

# *Optimizing Power System Restoration Resources and Actions*

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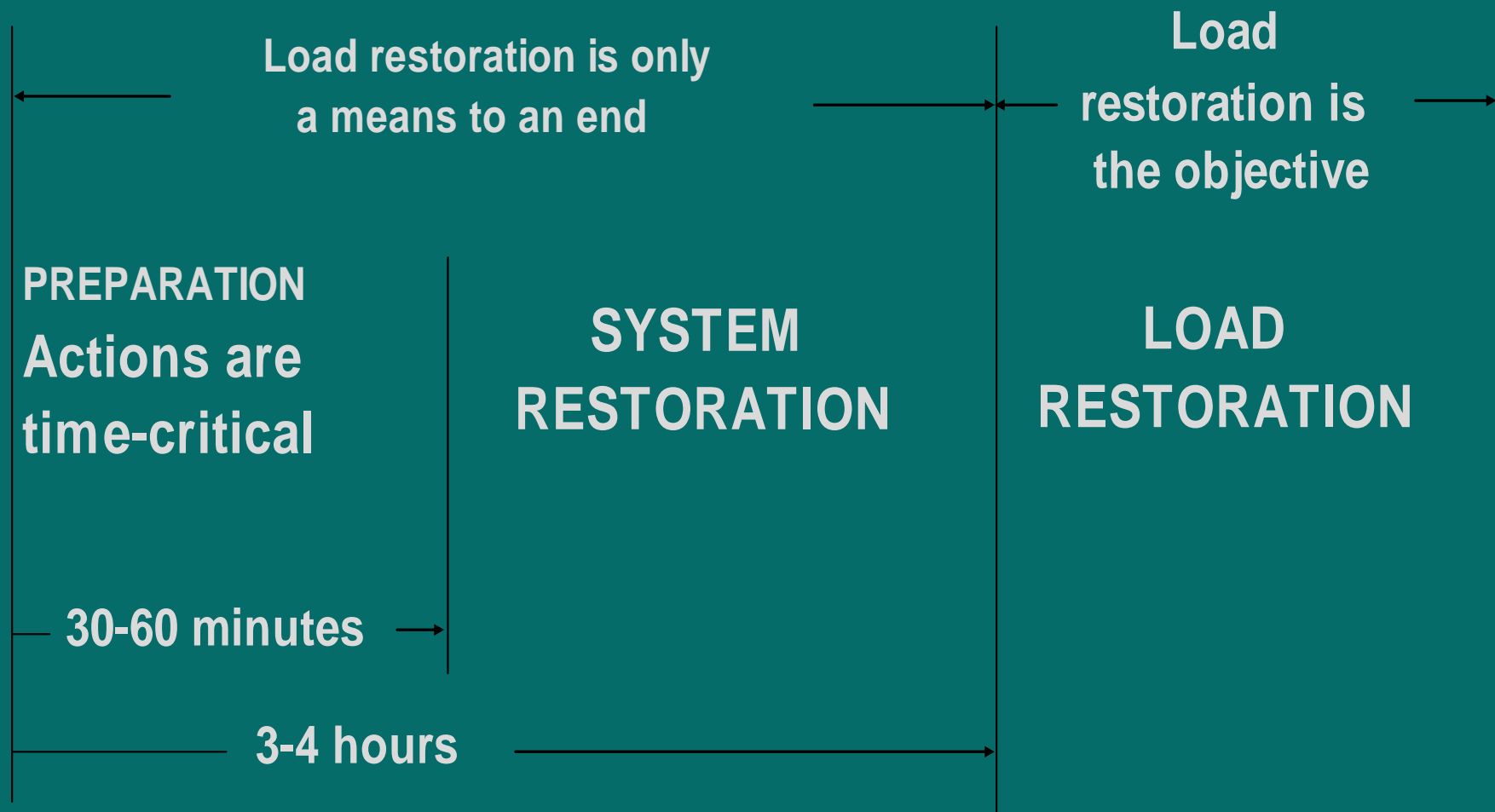
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# State of the Art

- Primarily manual work by operators
- Off line restoration planning
- Little progress has been made on system restoration methodology
- On line implementation limited
- Literature

# System Restoration Stages



# System Restoration Tasks

- Knowing status of the grid
- *Maximizing generation capabilities with the available black start resources*
- *Scheduling of tasks and resources during system restoration*
- Establishing transmission capability and paths while meeting operating constraints
- Picking up load while meeting operating constraints and load requirements

# Example Restoration Strategies

- Build-upward
- Build-downward
- Other variations

# First Stage

- **Basic operations common to all strategies**
- **Sub-processes defining early stages of restoration process**
- **Minimal configuration of autonomous stable source with necessary transmission**

# Restoration Building Blocks

- May include non-autonomous BTG, connection transmission, necessary compensation & load blocks
- Associated with schedule of switching & control actions

# Second Stage Target System

- System state achieved by end of restoration process
- May not be pre-disturbance system
- Restrict set of post-restoration configurations

