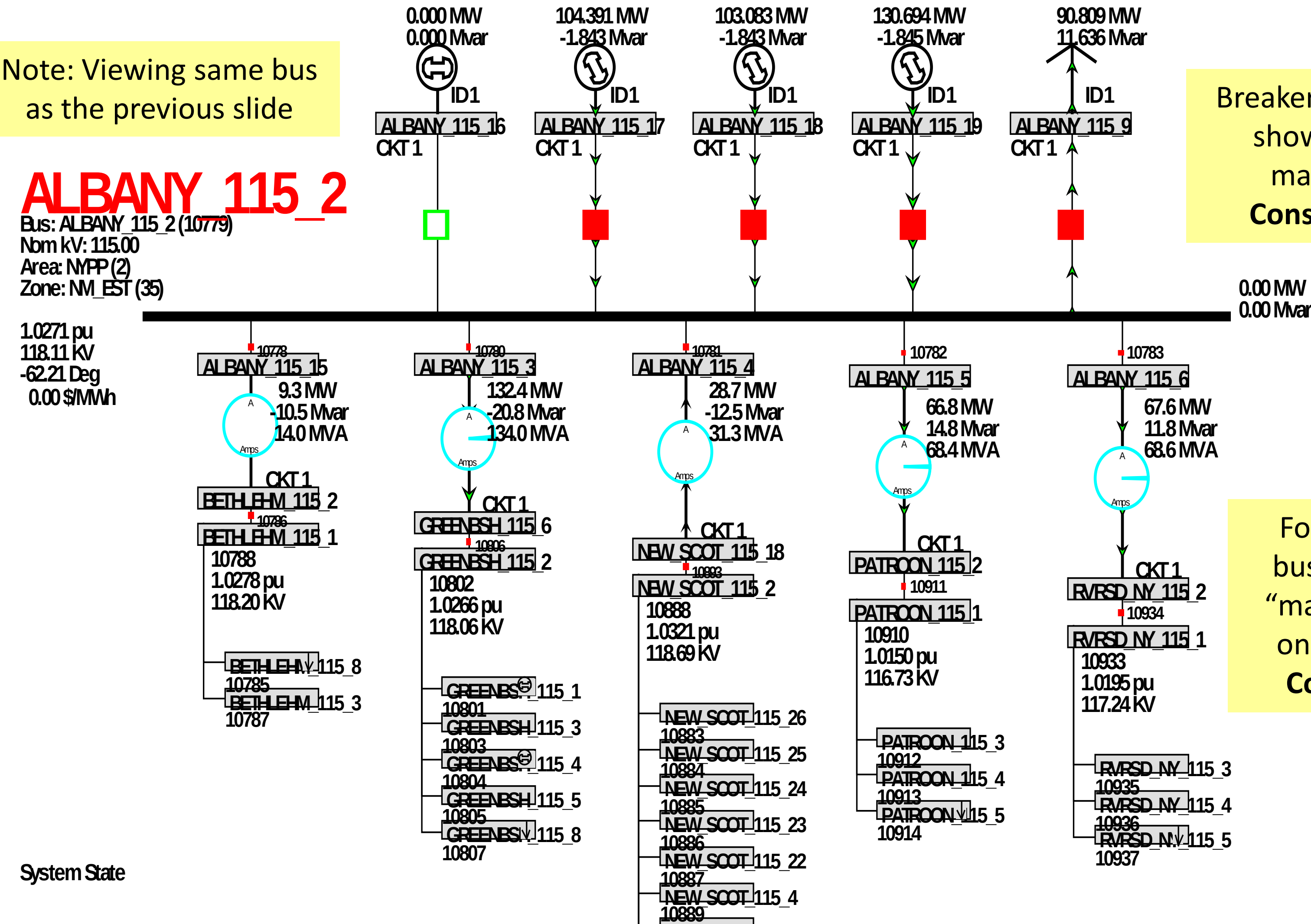
Option to only show breakers on branches marked as **Allow Consolidation** = *YES* is set

Because we're only showing branches that are not consolidated, then you will only see open breakers



With new features sometimes the Full Topology Bus View looks better

Note: Viewing same bus as the previous slide



Breaker symbols are only shown on branches marked as **Allow Consolidation** = *YES*

