

*Optimizing Power System
Restoration Resources and
Actions*

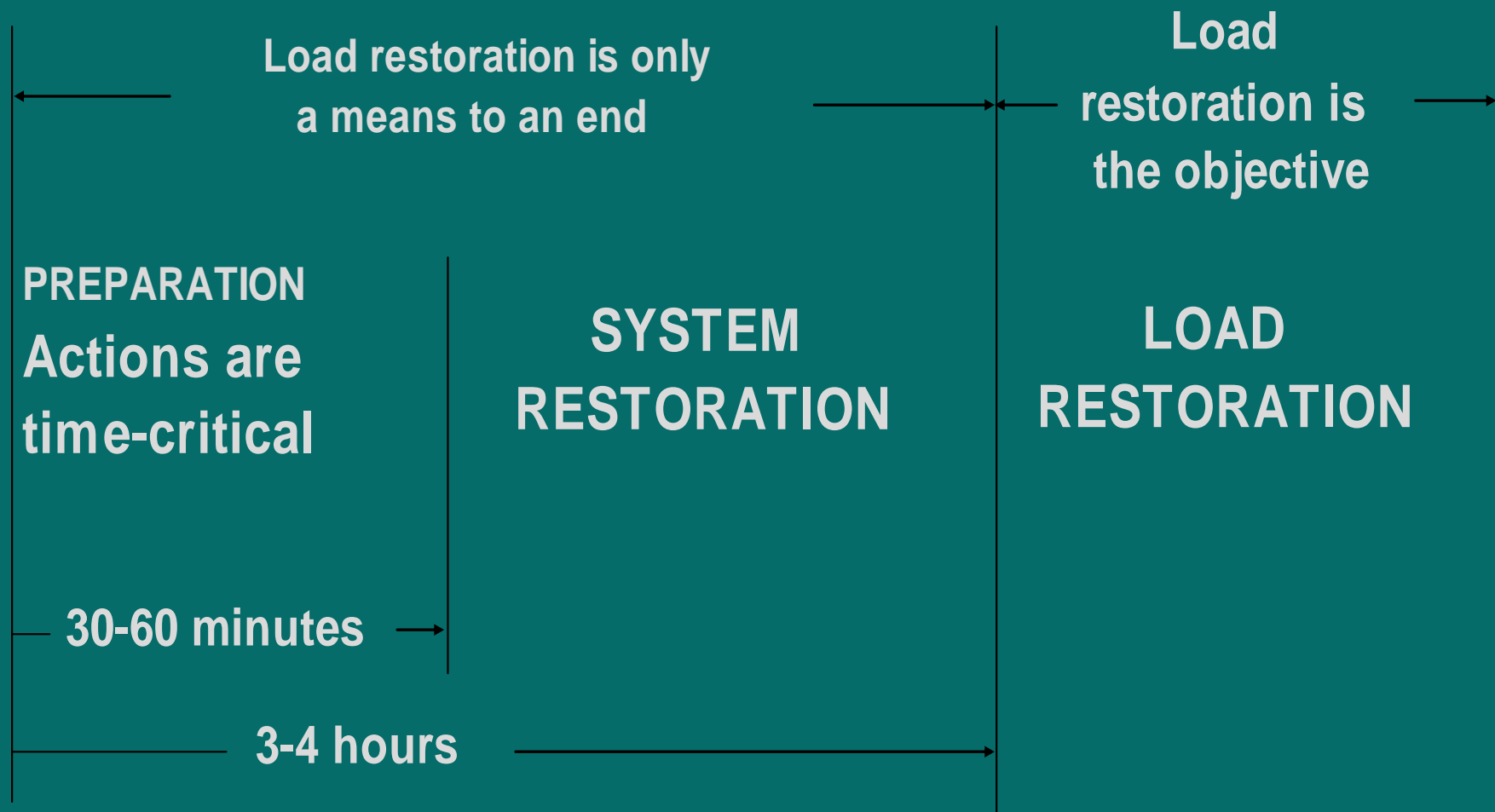
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PSERC Research Tele-seminar, November 2006