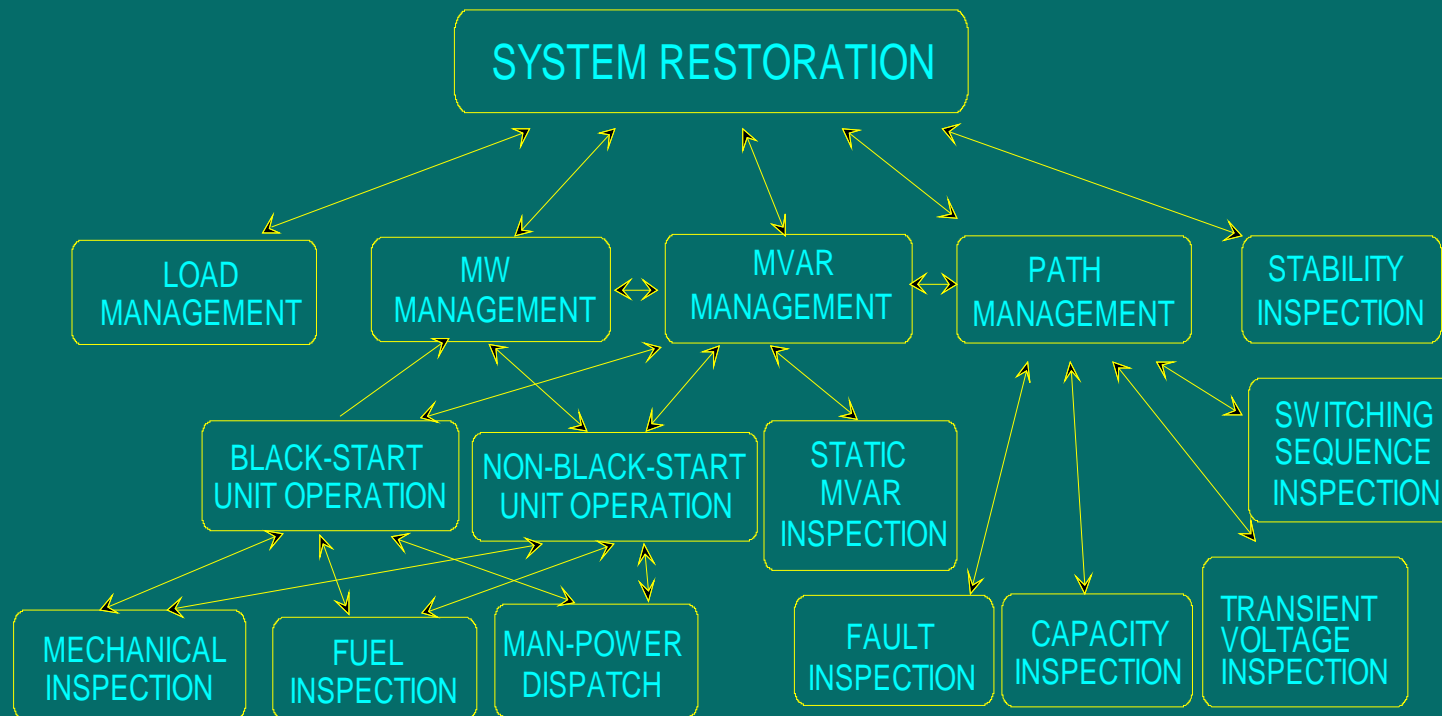
# Restoration Constraints

- Physical constraints
- Scheduling constraints
- Policy constraints

# Third Stage

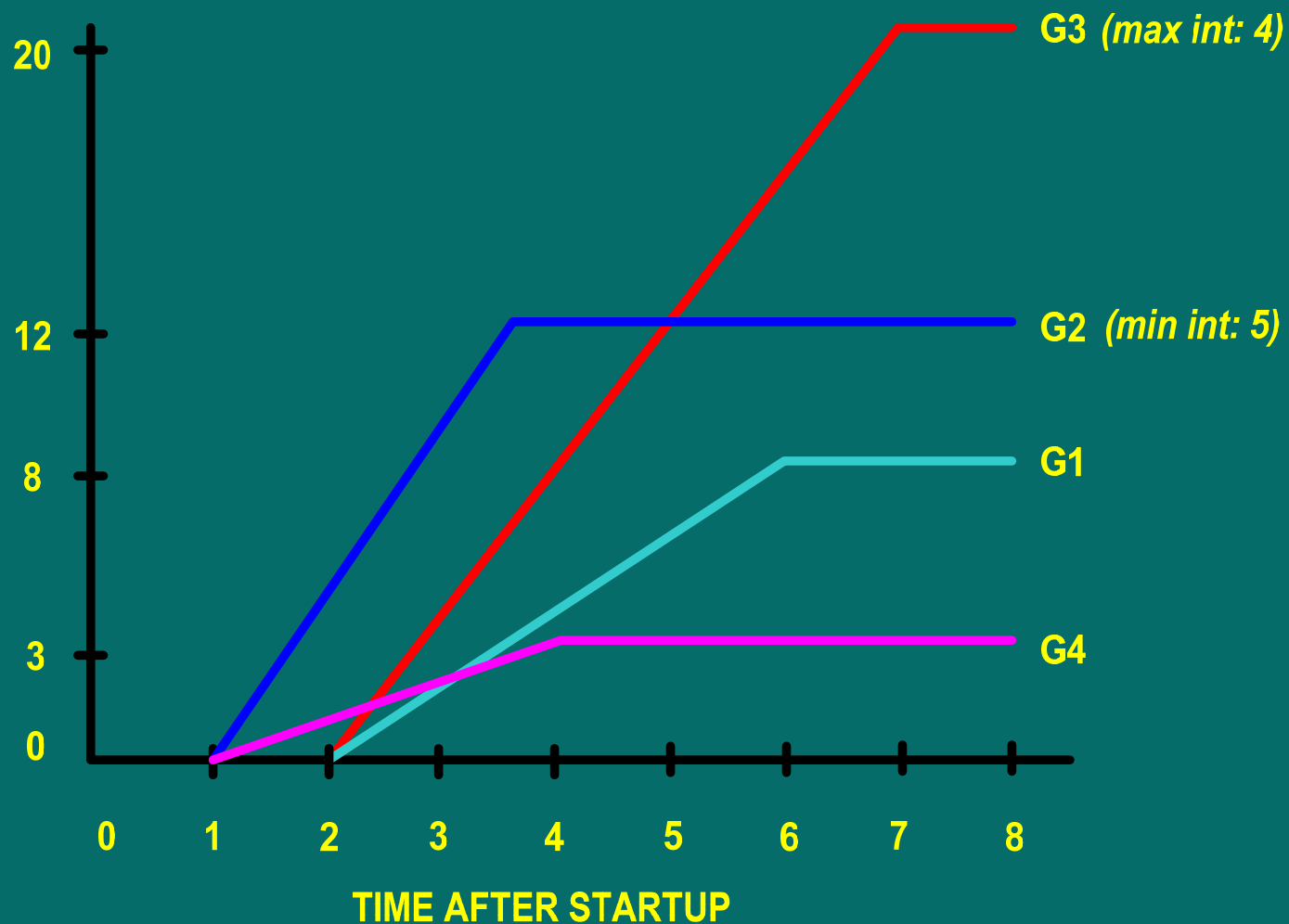
**Load Restoration – Pick Up Loads**

# Restoration Strategy

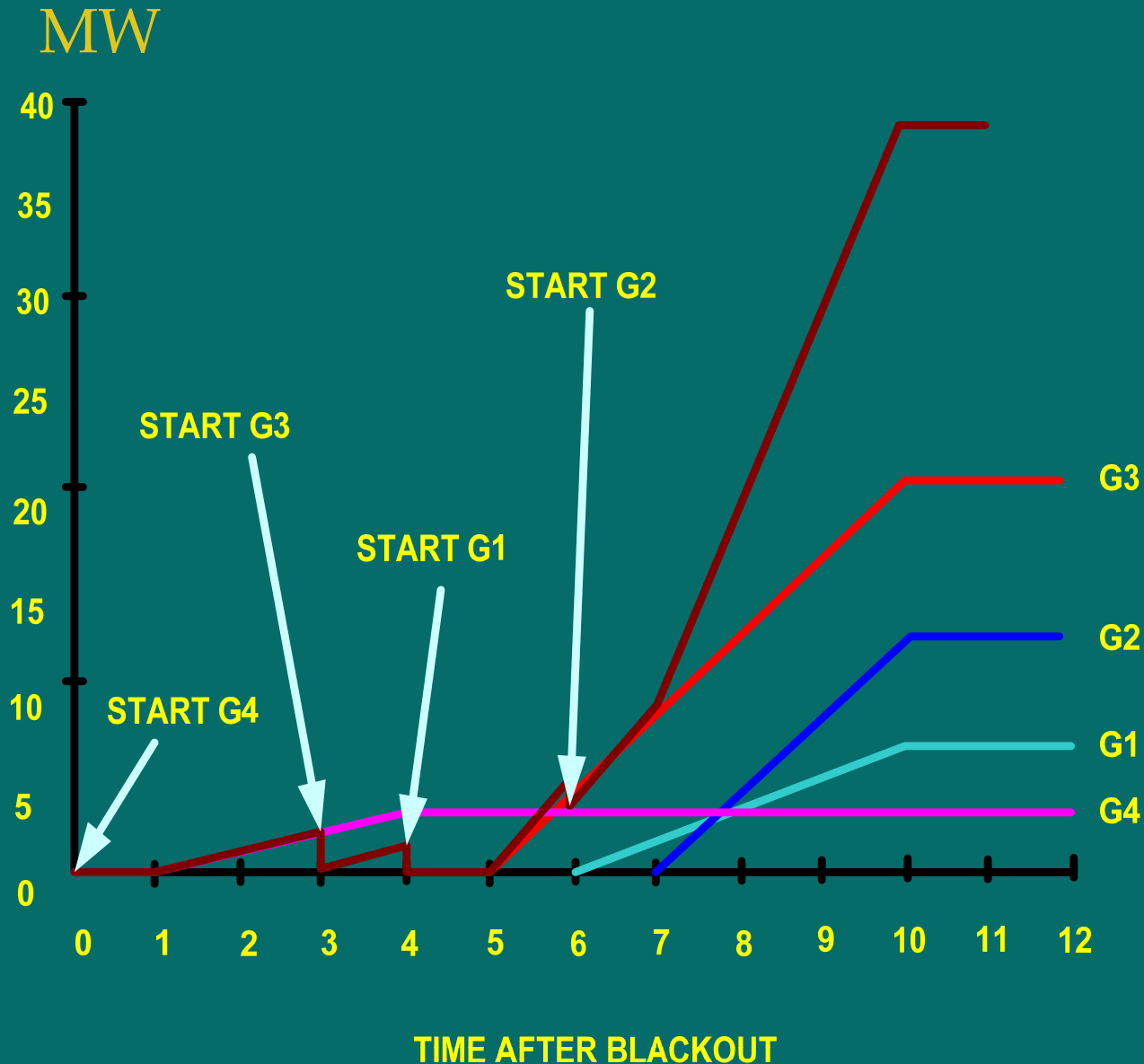


# Example - Generation Capabilities

*(4 Different Generating Units)*



# Example – *Optimal* Starting Sequence



# Cranking Priorities

- Units with critical maximum interval
- Critical max interval units with most urgent time constraint
- Units that can generate highest MWH within a given period

# PECO-Energy Generating Units

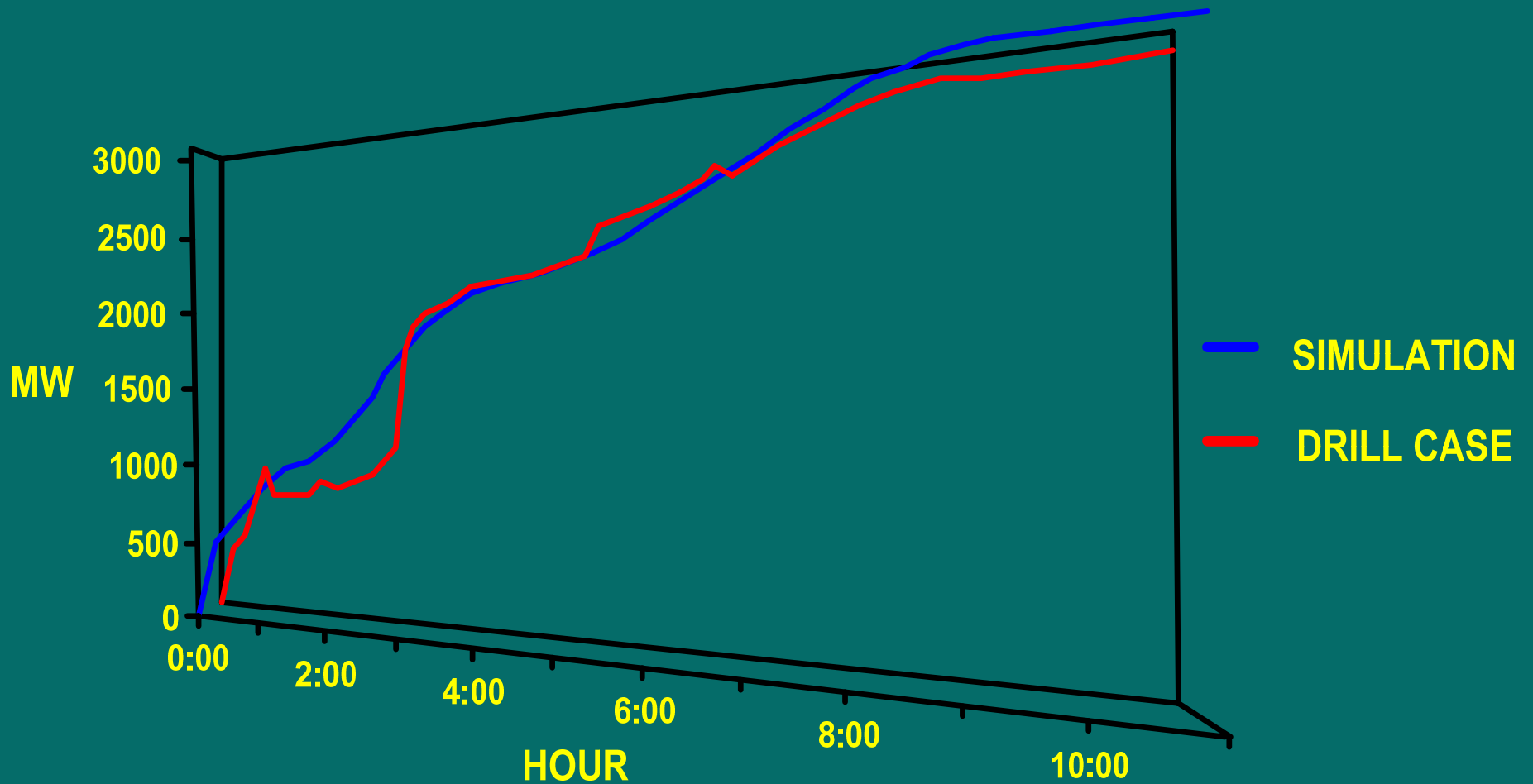
Unit	Type	MW Cap. (MW)	Ramp. rate (MW/hr)	Crank to paral. (hr)	Crit. max. int. (hr)	Crit. min. int. (hr)	Startup req. (MW)
Chester_4	CT	15	40	0	N/A	N/A	0
Chester_5	CT	15	40	0	N/A	N/A	0
Chester_6	CT	15	40	0	N/A	N/A	0
Chester_7-9	CT	45	120	0	N/A	N/A	0