For series connected buses we show as the "main" branch the first one marked as **Allow Consolidation** = *NO*

Topology Processing Algorithm

- In order to perform numerical solutions using Integrated Topology Processing, Simulator does the following:
  - Consolidates the system relocating the devices and removing not needed breakers and non primary buses
  - Performs the numerical calculation
  - De-consolidates the system by restoring breakers and relocating the devices to their original buses. This step also maps the values of the primary buses to all the buses in the superbus.
- This is transparent to the user, who only needs to tell Simulator to use consolidation

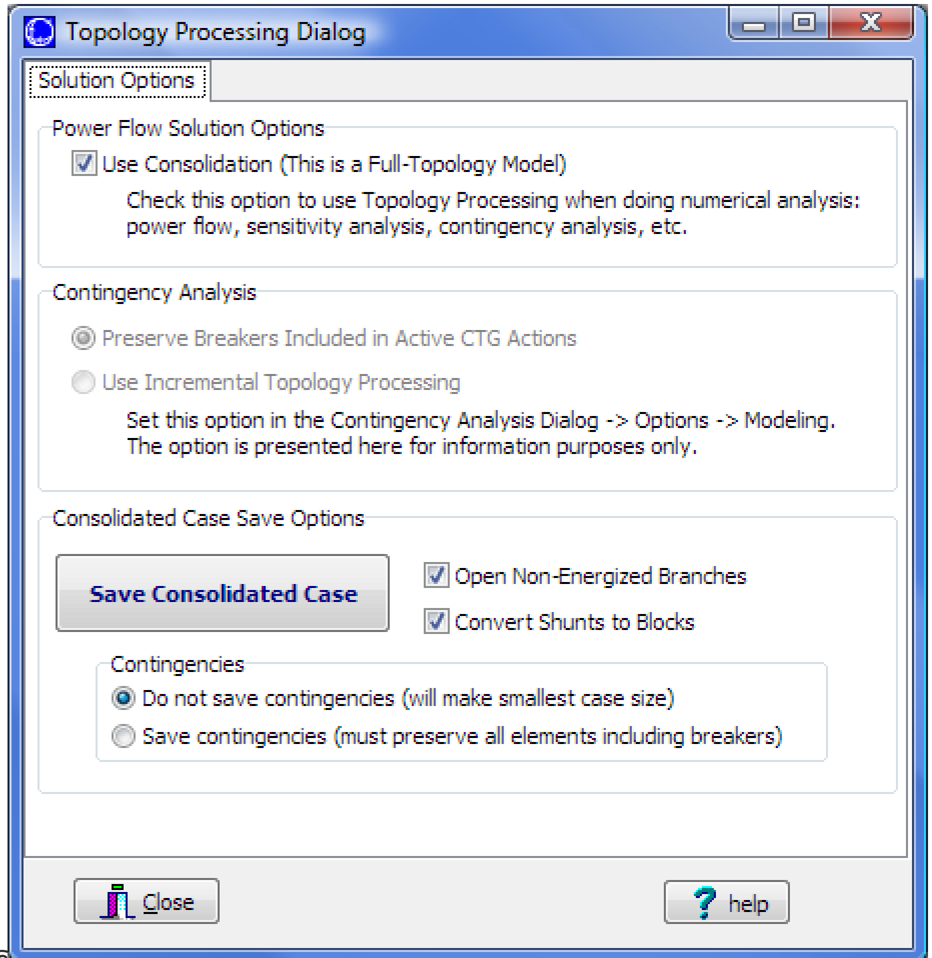
Topology Processing Dialog

- Add-Ons Ribbon → Topology Processing

Main Topology Processing Option

ITP Information for Contingency Analysis Option is actually set in **Contingency Analysis Dialog → Options → Modeling**

Save Consolidated Case Tool



Topology Processing Dialog

- Use Consolidation Option
  - Used for all Simulator Applications
  - If unchecked you will be trying to solve the full-topology model without removing the CBs (very large Jacobian)
  - For EMS models option should be ALWAYS checked
  - For planning models it should be ALWAYS unchecked
  - This option is repeated in the Power Flow Solution Options: **Options Ribbon**, **Simulator Options**, **Power Flow Solution Page**, **Common Options** tab