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

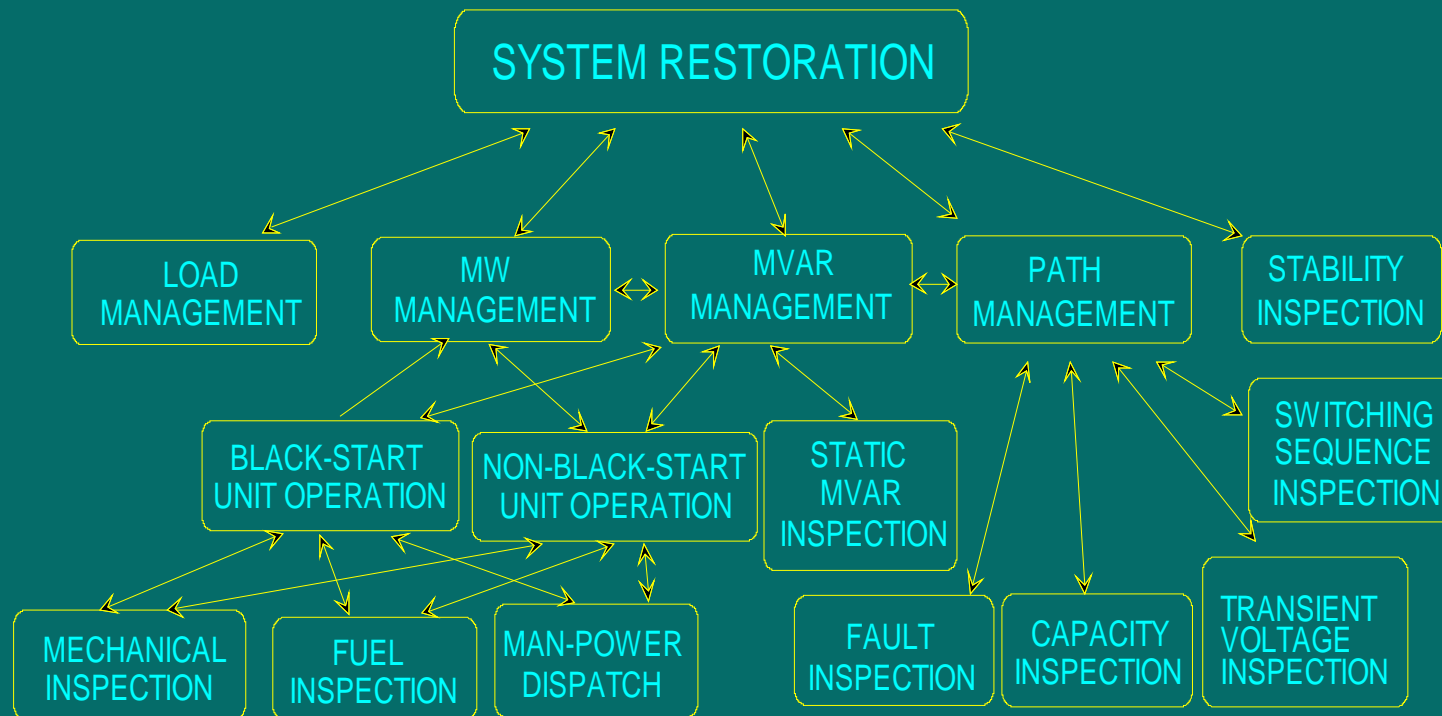
Restoration Constraints

- Physical constraints
- Scheduling constraints
- Policy constraints

Third Stage

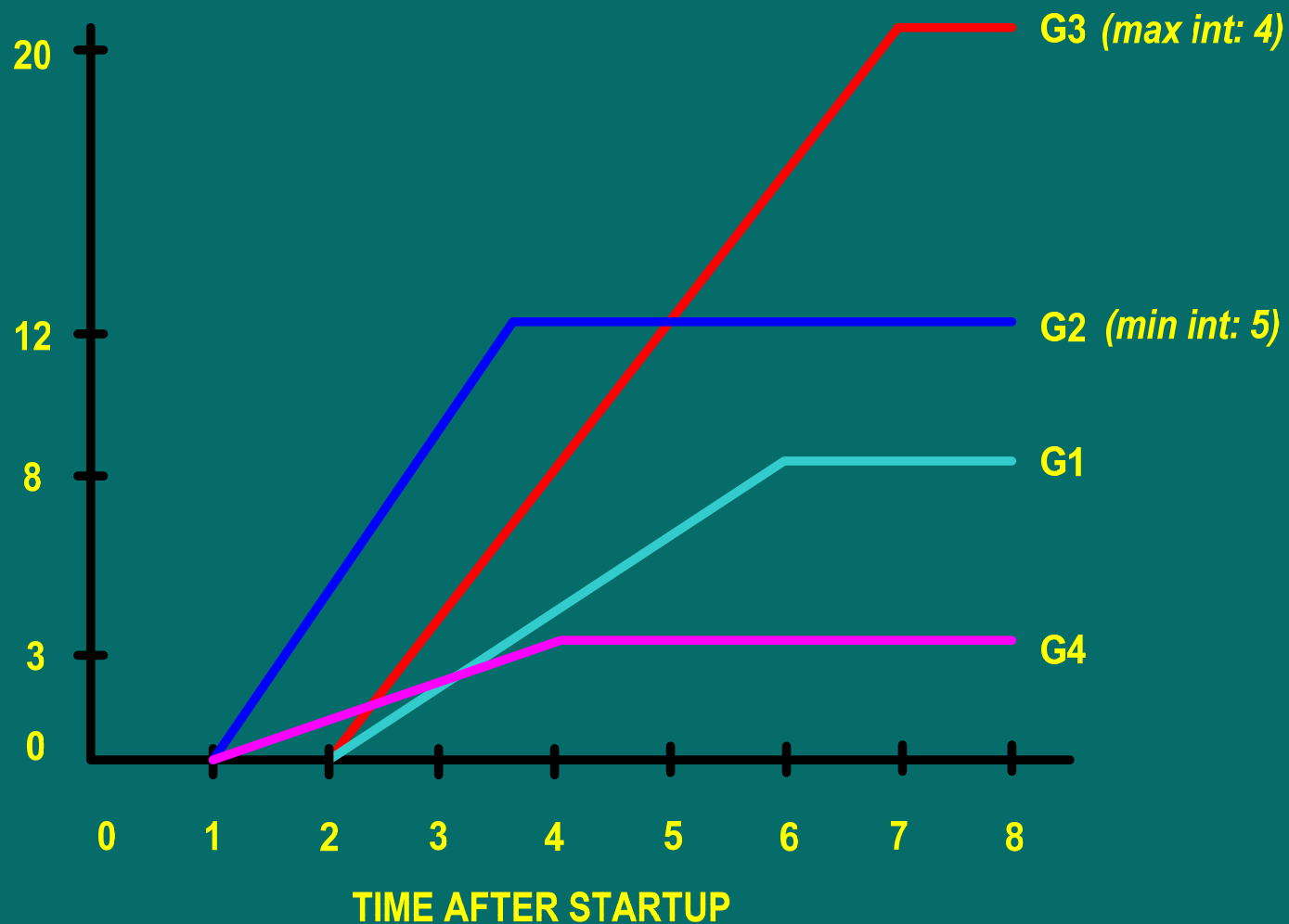
Load Restoration – Pick Up Loads

Restoration Strategy

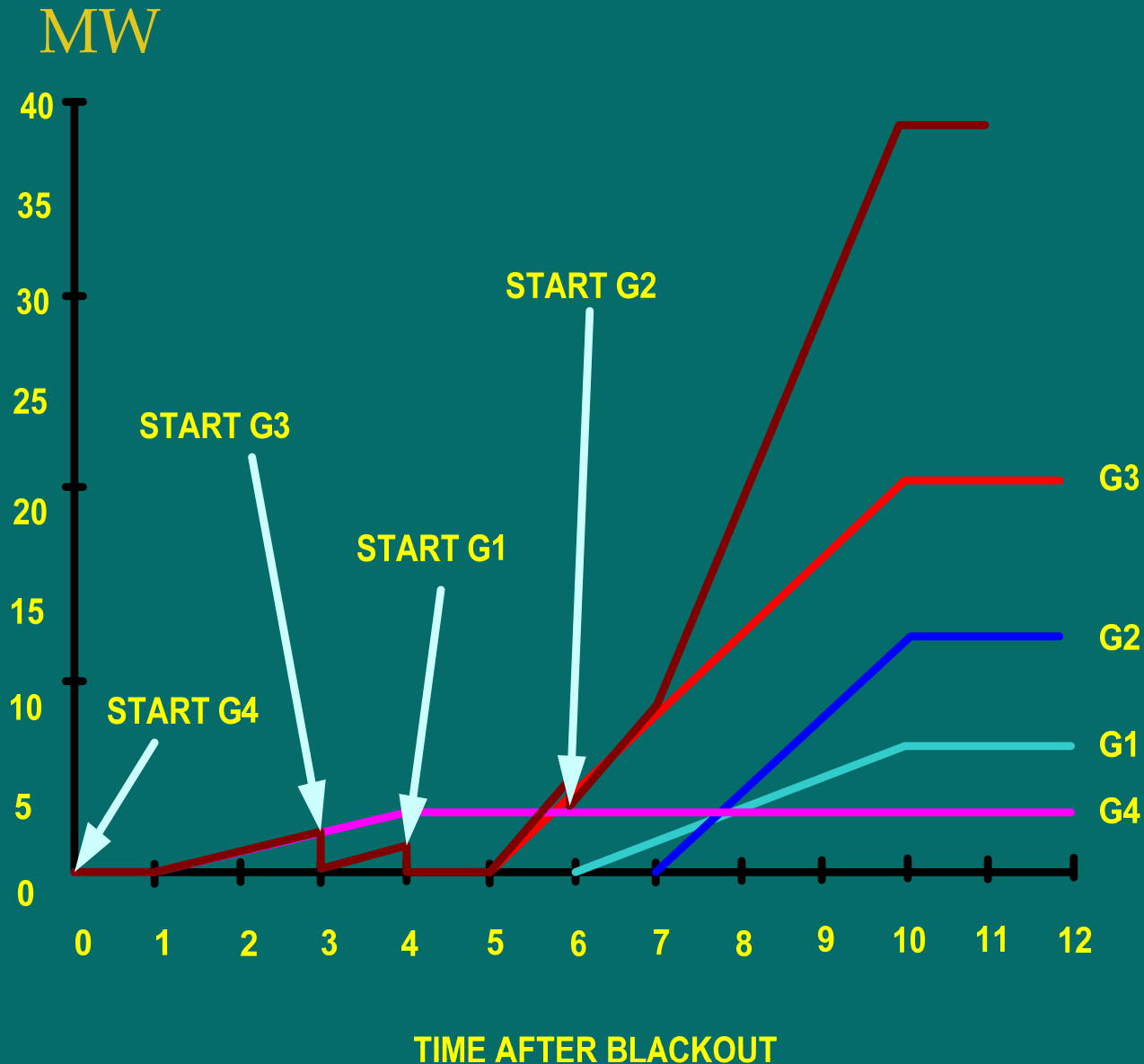


Example - Generation Capabilities

(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

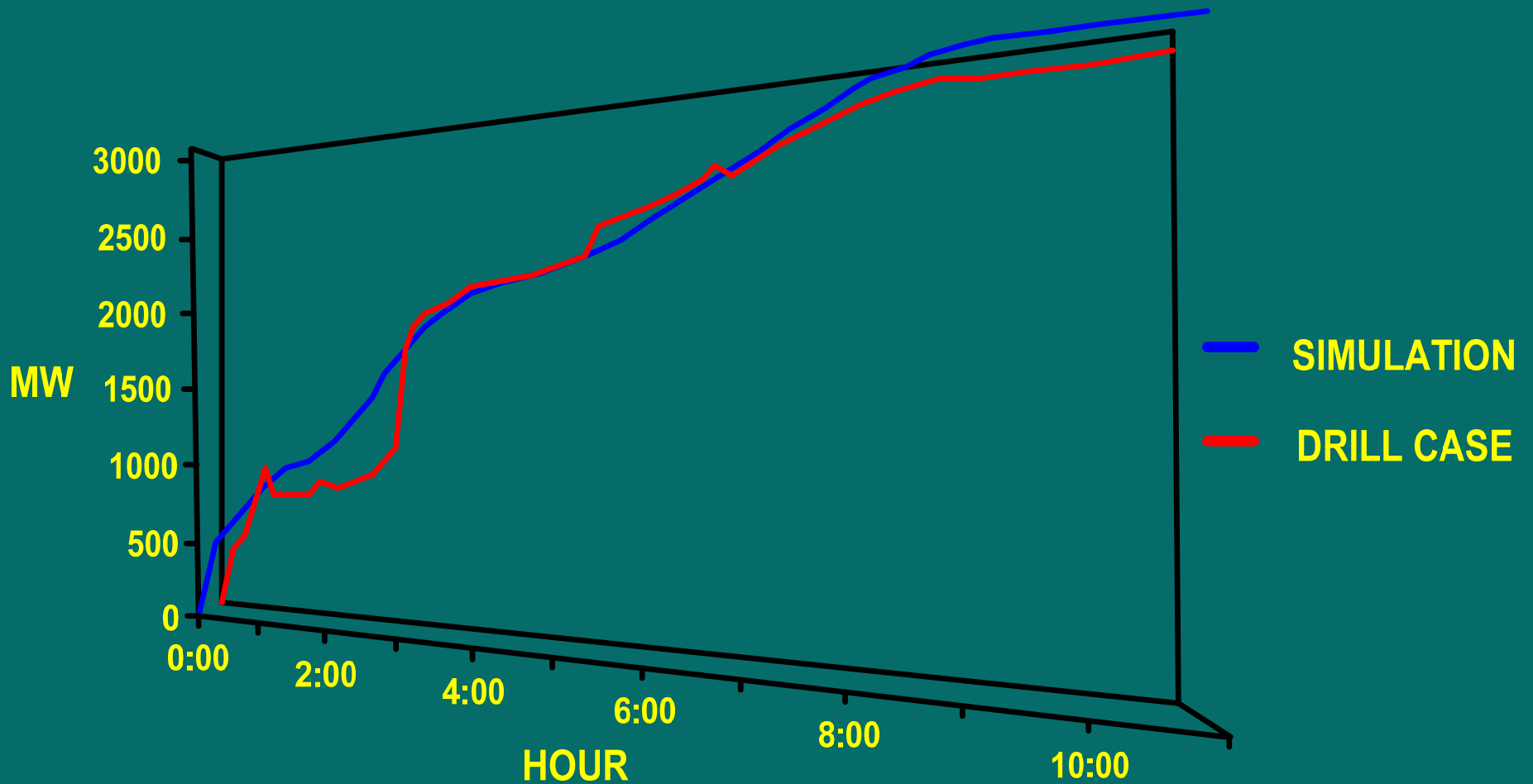
Unit	Type	MW Cap. (MW)	Ramp. rate (MW/hr)	Crank to paral. (hr)	Crit. max. int. (hr)	Crit. min. int. (hr)	Startup req. (MW)
Chester_4	CT	15	40	0	N/A	N/A	0
Chester_5	CT	15	40	0	N/A	N/A	0
Chester_6	CT	15	40	0	N/A	N/A	0
Chester_7-9	CT	45	120	0	N/A	N/A	0
Conowingo_1-7	Hydro	200	200	0	N/A	N/A	0
Conowingo_8-11	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_10	CT	15	45	0	N/A	N/A	0
Eddystone_11	CT	15	45	0	N/A	N/A	0
Eddystone_12	CT	15	45	0	N/A	N/A	0
Falls_1-3	CT	15	45	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