Conowingo_1-7	Hydro	200	200	0	N/A	N/A	0
Conowingo_8-11	Hydro	200	200	0	N/A	N/A	0
				1:40	N/A	N/A	8
				1:40	N/A	N/A	8
				0:30	N/A	5:00	6
Delaware_7	Steam	130	60	2:40	3:20	N/A	5
Delaware_8	Steam	130	60	2:40	3:20	N/A	5
Delaware_9-10	CT	30	90	0	N/A	N/A	0
Delaware_11	CT	30	90	0	N/A	N/A	0
Eddystone_1	CT	15	45	0	N/A	N/A	0
Eddystone_2	CT	15	45	0	N/A	N/A	0
Eddystone_3	Steam	150	40	1:40	N/A	3:20	12
Eddystone_4	Steam	150	40	1:40	N/A	3:20	12
Eddystone_5	CT	15	45	0	N/A	N/A	0
Eddystone_6	CT	15	45	0	N/A	N/A	0
Eddystone_7	CT	15	45	0	N/A	N/A	0
Eddystone_8	CT	15	45	0	N/A	N/A	0
Eddystone_9	CT	15	45	0	N/A	N/A	0
Falls_1-3	Hydro	150	150	0	N/A	N/A	0
Moser_1	CT	30	90	0	N/A	N/A	0
Muddy Run_1-4	Hydro	400	150	0:30	N/A	N/A	6.6
Muddy Run_5-8	Hydro	400	150	0:30	N/A	N/A	6.6
Richmond_3	CT	50	100	0	N/A	N/A	0
Richmond_4	CT	50	100	0	N/A	N/A	0
Schuylkill_1	Steam	135	135	2:00	2:30	N/A	2.7
Schuylkill_3	Steam	135	135	2:00	2:30	N/A	2.7

