ECEN 460
Power System Operation and Control
Spring 2025

Lecture 10: Contingency Analysis, Economic Dispatch

Prof. Tom Overbye

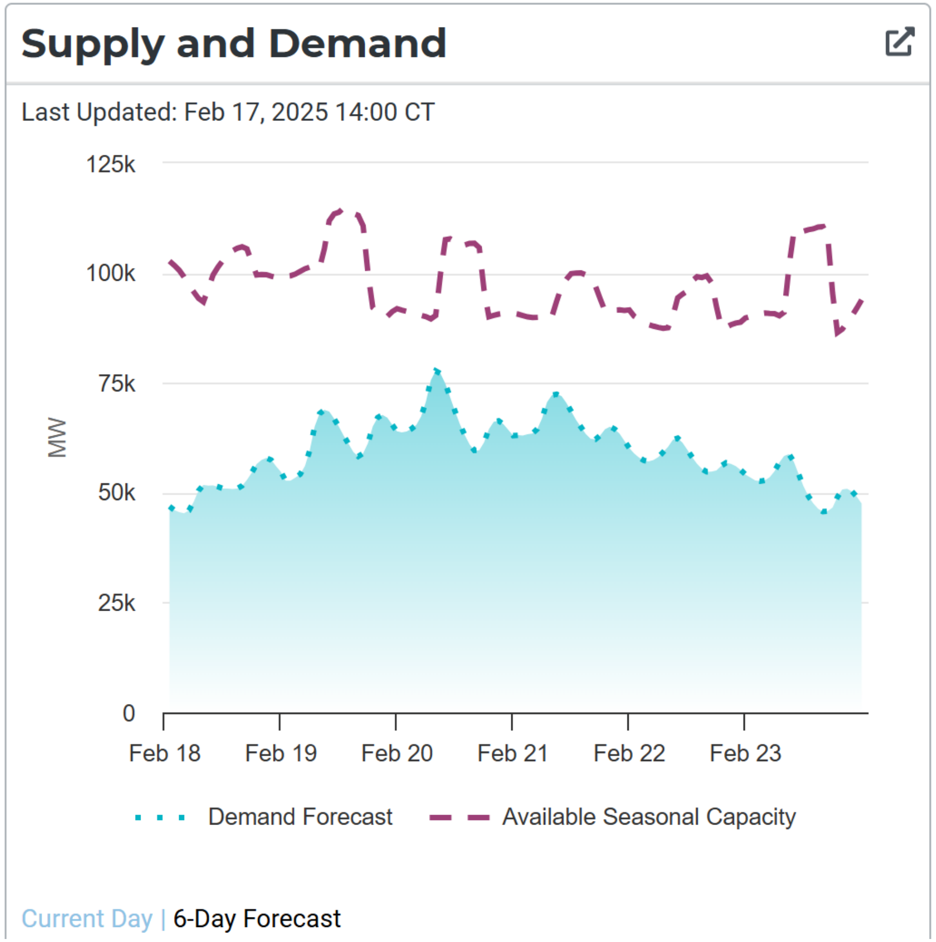
Dept. of Electrical and Computer Engineering

Texas A&M University

overbye@tamu.edu

In the News: The Coming Cold Weather

- With the low temperatures forecasted for February 19, 2025, the ERCOT grid will be stressed; here is the six day forecast (as of Feb 17)
  - The forecasted demand of 78.5 GW would be a new ERCOT Winter Peak, with the current value 78.1 GW from Jan 16, 2024



Power Flow Topology Processing

- Commercial power flow software must have algorithms to determine the number of asynchronous, interconnected systems in the model
  - These separate systems are known as Islands
  - In large system models such as the Eastern Interconnect it is common to have multiple islands in the base case (one recent EI model had nine islands)
  - Islands can also form unexpectedly as a result of contingencies
  - Power can be transferred between islands using dc lines
  - Each island must have a slack bus

Power Flow Topology Processing

- Anytime a status change occurs the power flow must perform topology processing to determine whether there are either 1) new islands or 2) islands have merged
- Determination is needed to determine whether the island is "viable." That is, could it truly function as an independent system, or should the buses just be marked as dead
  - A quite common occurrence is when a single load or generator is isolated; in the case of a load it can be immediately killed; generators are more tricky