Power Flow Solution

- Check **Use Consolidation**
- Solve the power flow: **Single Solution**
- Solution will automatically involve a Consolidation → Solution → Deconsolidation process

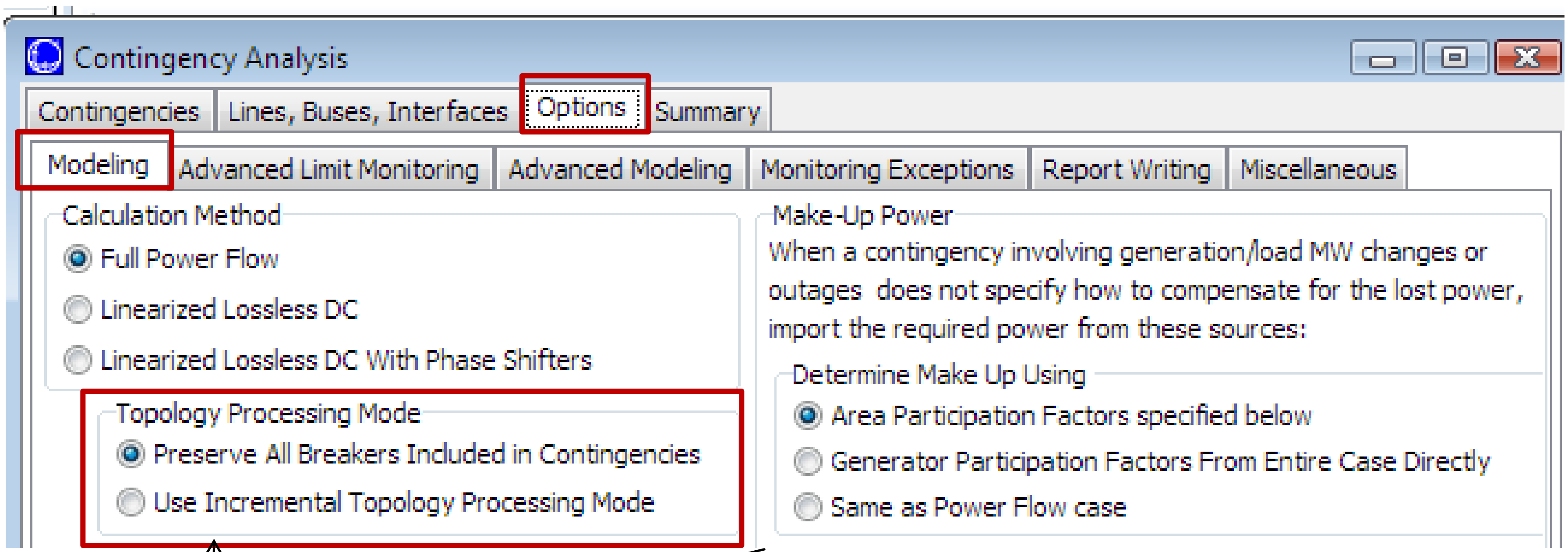
Starting Solution using Rectangular Newton-Raphson
Consolidated 11 Buses into 4 SuperBuses at 1/31/2008 5:07:37 PM
Number: 0 Max P: 128.113 at bus 7 Max Q: 100.377 at bus 11
Number: 1 Max P: 1.015 at bus 7 Max Q: 8.728 at bus 1
Number: 2 Max P: 0.015 at bus 1 Max Q: 0.044 at bus 1
Finished voltage control loop iteration: 1
Deconsolidated 4 SuperBuses into 11 Buses at 1/31/2008 5:07:37 PM
Solution Finished in 0.026 Seconds
Simulation: Successful Power Flow Solution

Sensitivity Analysis

- Consolidation will take place automatically for TLR, PTDF, LODF, etc.
- Line Sensitivities will be calculated for non-consolidated branches only
- Bus sensitivities of non-primary buses will be made equal to that of the primary bus