*Ramping Rate*

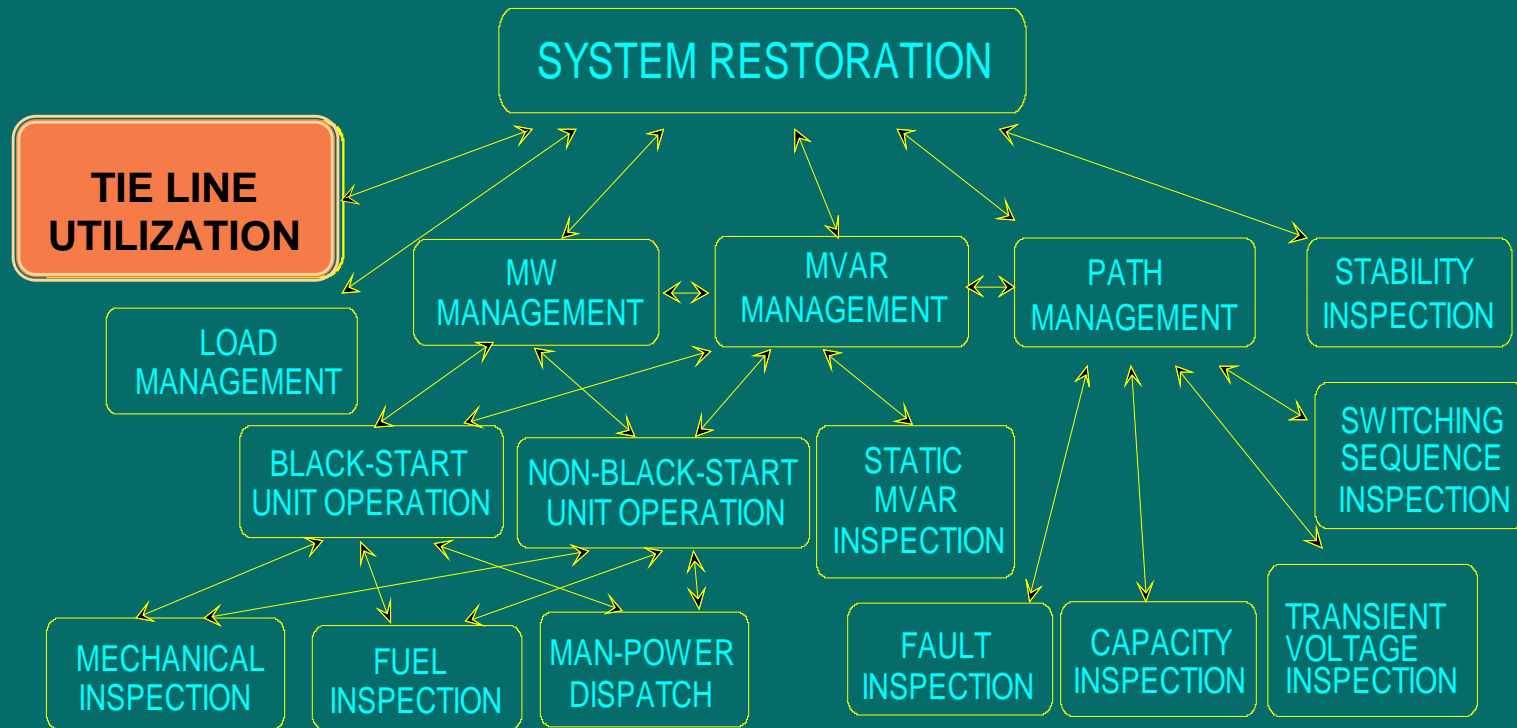
*Critical Min. Interval*

*Critical Max. Interval*

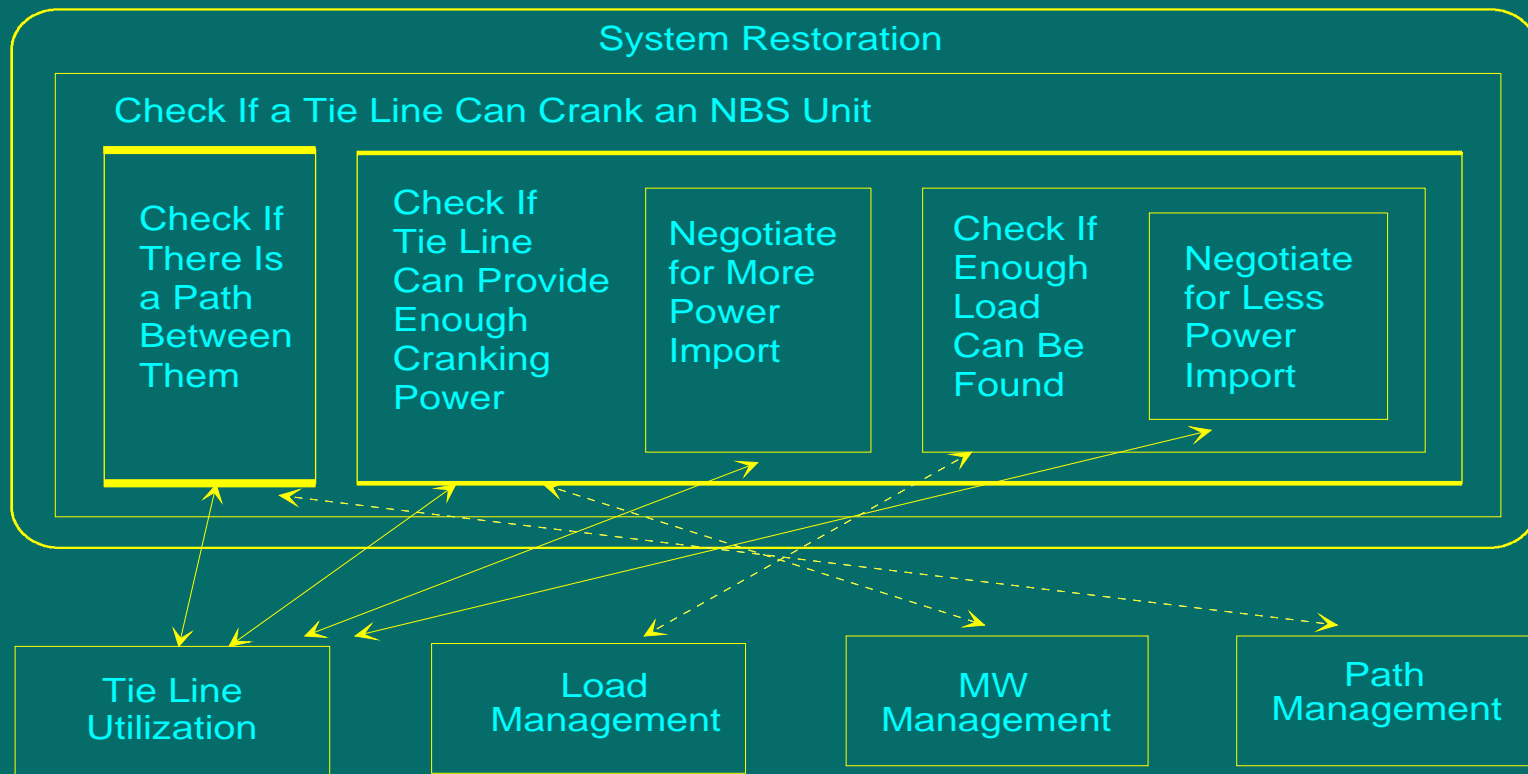
# MW Capability Curves



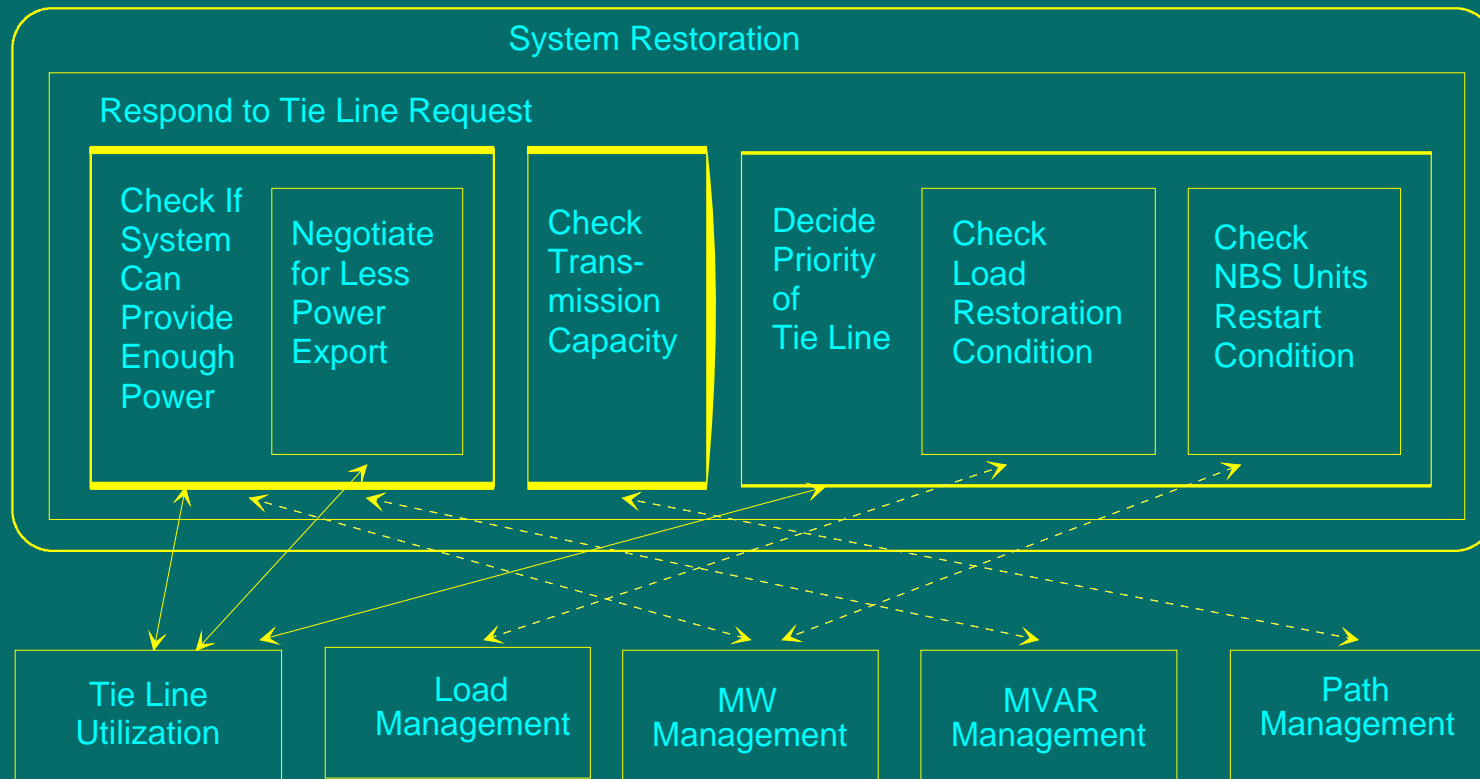
# Restoration Strategy with Tie Lines



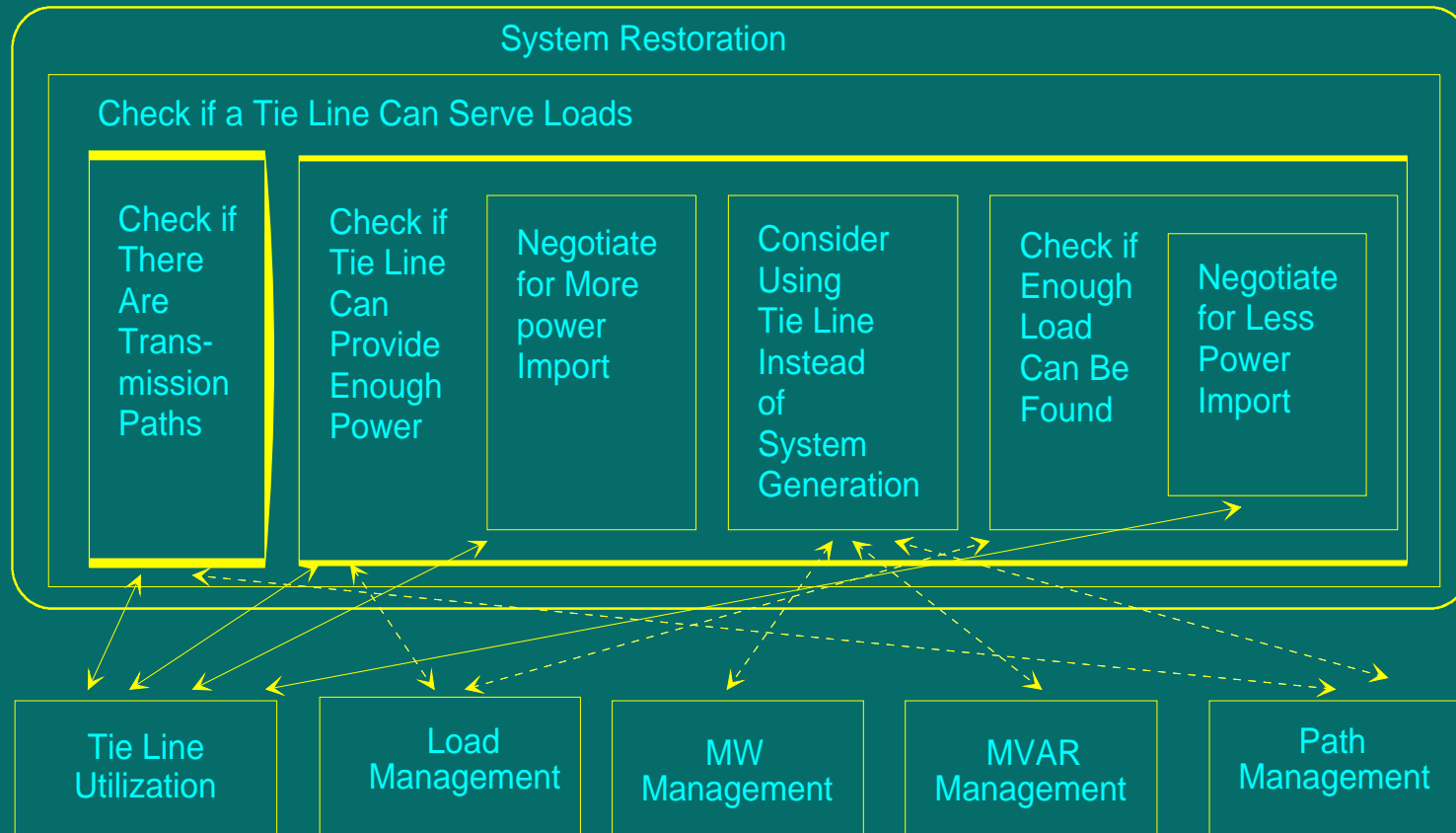
# Crank NBS Units



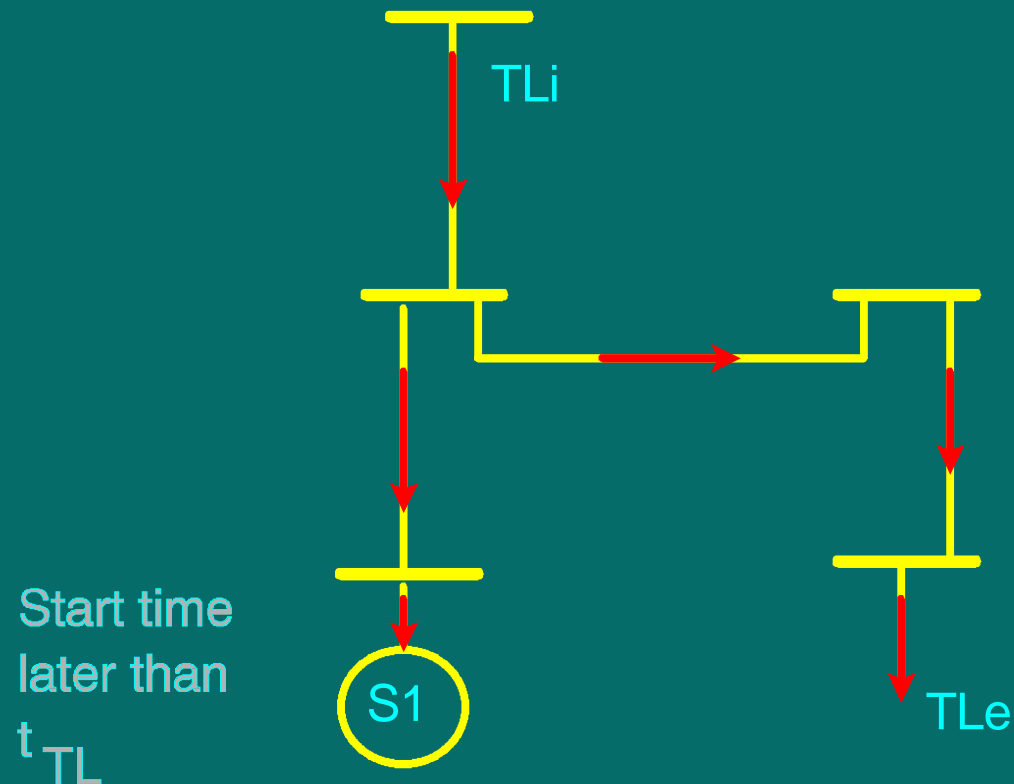
# Respond to Request



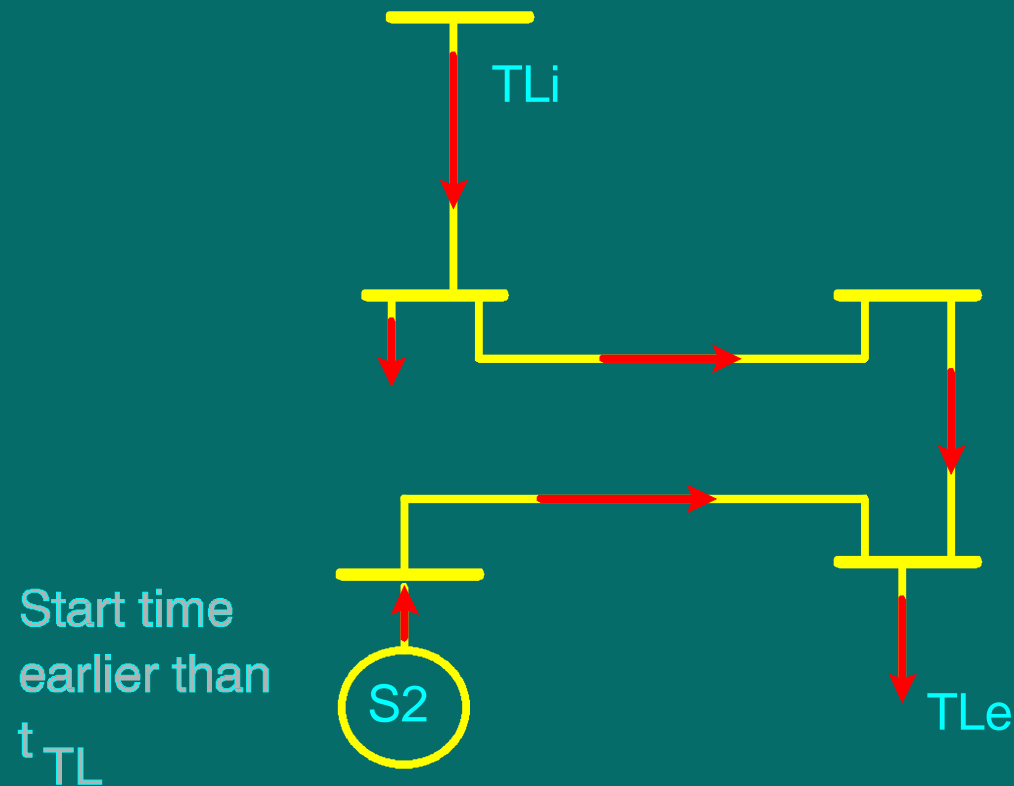
# Serve Load



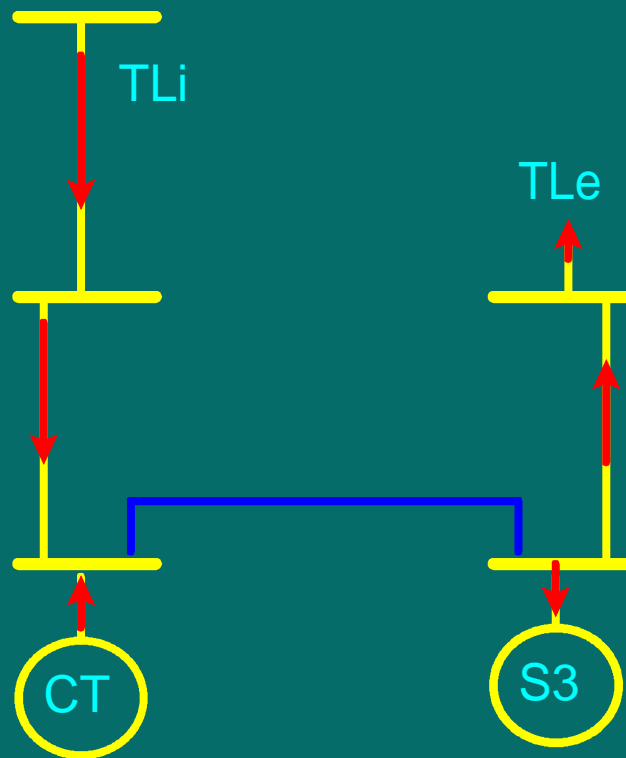