Topology Processing Algorithm

- Since topology processing is performed often, it must be quick (order n ln(n))!
- Simple, yet quick topology processing algoritm
  - Set all buses as being in their own island (equal to bus number)
  - Set ChangeInIslandStatus true
  - While ChangeInIslandStatus Do
    - Go through all the in-service lines, setting the islands for each of the buses to be the smaller island number; if the island numbers are different set ChangeInIslandStatus true
  - Determine which islands are viable, assigning a slack bus as necessary

This algorithm does depend on the depth of the system

Bus Branch versus Node Breaker

- Due to a variety of issues during the 1970's and 1980's the real-time operations and planning stages of power systems adopted different modeling approaches

Real-Time Operations

Use detailed node/breaker model

EMS system as a set of integrated applications and processes

Real-time operating system

Real-time databases

Planning

Use simplified bus/branch model

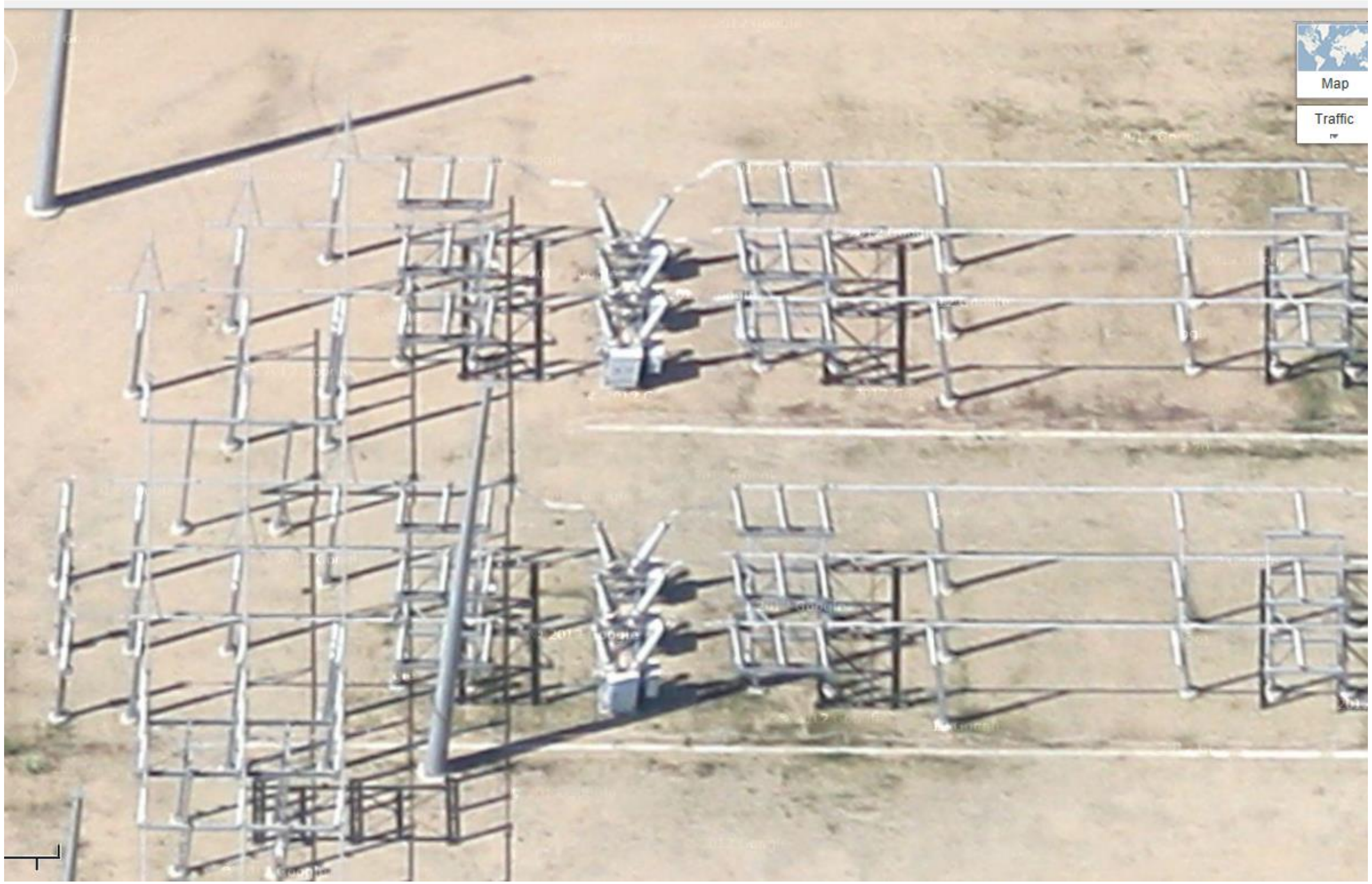
PC approach

Use of files

Stand-alone applications

Entire data sets and software tools developed around these two distinct power system models