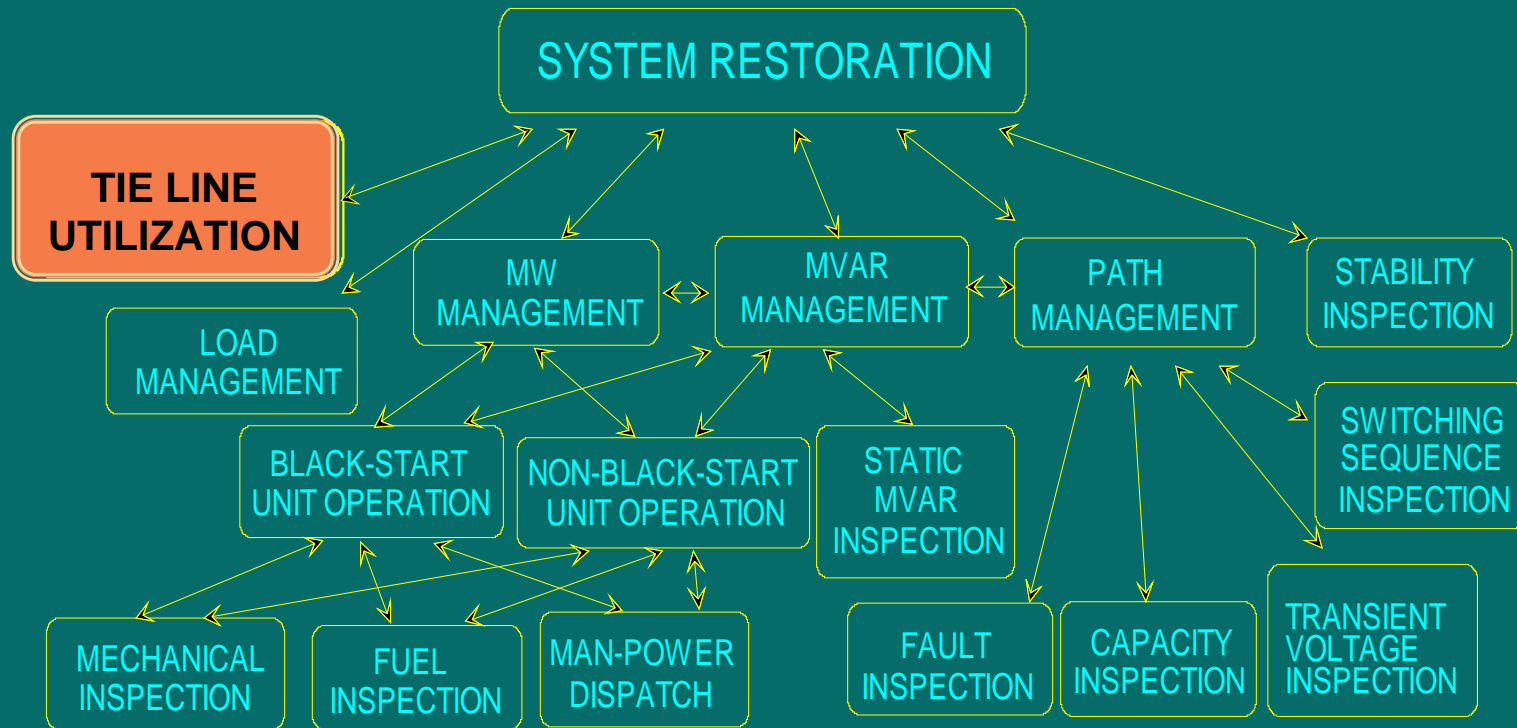
Critical Min. Interval

Critical Max. Interval

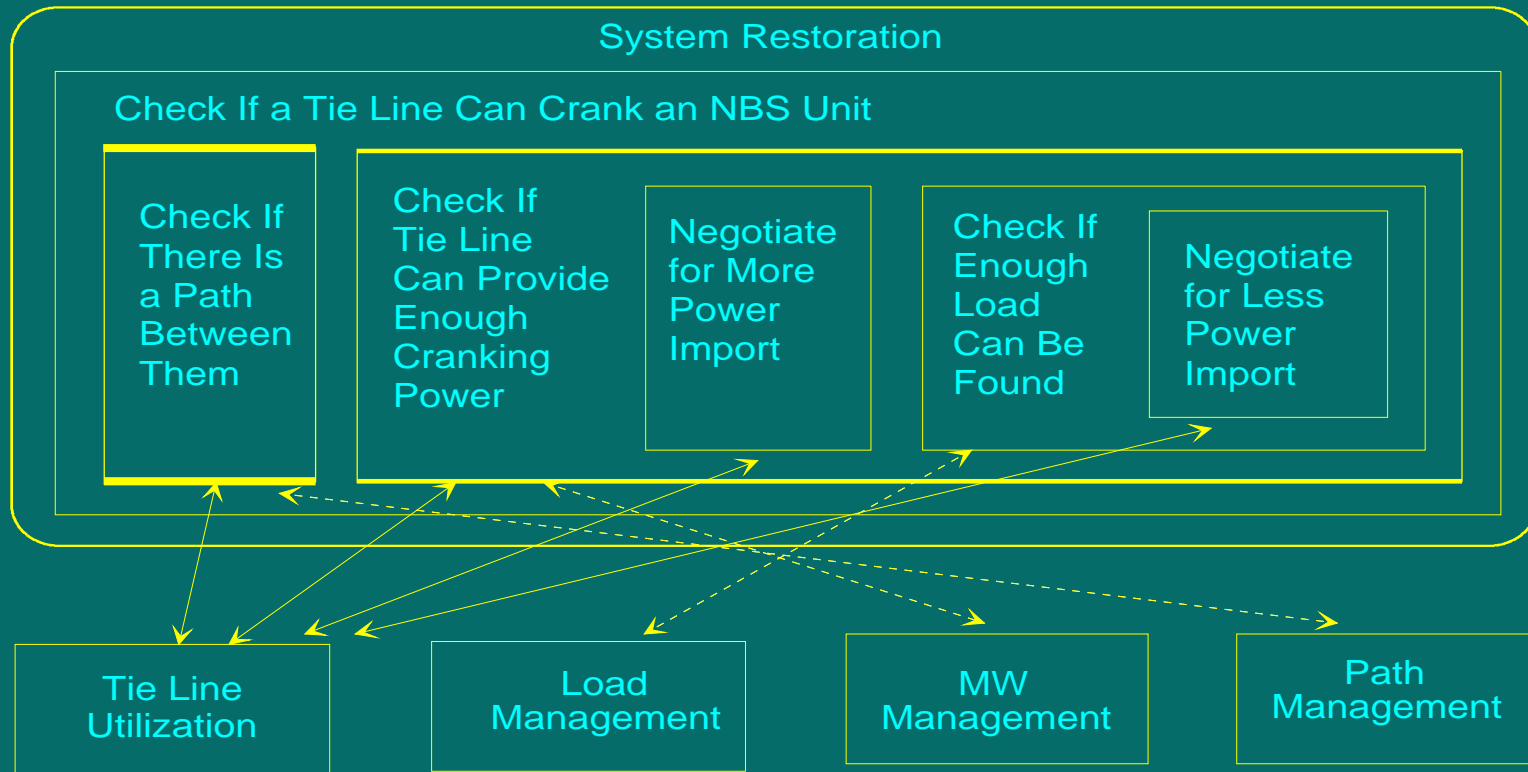
MW Capability Curves



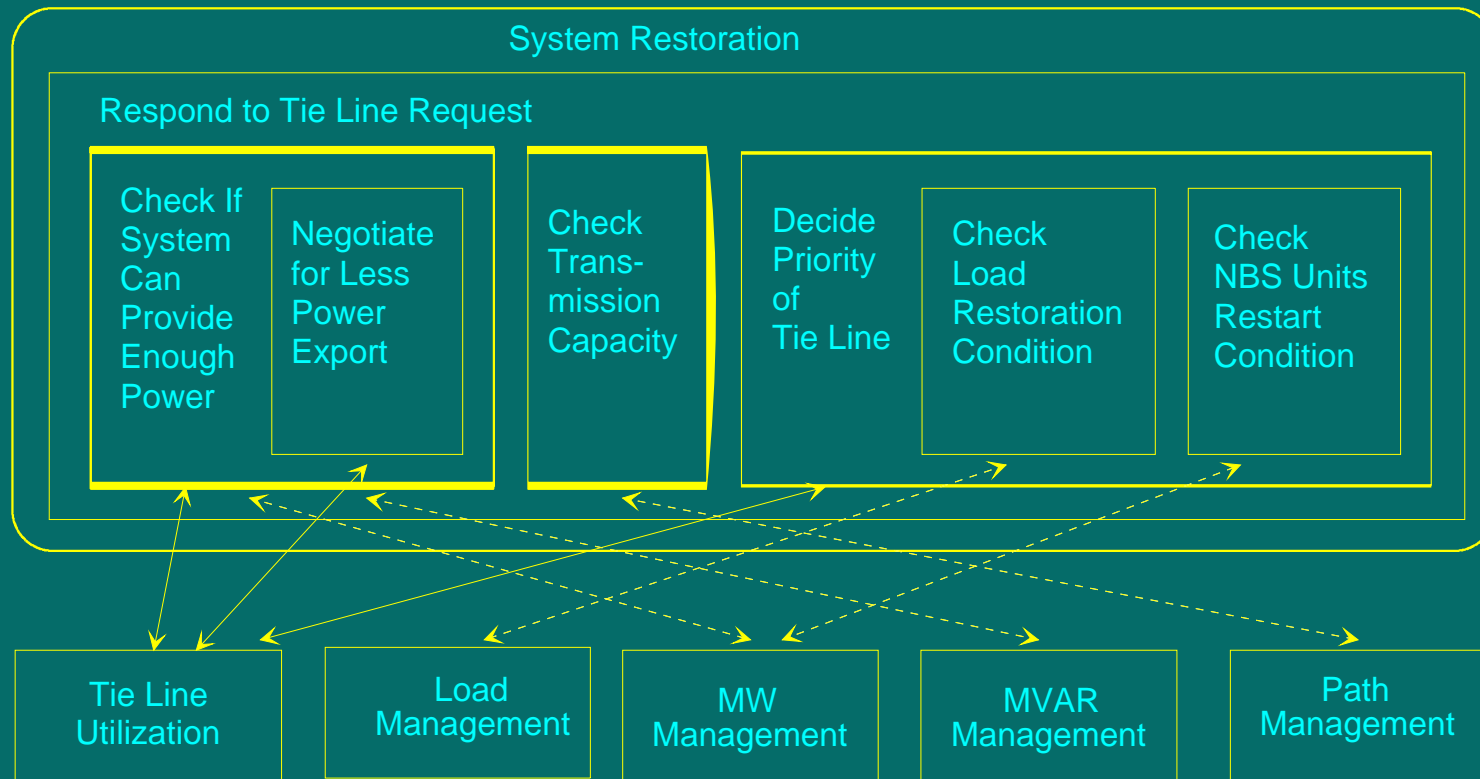
Restoration Strategy with Tie Lines



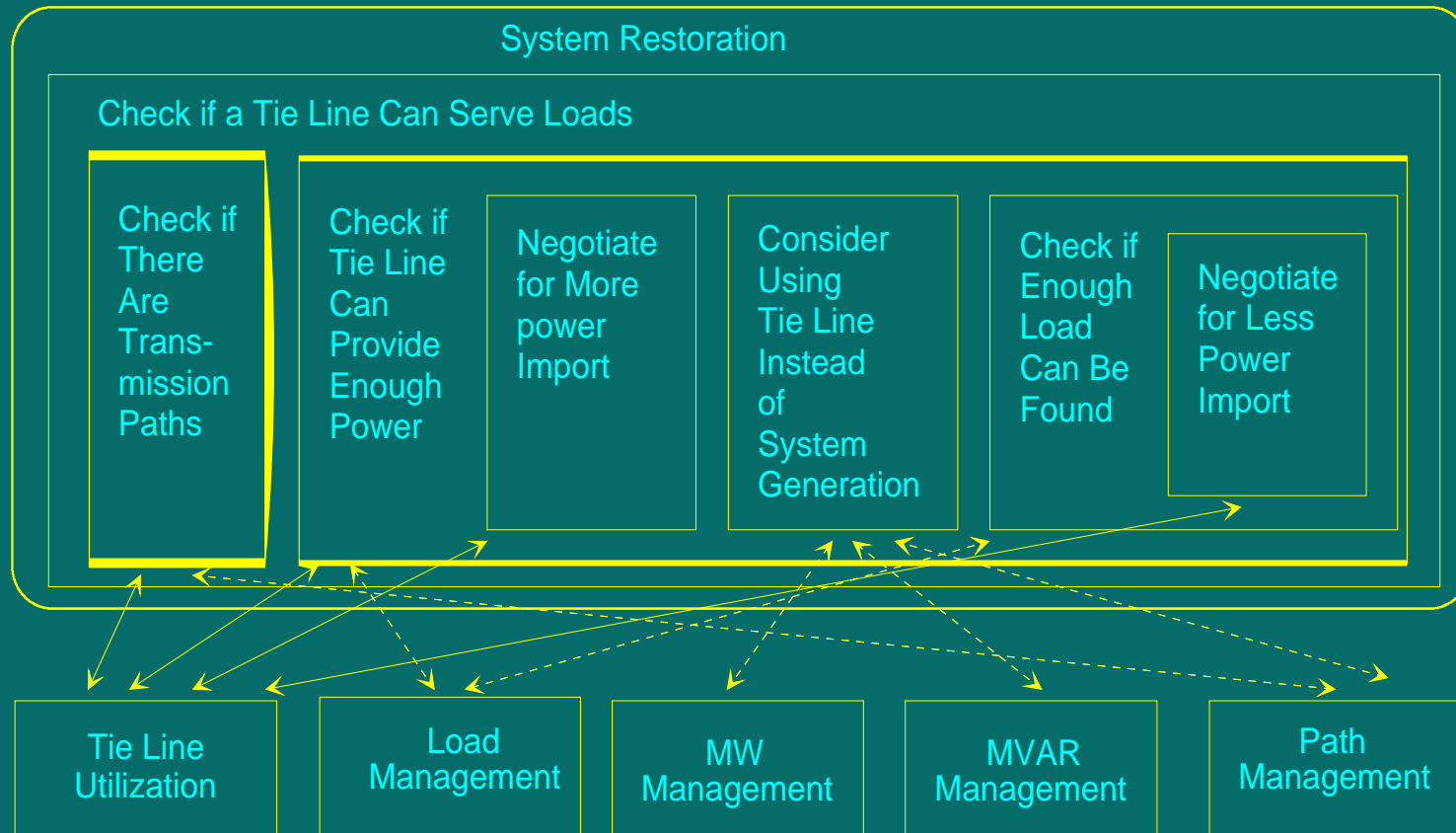