Contingency Analysis Options

- Select **Tools** → **Contingency Analysis** → **Options** → **Modeling**



Only available when **Full Power Flow** Calculation Method is checked

Information about this option is repeated in the Topology Processing Dialog

Contingency Analysis Options

- EMS systems model contingencies through a list of real system actions. For instance, opening a line involves opening the set of breakers that electrically isolate the device.
- Preserve Contingency Breakers Option
  - Contingency analysis will not treat contingency breakers as zero impedance branches and will keep them in the model
  - The consolidated representation is obtained only once upfront before the first contingency, and this representation is used to solve all the contingencies
  - Using this option, the consolidated representation is smaller than the full model, but is not the smallest possible

Contingency Analysis Options

- Incremental Topology Processing does the following:

Begin

    Consolidate entire case

    for each contingency **do**

        Apply breaker actions and identify subnets with changed topology

        Expand affected subnets to full-topology detail

        Reconsolidate affected subnets with post-contingency topology

        Solve post-contingency power flow

        Determine and store limit violations

        Reset affected subnets to pre-contingency topology

        Restore pre-contingency power system state

    end;

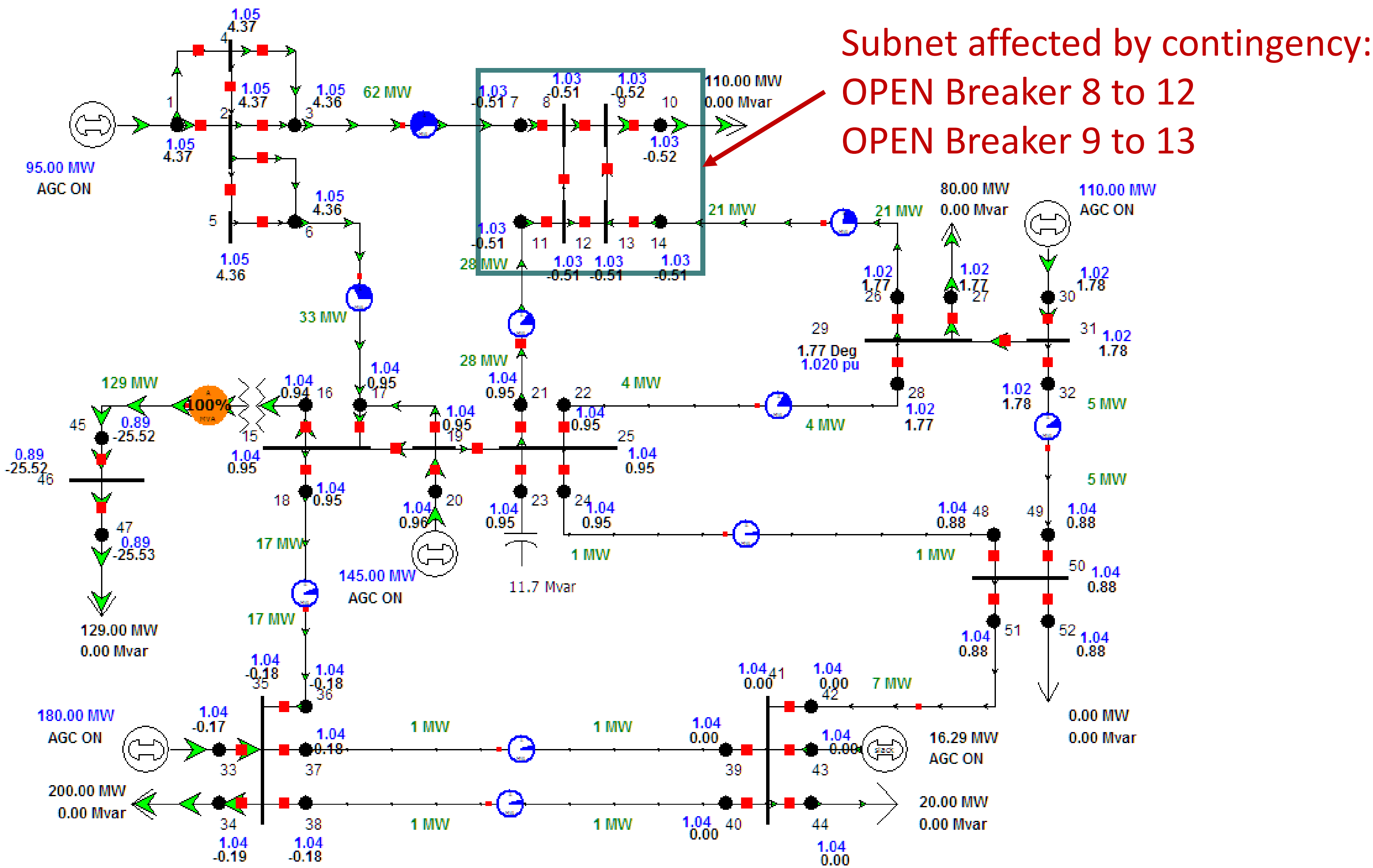
    Deconsolidate entire case

End;

Contingency Analysis Options

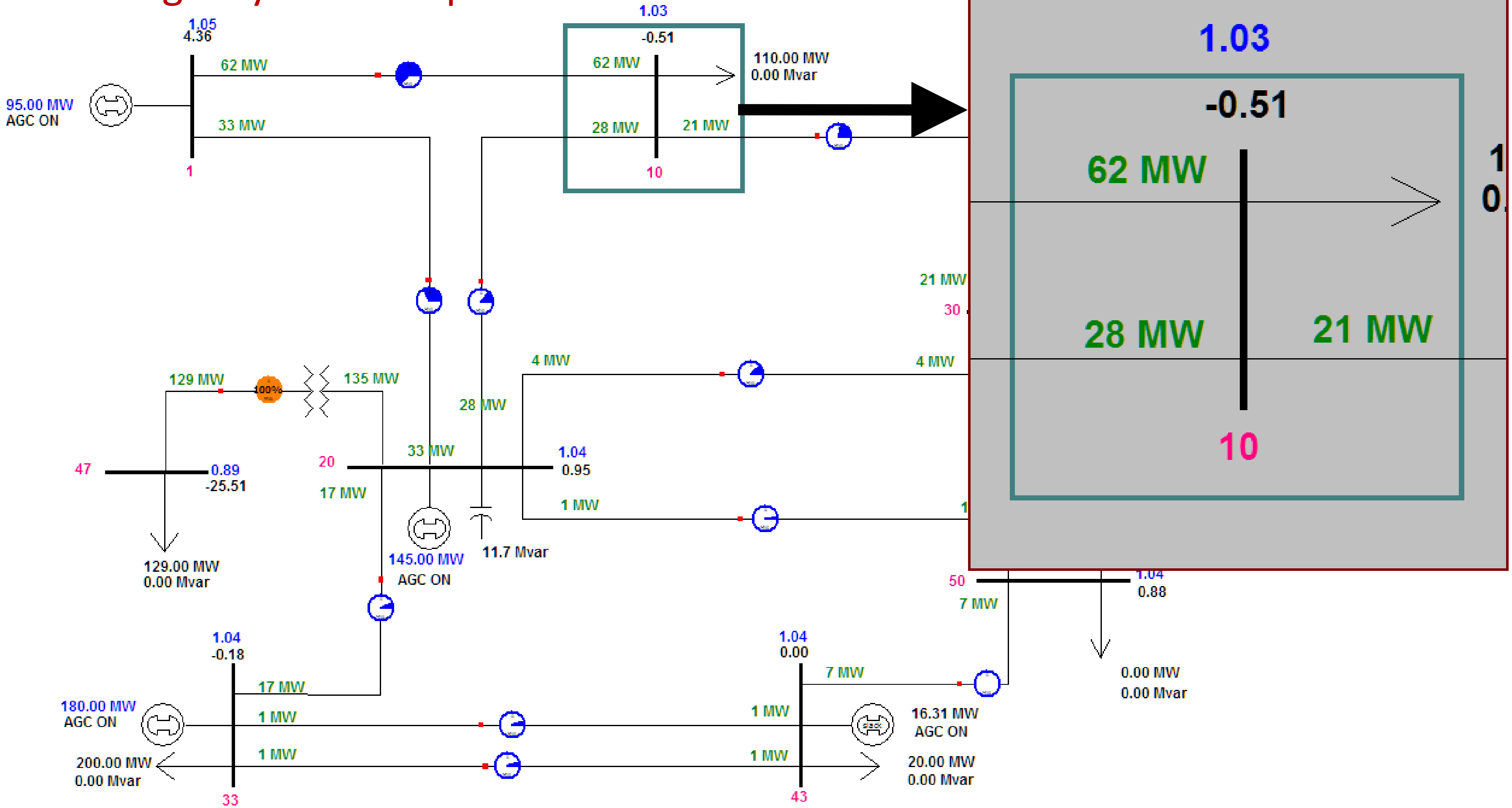
- Incremental Topology Processing provides a more robust solution and should be used whenever possible
- However, if the number of contingencies is not too large, then preserving the breakers will run faster
- Incremental topology processing cannot be used for applications that use linearization and that require a constant size sensitivity matrix. For instance, ATC will automatically use the Preserve Breakers option.