Google View of a 345 kV Substation



Substation Configurations

- Several different substation breaker/disconnect configurations are common:
- Single bus: simple but a fault any where requires taking out the entire substation; also doing breaker or disconnect maintenance requires taking out the associated line

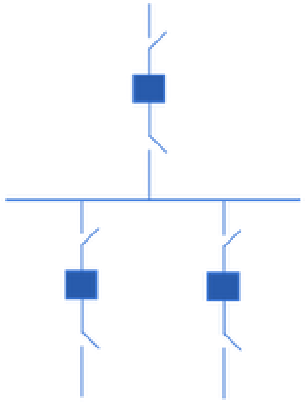


Fig B: Single Bus

Source: http://www.skm-eleksys.com/2011/09/substation-bus-schemes.html

Substation Configurations, cont.

- Main and Transfer Bus:
  Now the breakers can be taken out for maintenance without taking out a line, but protection is more difficult, and a fault on one line will take out at least two
- Double Bus Breaker:
  Now each line is fully protected when a breaker is out, so high reliability, but more costly

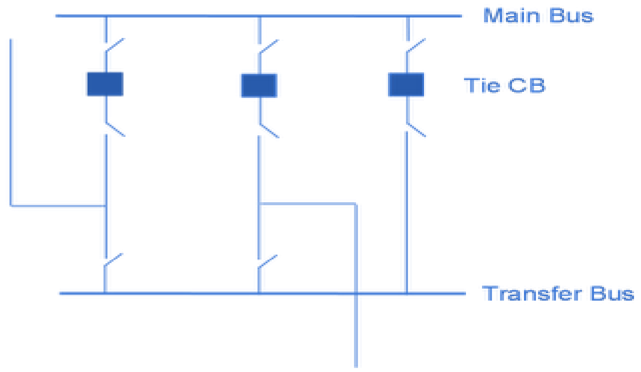


Fig C: Main and Transfer Bus

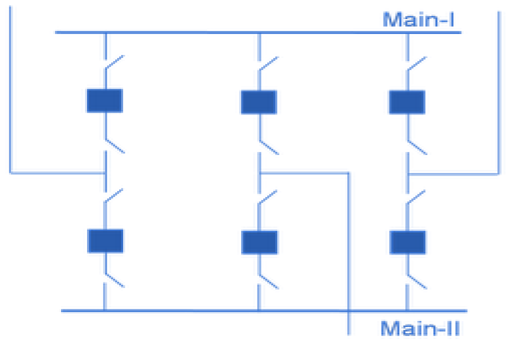


Fig D: Double Bus Double Breaker

Source: http://www.skm-eleksys.com/2011/09/substation-bus-schemes.html

Ring Bus, Breaker and Half

- As the name implies with a ring bus the breakers form a ring; number of breakers is same as number of devices; any breaker can be removed for maintenance
- The breaker and half has two buses and uses three breakers for two devices; both breakers and buses can be removed for maintenance