Crank NBS Units



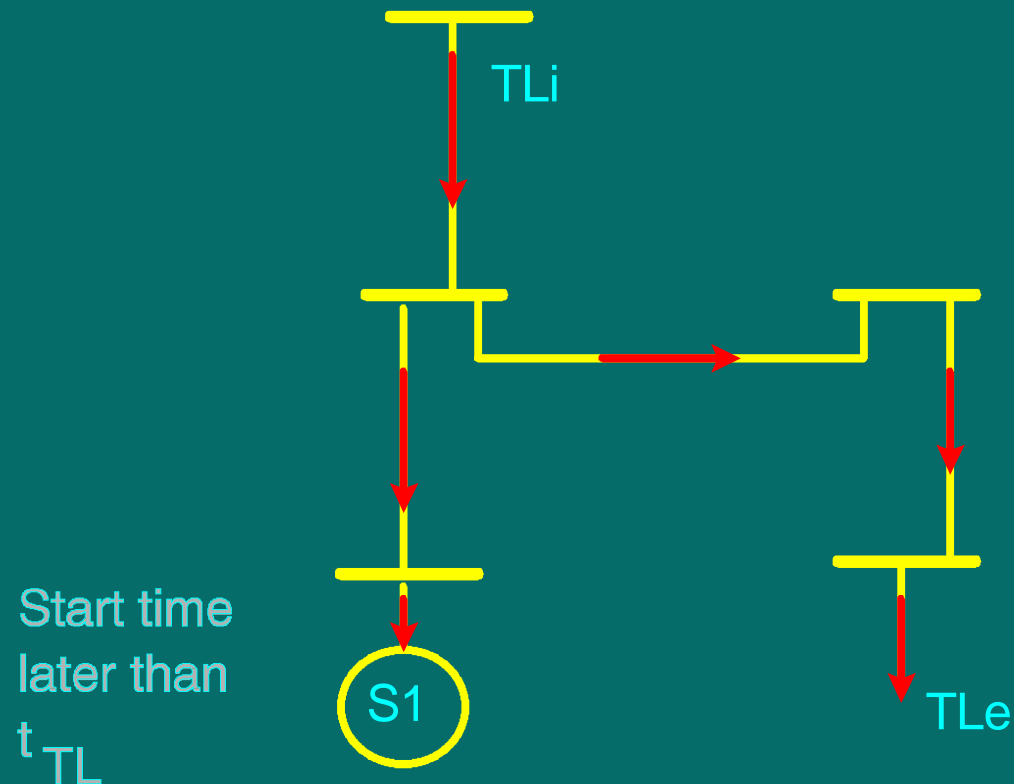
Respond to Request



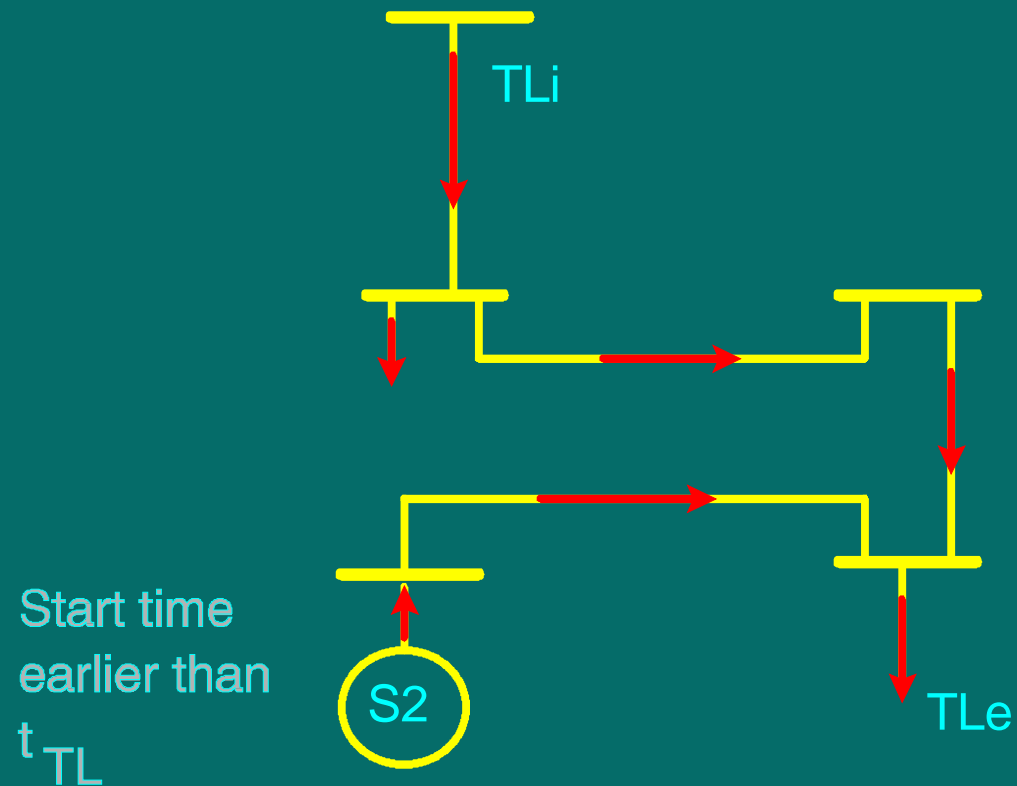
Serve Load



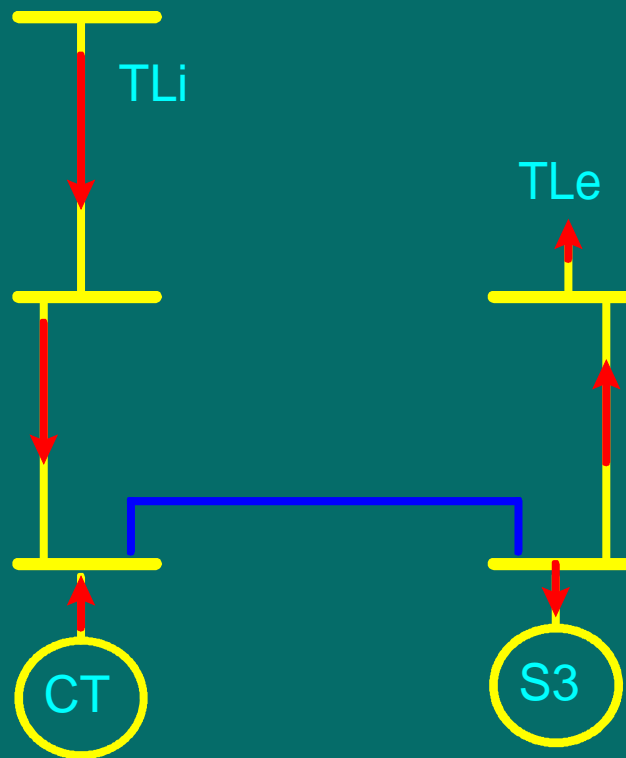
Internal Units to be Cranked by TLi



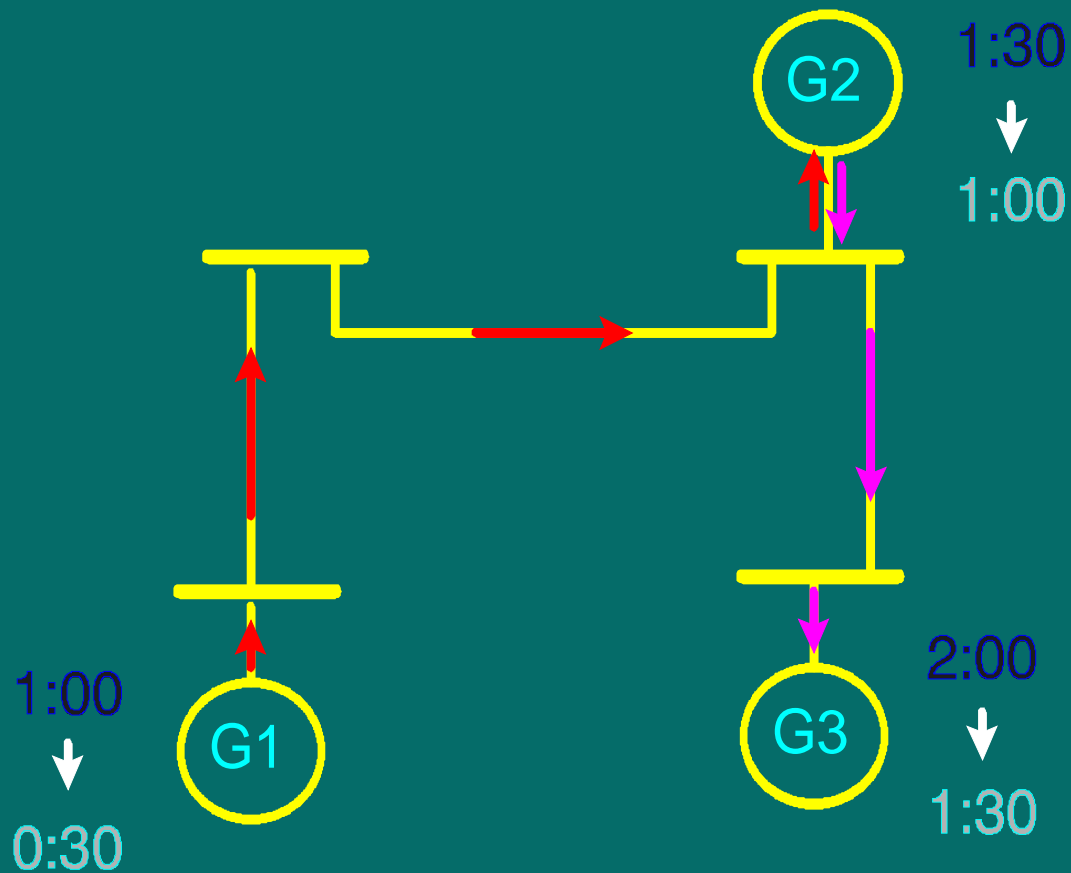