# Internal Units to be Cranked by TLi



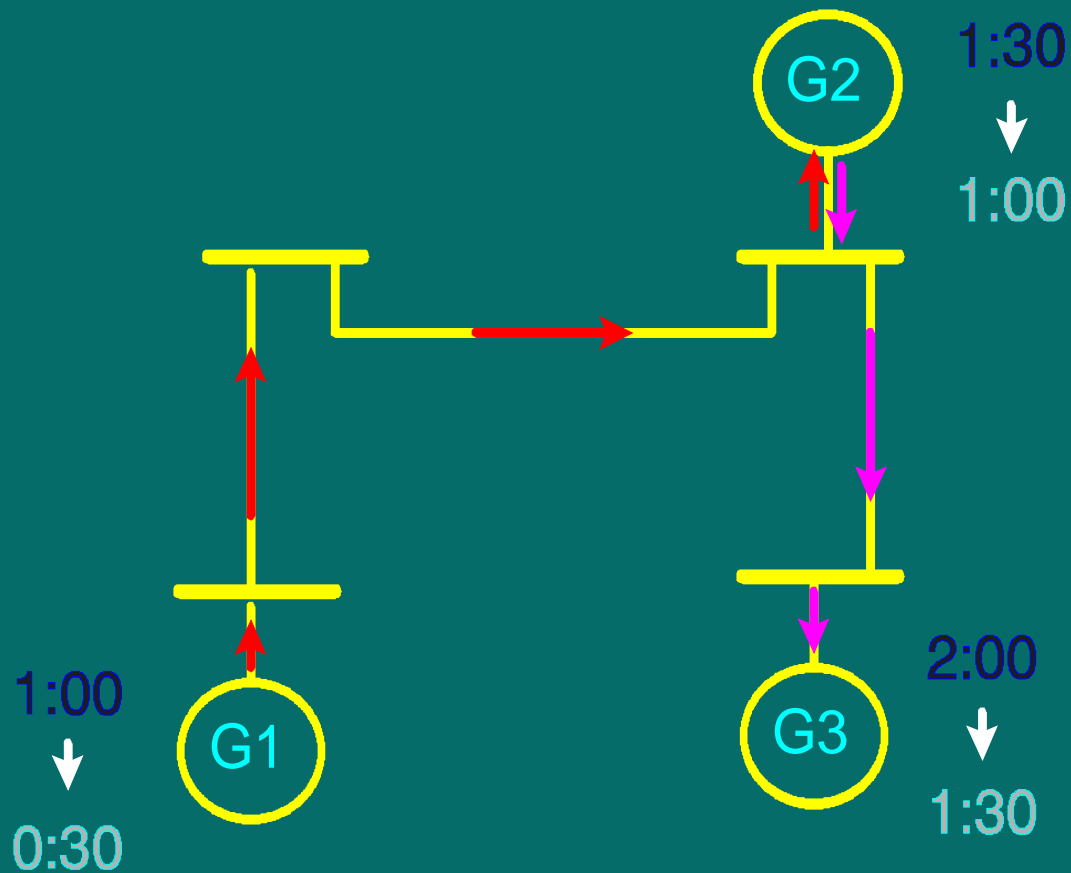
# Internal Units to Provide TLe - TLi



# Cranking Paths Affected



# Induced MWh Increase



# Tie Line Utilization

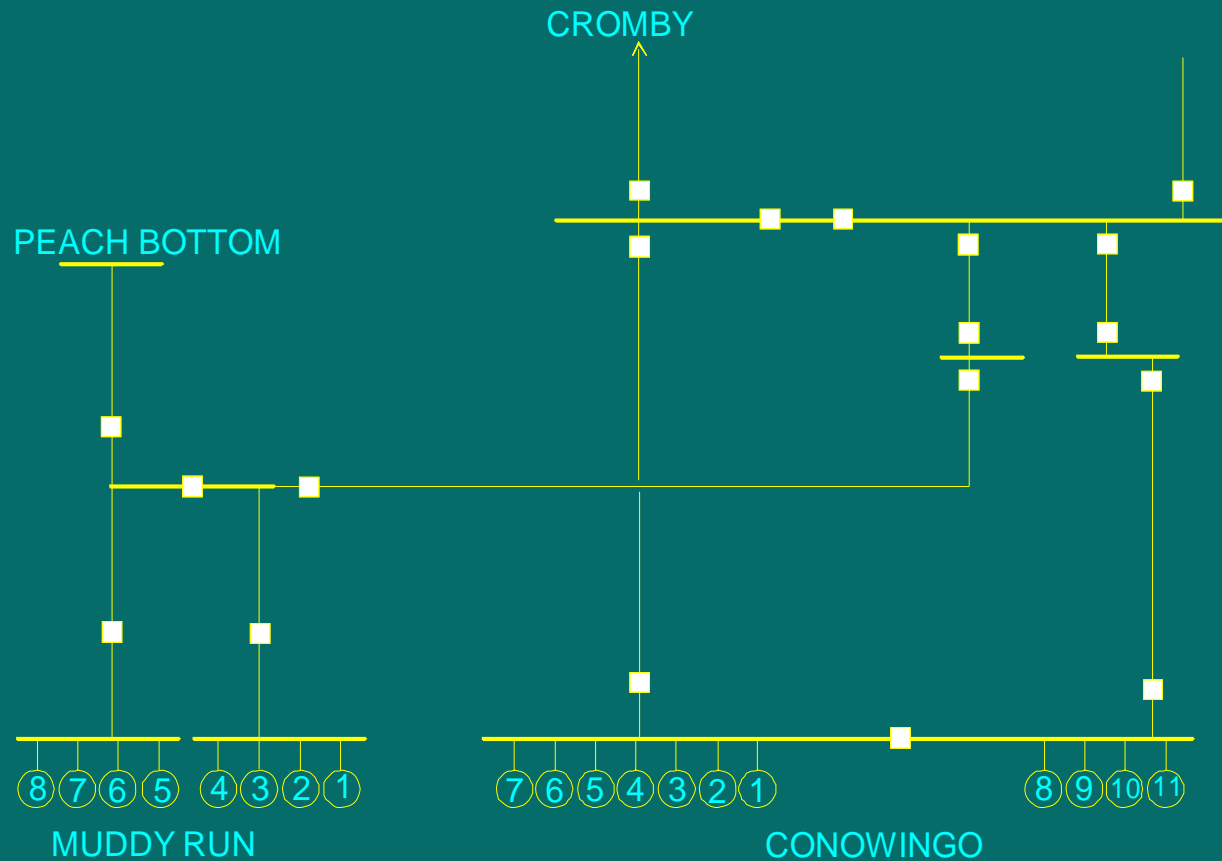
## *MWh Increase by S1*

- *Increase from Earlier Startup of S1*
- *Increase **Induced** by S1*

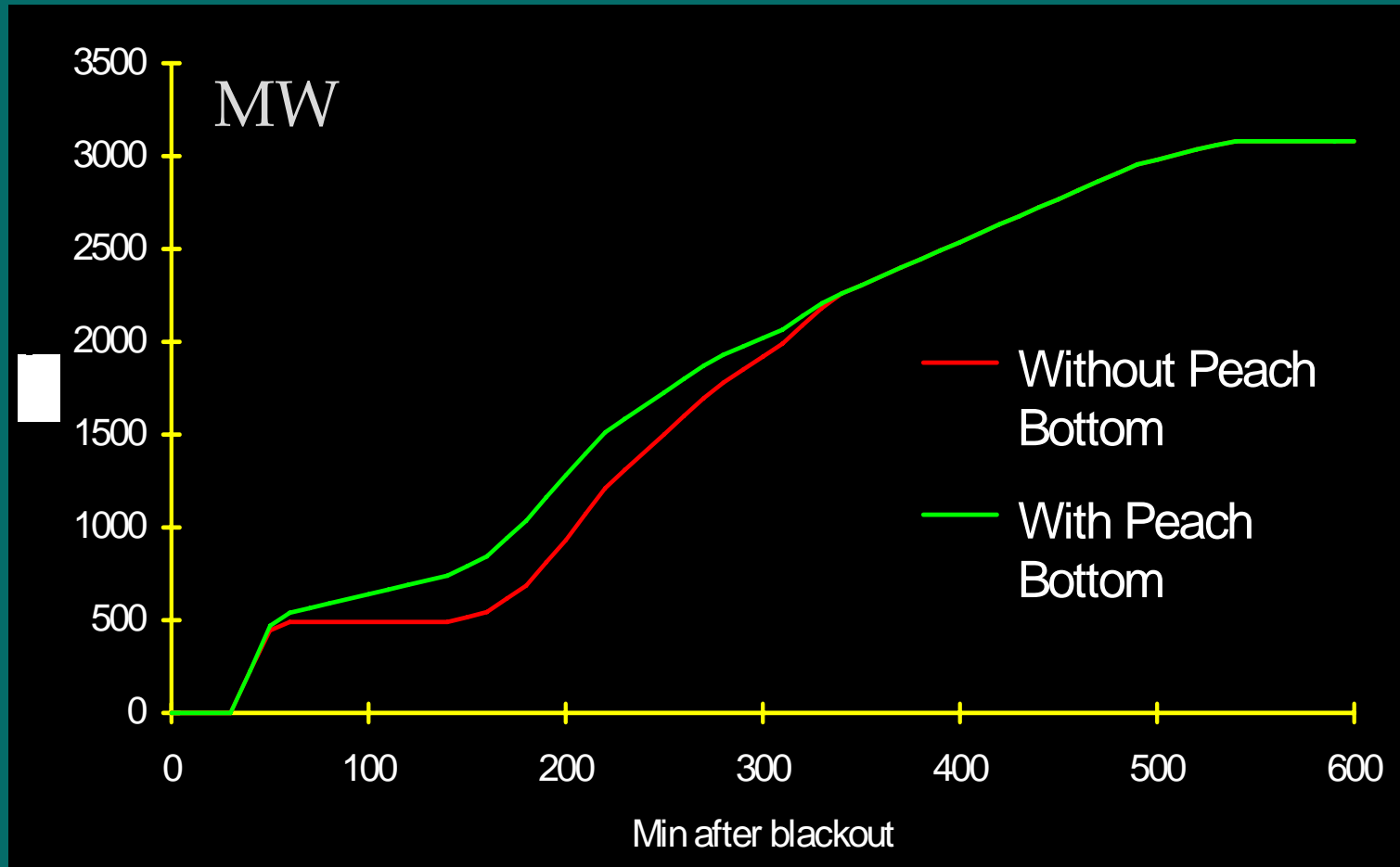
## *MWh Decrease by S2 (S3)*

- *Decrease from Delayed Startup of S2 (S3)*
- *Decrease **Induced** by S2 (S3)*