Incremental Topology Processing Full-Topology Representation



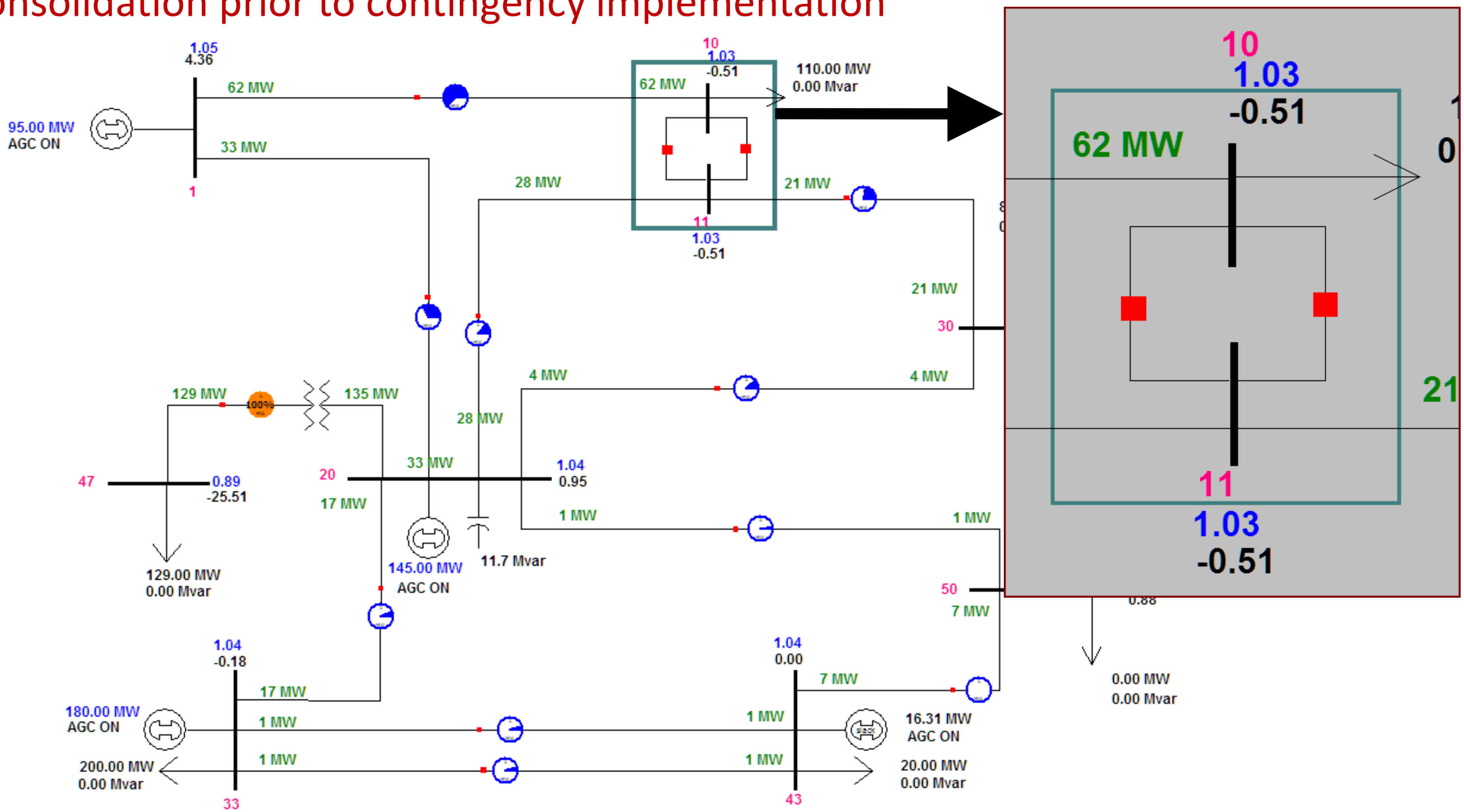
Incremental Topology Processing Consolidated Representation