Internal Units to Provide TLe - TLi



Cranking Paths Affected



Induced MWh Increase



Tie Line Utilization

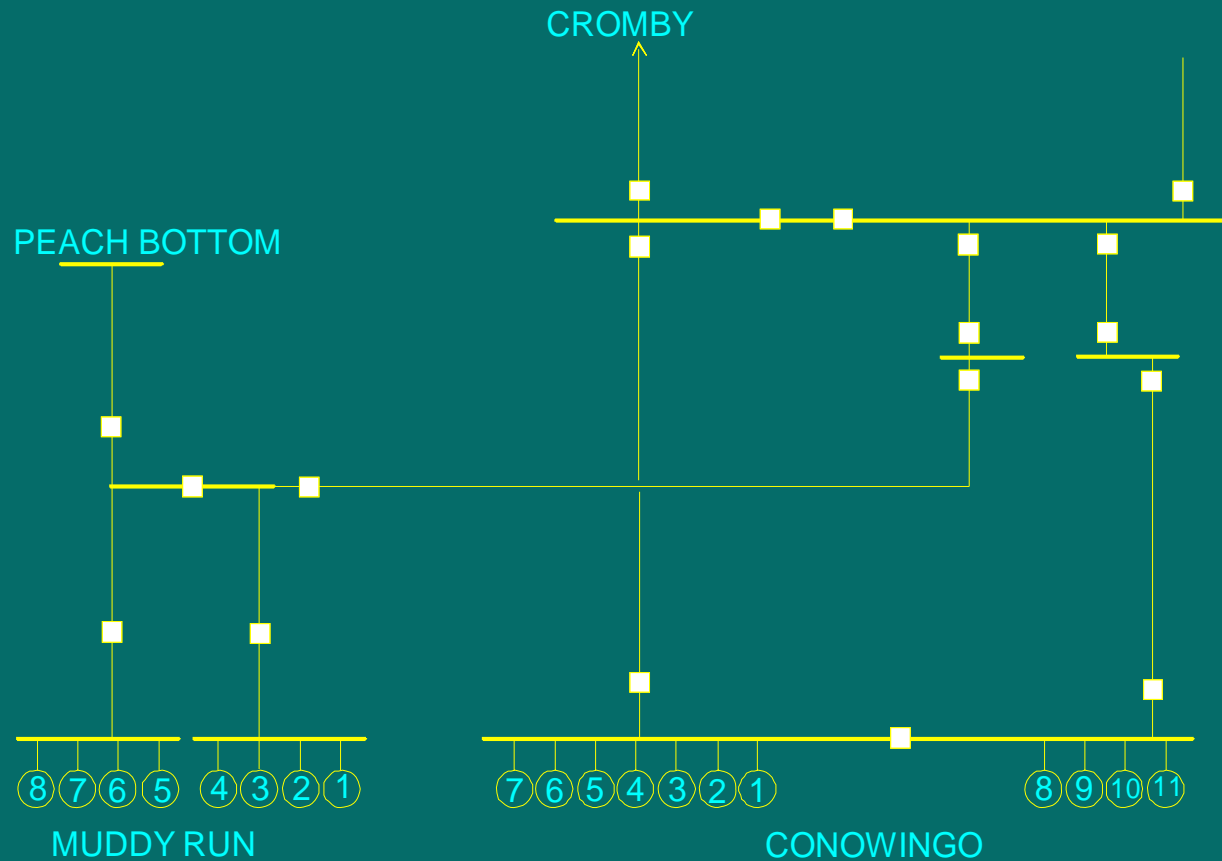
MWh Increase by S1

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

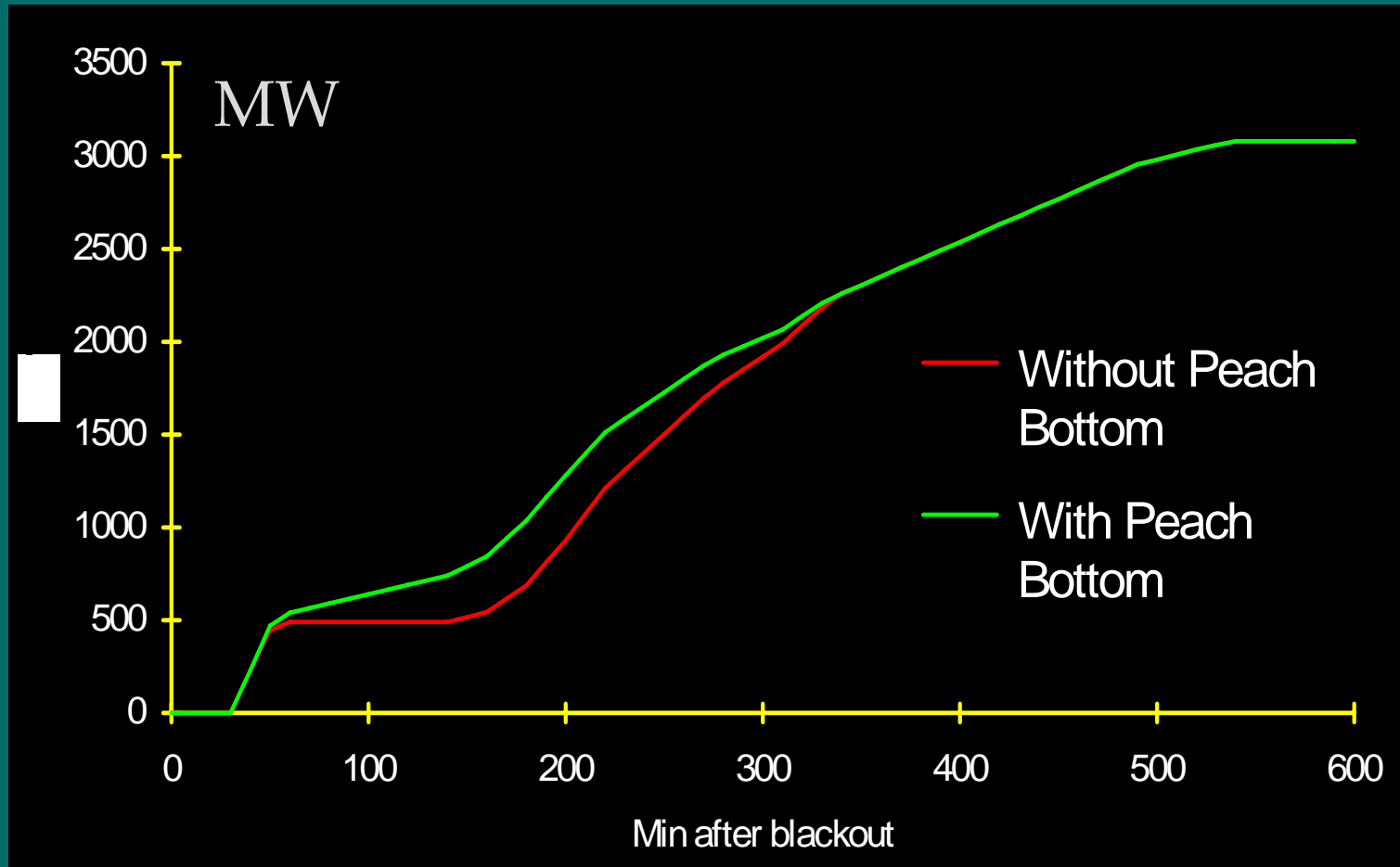
MWh Decrease by S2 (S3)