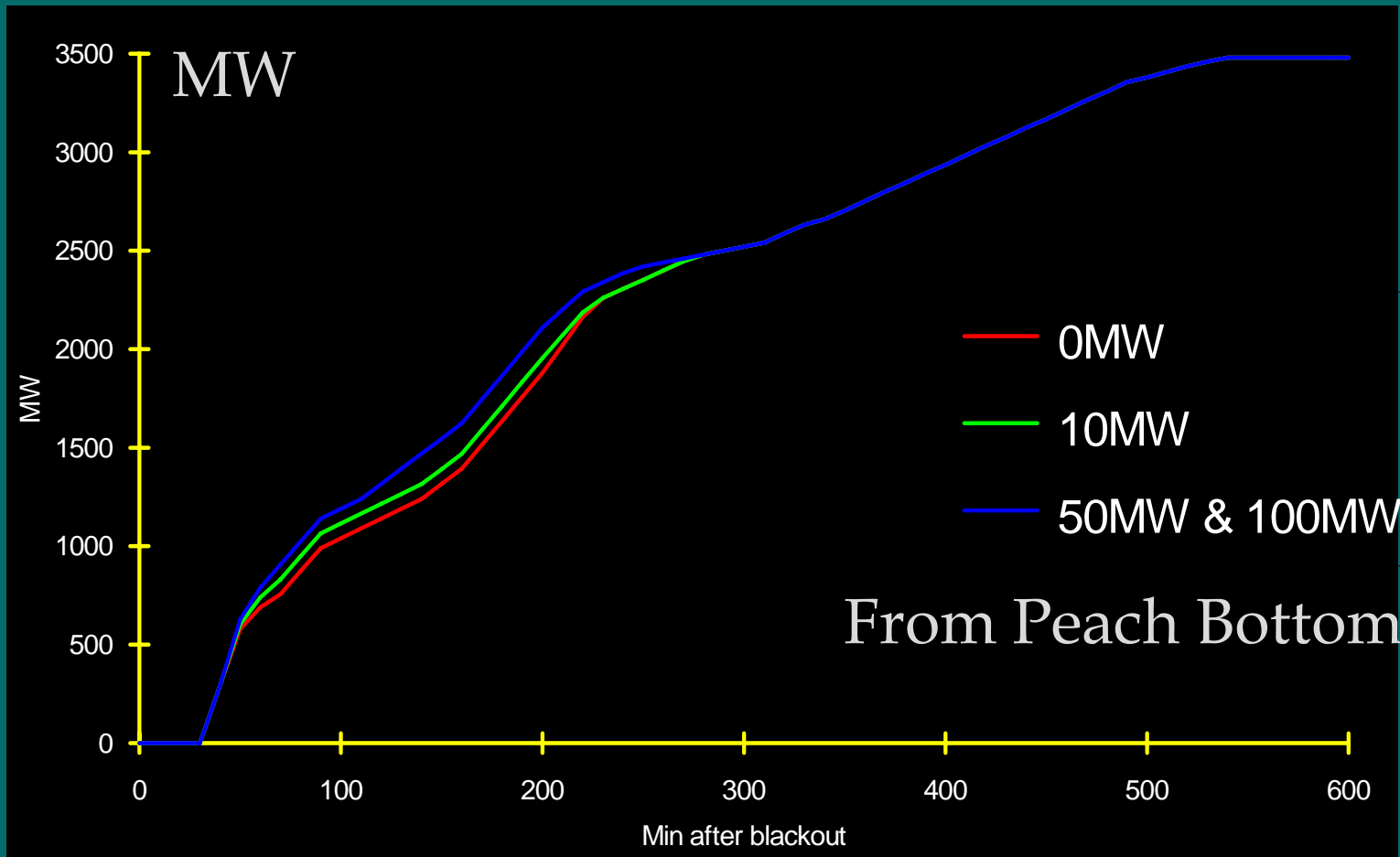
# Test Subsystem



# System Generation Capability



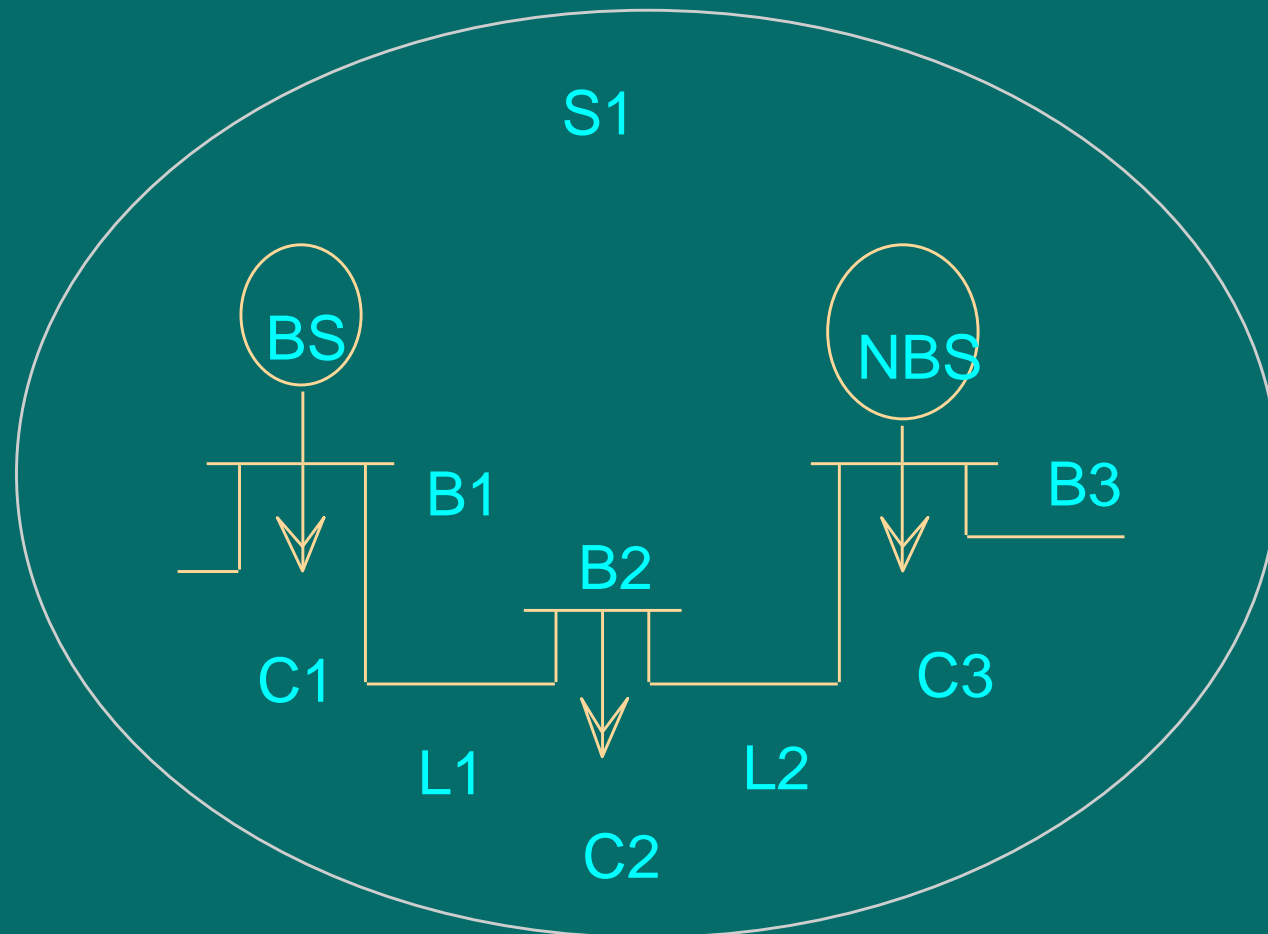
# System Generation Capability



# Generic Restoration Actions (GRAs)

- start\_black\_start\_unit (X)
- find\_path (X,Y)
- energize\_line (X)
- pick\_up\_load (X)
- synchronize (X,Y)
- connect\_tie\_line (X)
- crank\_unit (X)
- energize\_busbar (X)

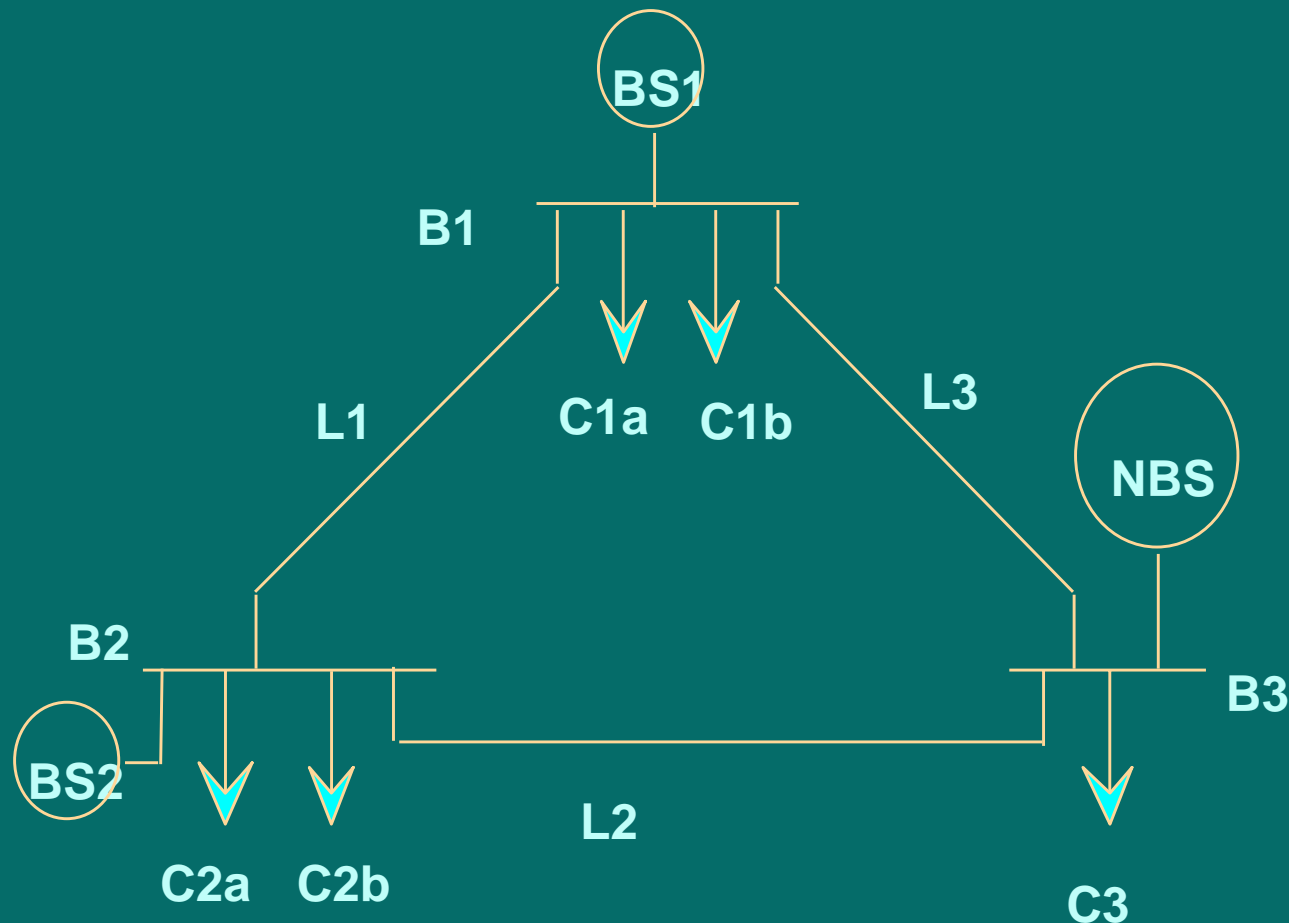
# Using GRAs to Construct RBBs



# Using GRAs to Construct RBBs

- Find transmission path between BS & NBS