No contingency breakers preserved



Incremental Topology Processing Incremental Expansion

Consolidation prior to contingency implementation



“Open with Breakers” Contingency Action

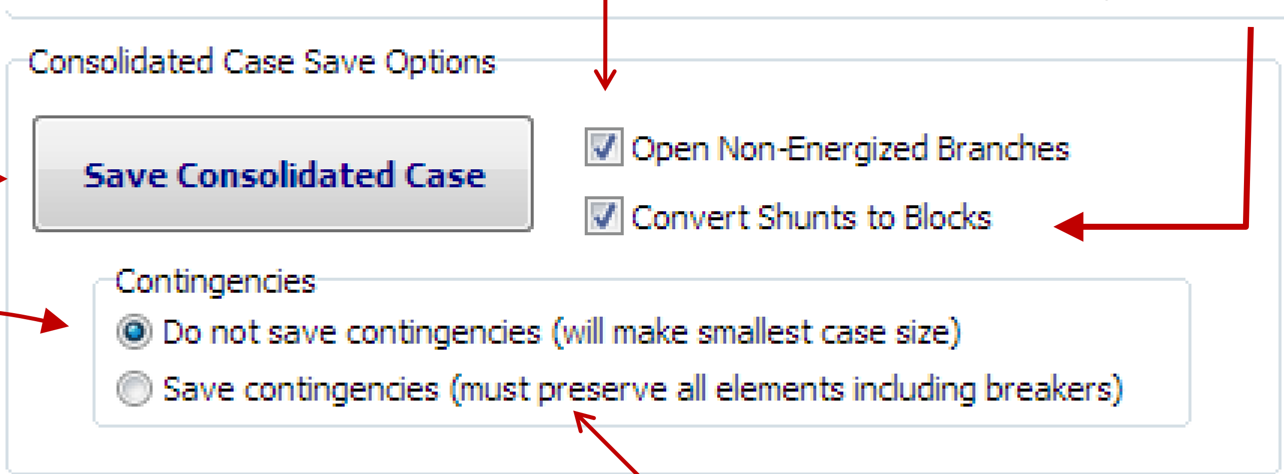
- Open a device using breakers instead of changing the status of that device
- Ensures that accurate modeling of real-time system is achieved
- Breakers that need to open to isolate an element are automatically determined
- Breaker failure scenarios can be modeled by applying this action to a breaker

Saving the Consolidated Case

Save the case in any of the supported formats

If the terminal buses of a line are not energized, the assume the line is open

Needed because some systems have several one shunts in a superbus, and some formats (PSSE) support only one shunt per bus



Use if you won't need to solve contingency analysis on the saved consolidated model

Use if you want the case to include the contingency list and all the devices included in the contingency actions

Saving the Consolidated Case

- The saved consolidated case can be reopened in Simulator (or in other Simulator instance)
- Recall that the consolidated case will depend on the assumed statuses of the breakers in the full model
  - Since breaker statuses change in real-time, superbuses merge and split dynamically
  - Thus the topology of consolidated cases will change a little from minute to minute

Script Commands

- Set option to use consolidation
  - `SETDATA(SIM_SOLUTION_OPTIONS, [SEOUseConsolidation],["YES"]);`
- Set option to use incremental TP
  - `SETDATA(CTG_OPTIONS,[RTCTGAnaMode],["YES"]);`
- Save the consolidated case
  - `SAVECONSOLIDATEDCASE("filename",FileType);`
- Other TP options
  - `RT_STUDY_OPTIONS`