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

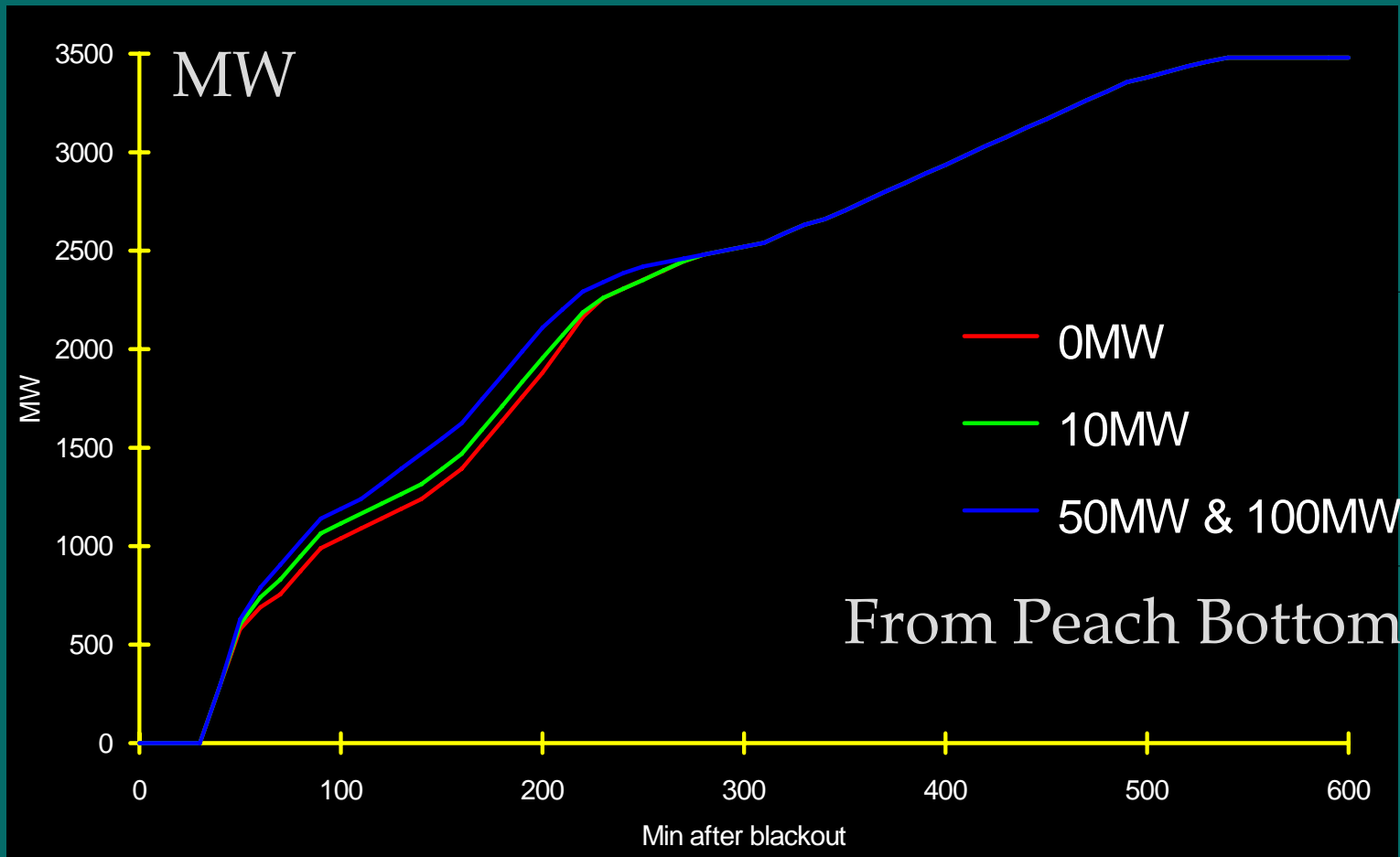
Test Subsystem



System Generation Capability



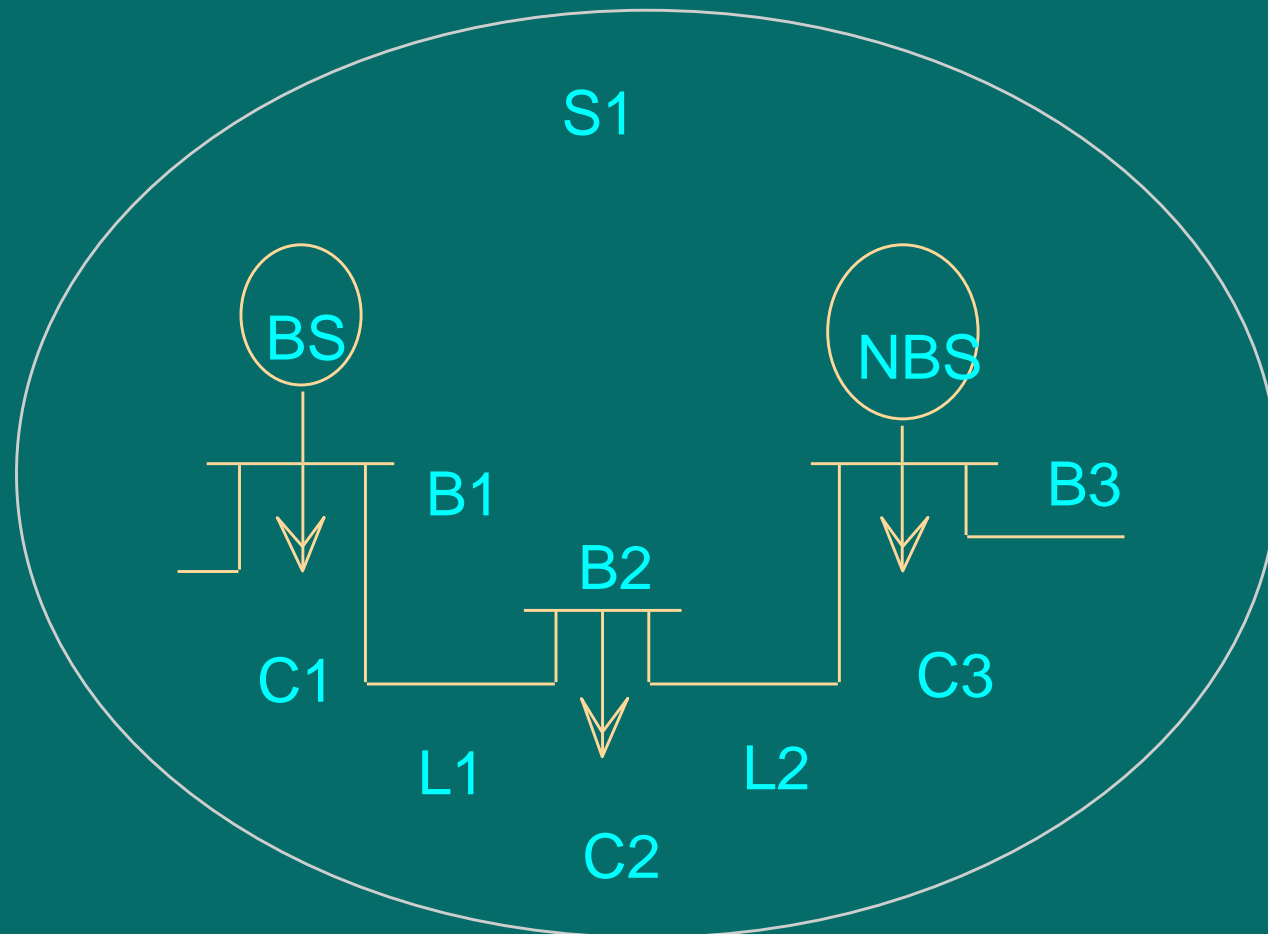
System Generation Capability



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)

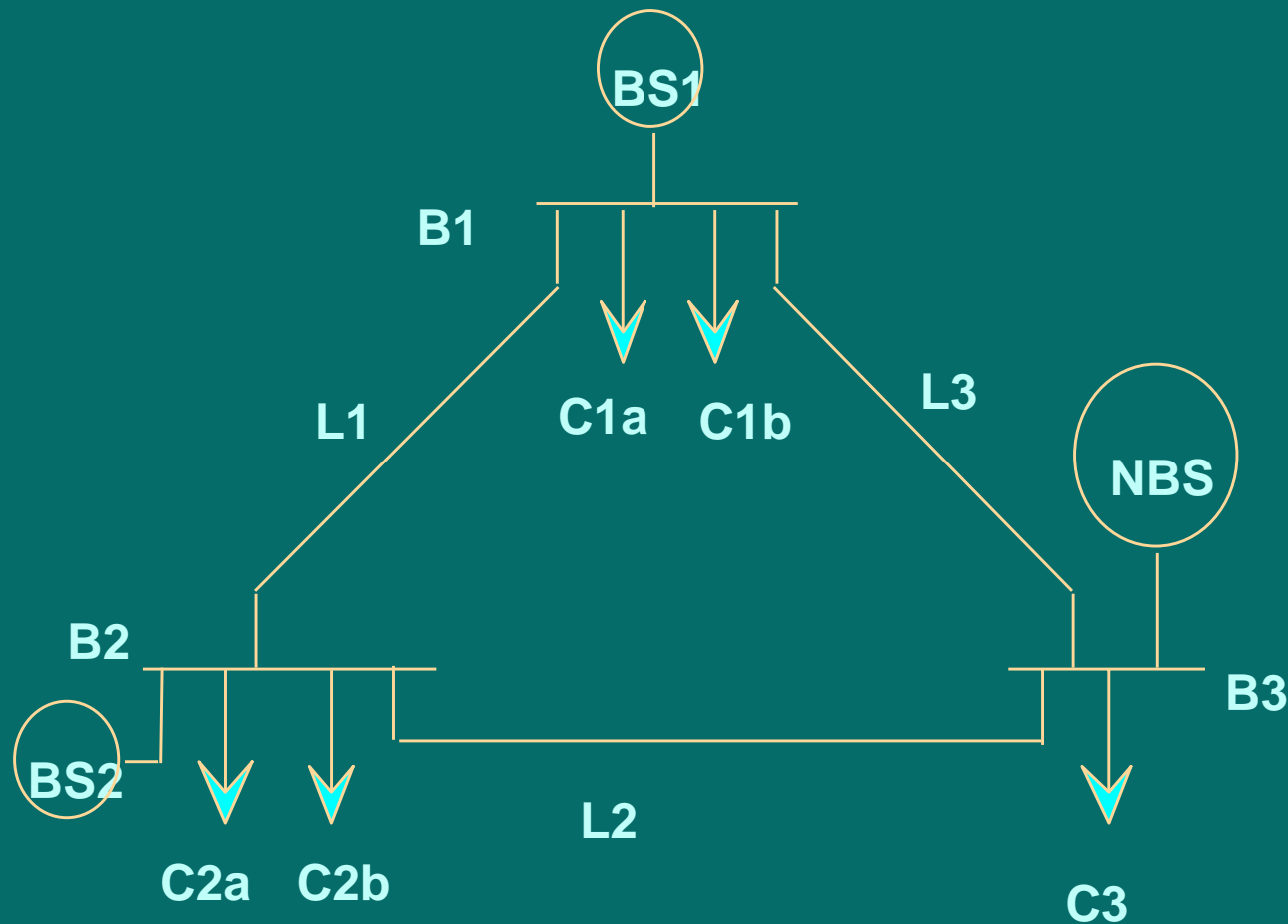
Using GRAs to Construct RBBs



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



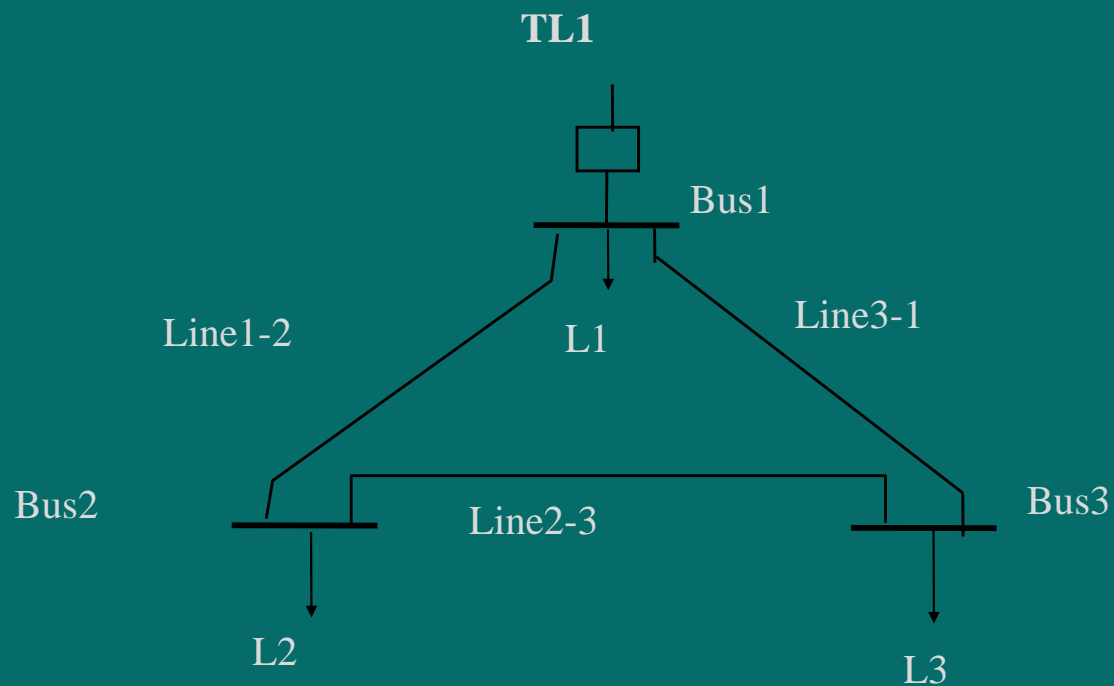
Using RBBs & GRAs to Build Restoration Strategies