- Start black-start unit BS
- Build transmission path from busbar B1 to B3 and pick up loads for stabilization
- Crank non-black-start unit NBS

# Using RBBs & GRAs to Build Restoration Strategies



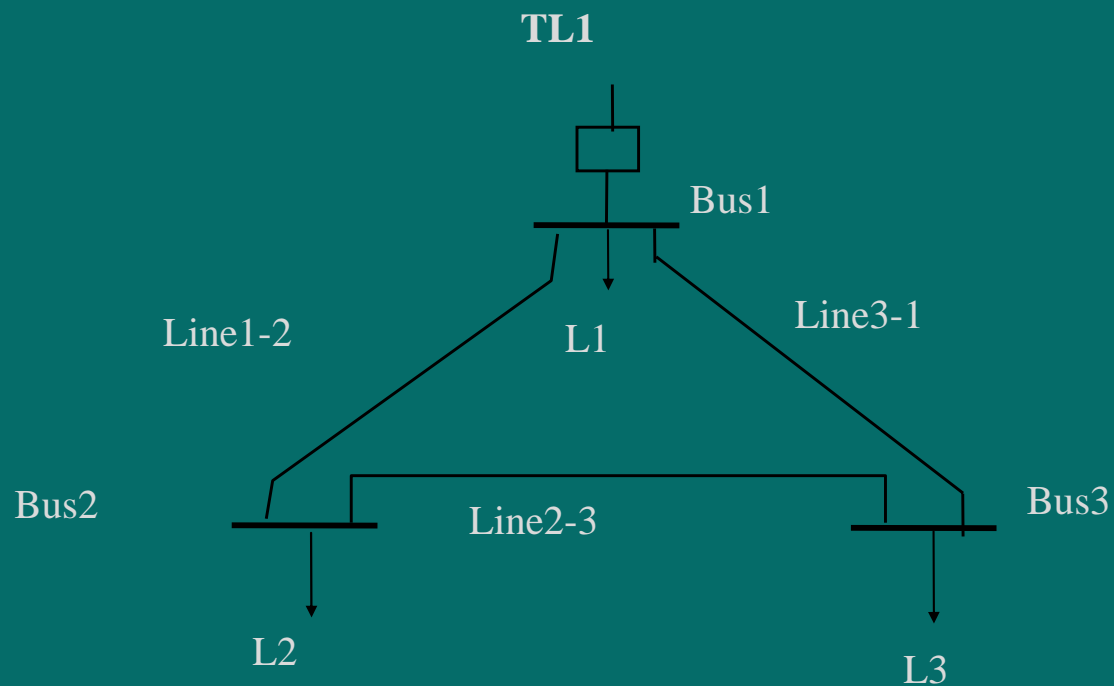
# Using RBBs & GRAs to Build Restoration Strategies

- **Select Two RBBs**
  - RBB1: Use BS1 to energize B1
  - RBB2: Use BS2 to energize B2
- **Build RBB1**
  - Prepare load
  - Start BS unit
  - Energize bus