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

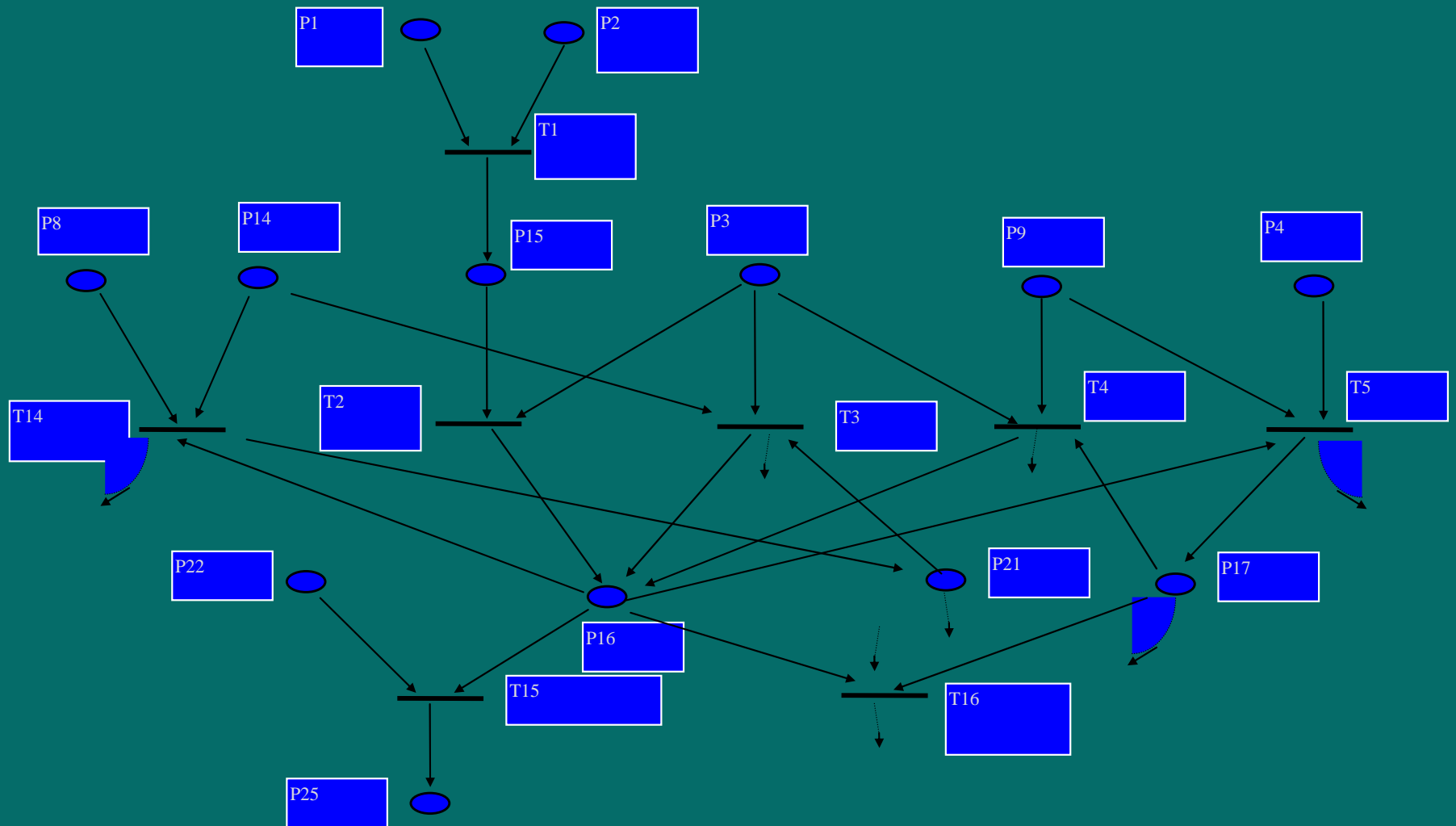
Using RBBs & GRAs to Build Restoration Strategies (Cont.)

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

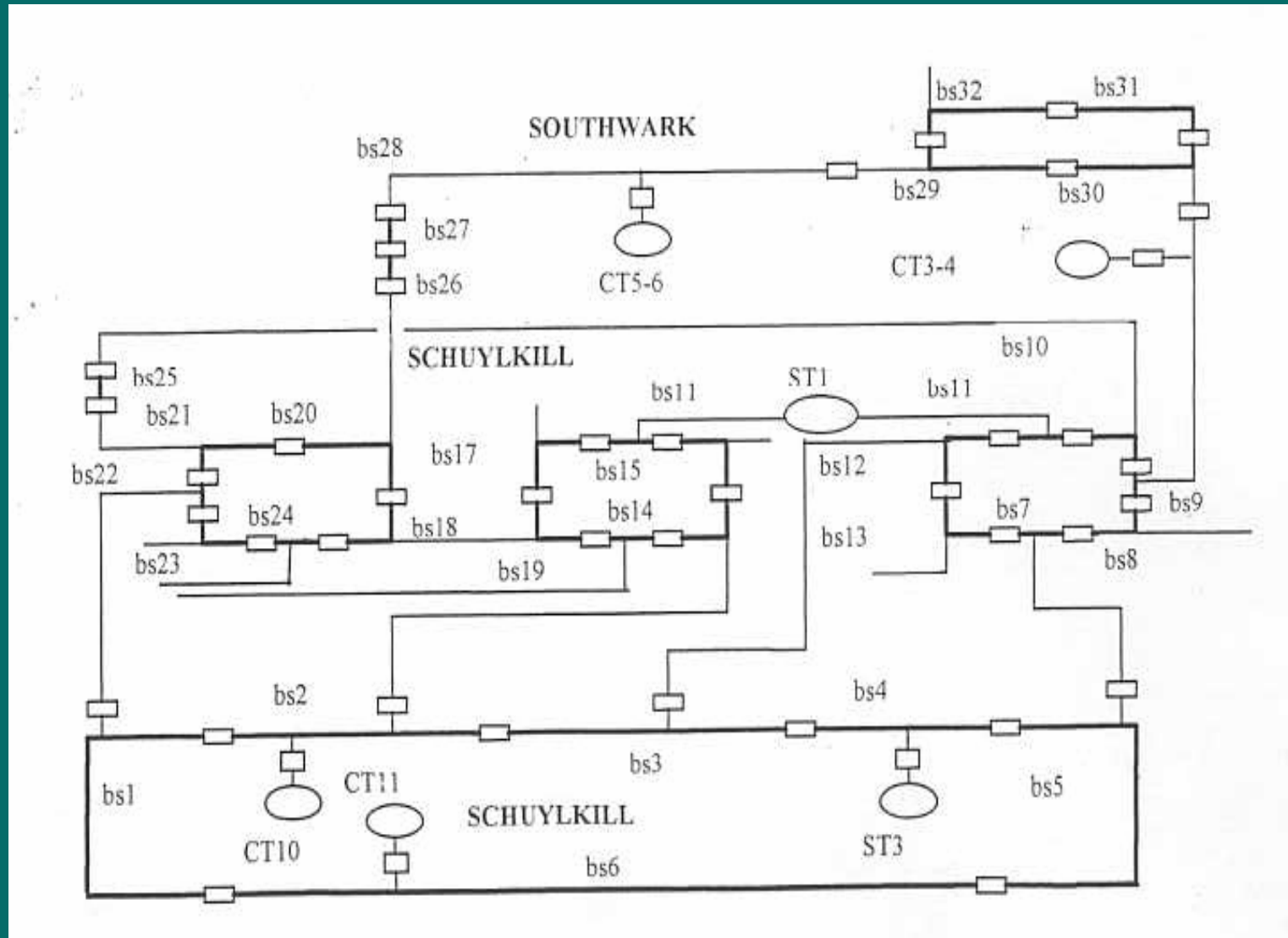
Petri Net Algorithm to Optimize Sequence of GRAs



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

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.
- K. L. Liou, C. C. Liu, and R. Chu, "Tie Line Utilization during Power System Restoration," *IEEE Trans. Power Systems*, Feb. 1995, pp. 192-199.
- 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.