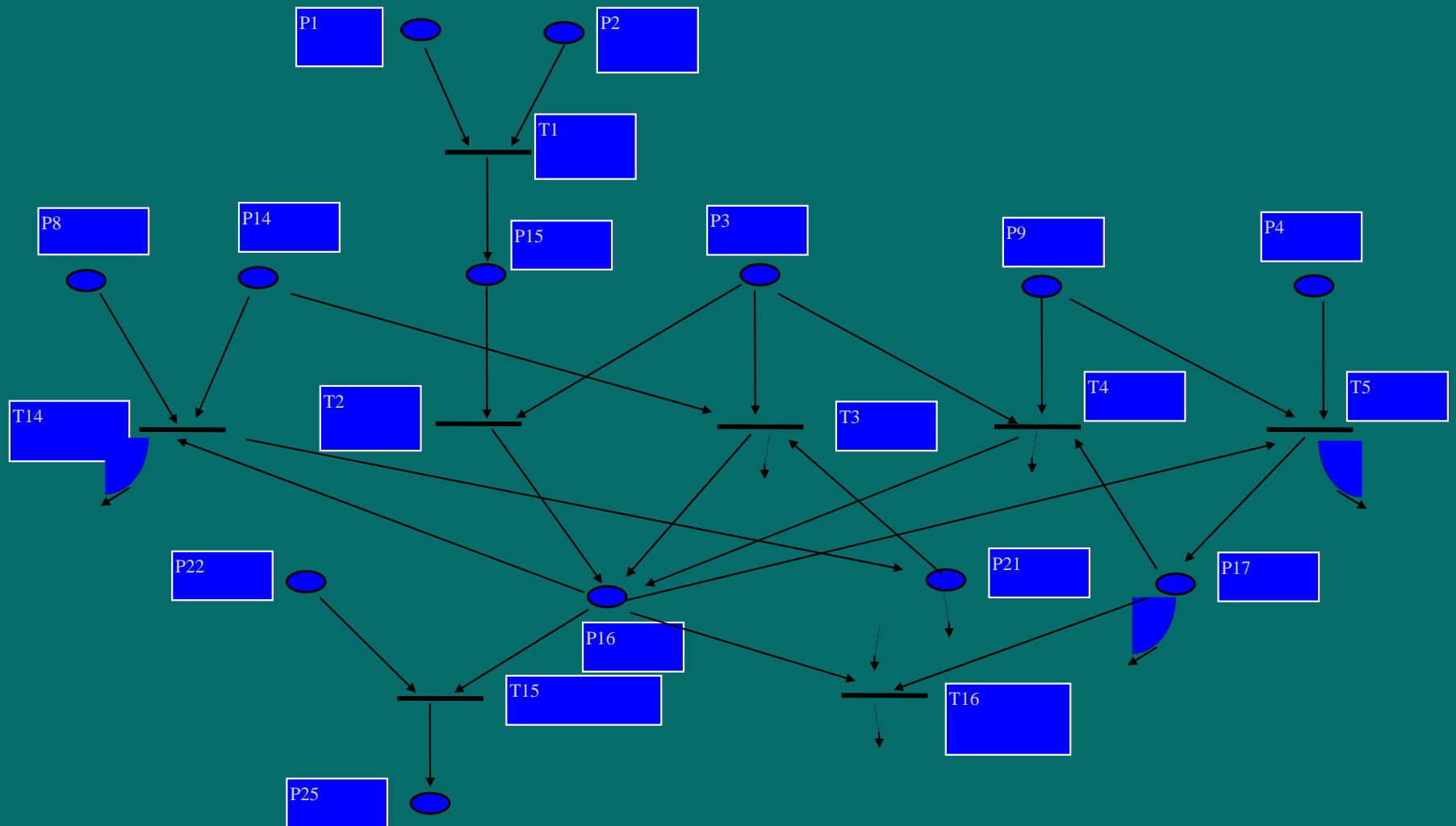
# Using RBBs & GRAs to Build Restoration Strategies (Cont.)

- Build RBB2
- Energize ring
- Restart non-black-start unit NBS
- Pick up loads along ring

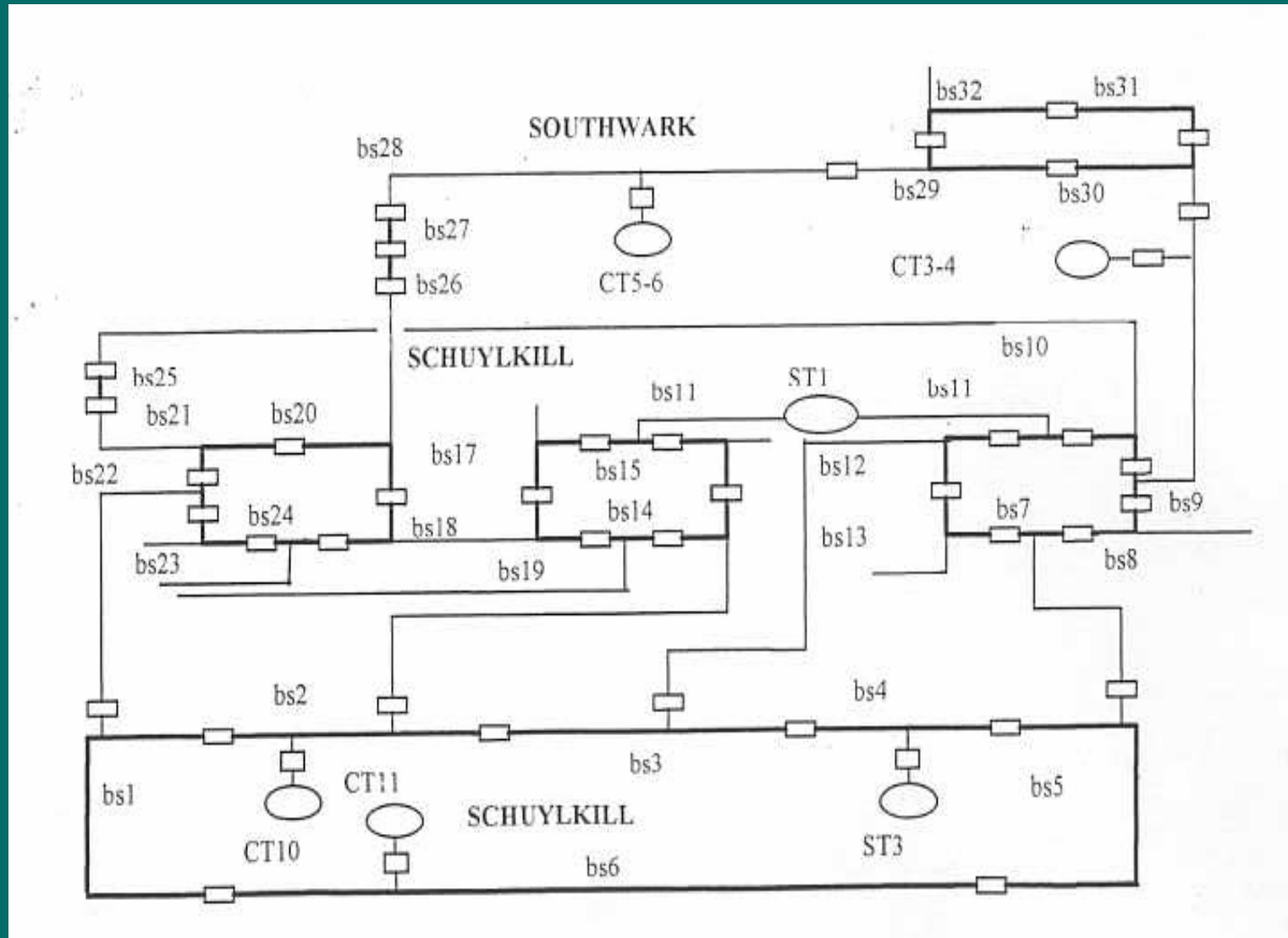
# Petri Net Algorithm to Optimize Sequence of GRAs



# Petri Net Model



# Schulykill-Southwark Subsystem



# Time to Complete GRAs

Generic Restoration Action (GRA)	Time (mins.)
Restart BSU	15
Energize Busbar from BSU/busbar/line	5
Connect Tie Line	25
Crank a NBSU	15
Synchronize between Busbars/Lines	20
Pick up Load	10

# Sequence of Actions for Schuylkill-Southwark

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Time (min.)	Actions
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## Restoration Building Block 1:

0	Connect BSU CT10
15	Energize bs2 from CT10
20	Energize bs3 from bs2
25	Energize bs4 from bs3
30	Crank NBSU ST3 from bs4
45	Synchronize ST3 with bs4

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# Sequence of Actions for Schuylkill-Southwark



Time (min.)	Actions
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## Restoration Building Block 2:

0	Connect BSU CT3-4
15	Energize bs9 from CT3-4
20	Energize bs10 from bs9
25	Energize bs11 from bs10
30	Crank NBSU ST1 from bs11
45	Synchronize ST1 with bs11

# Sequence of Actions for Schuylkill-Southwark

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- 65 Energize bs1 from bs2, bs14 from bs2, bs12 from bs3, bs5 from bs4, bs30 from bs9, bs8 from bs9, bs17 from bs11, bs15 from bs11, bs25 from bs10
- 70 Energize bs22 from bs1, bs19 from bs14, bs13 from bs12, bs7 from bs5, bs31 from bs39, bs21 from bs25, and synchronize bs14 with bs15
- 75 Energize bs32 from bs31, bs20 from bs21, bs23 from bs22, and connect bs7 with bs13, bs8 with bs7, and bs22 with bs21
- 80 Energize bs24 from bs23, bs26 from bs20
- 85 Energize bs27 from bs26
- 90 Energize bs28 from bs27
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# Further Information

- M. M. Adibi (Ed), *Power System Restoration Methodologies & Implementation Strategies*, IEEE Press, 2000.
- J. Wu, C. C. Liu, and R. Chu, "A Petri Net Algorithm for Scheduling of Generic Restoration Actions," *IEEE Trans. Power Systems*, Feb. 1997, pp. 69-76.
- L. Fink, K. L. Liou, and C. C. Liu, "From Generic Restoration Actions to Specific Restoration Strategies," *IEEE Trans. Power Systems*, May 1995, pp. 745-752.
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- C. C. Liu, K. L. Liou, et al., "Generation Capability Dispatch for Bulk Power System Restoration – A Knowledge-Based Approach," *IEEE Trans. Power Systems*, Feb. 1993, pp. 316-325.