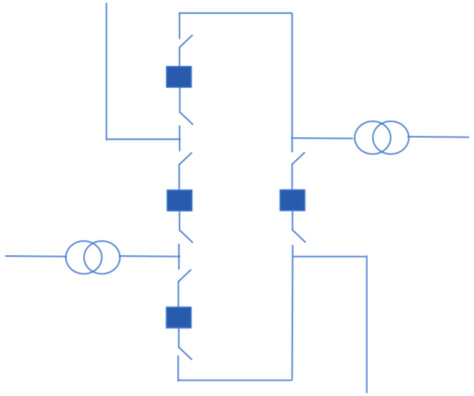


Fig F: Ring Bus

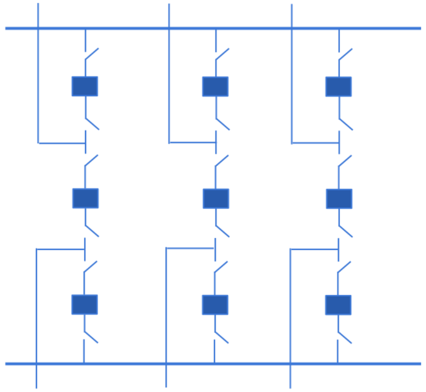
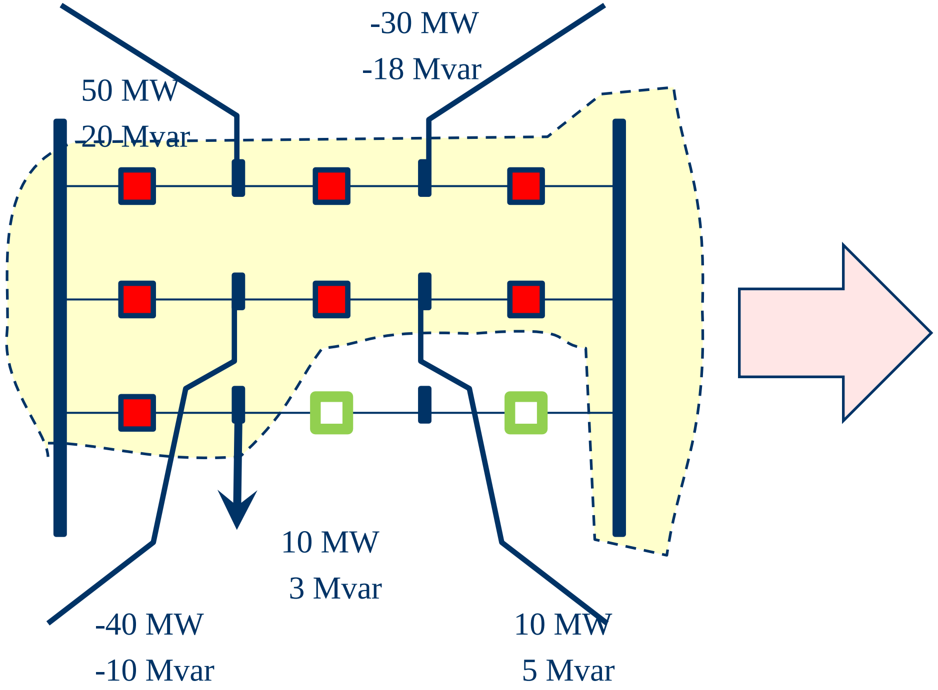


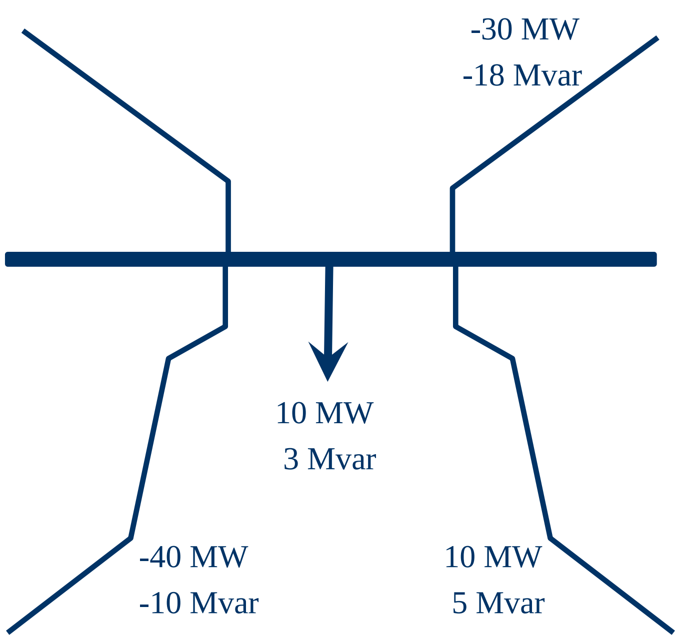
Fig G: Breaker and Half

Source: http://www.skm-eleksys.com/2011/09/substation-bus-schemes.html

EMS and Planning Models

- EMS Model
  - Used for real-time operations
  - Called full topology model
  - Has node-breaker detail
- Planning Model
  - Used for off-line analysis
  - Called consolidated model by PowerWorld
  - Has bus/branch detail

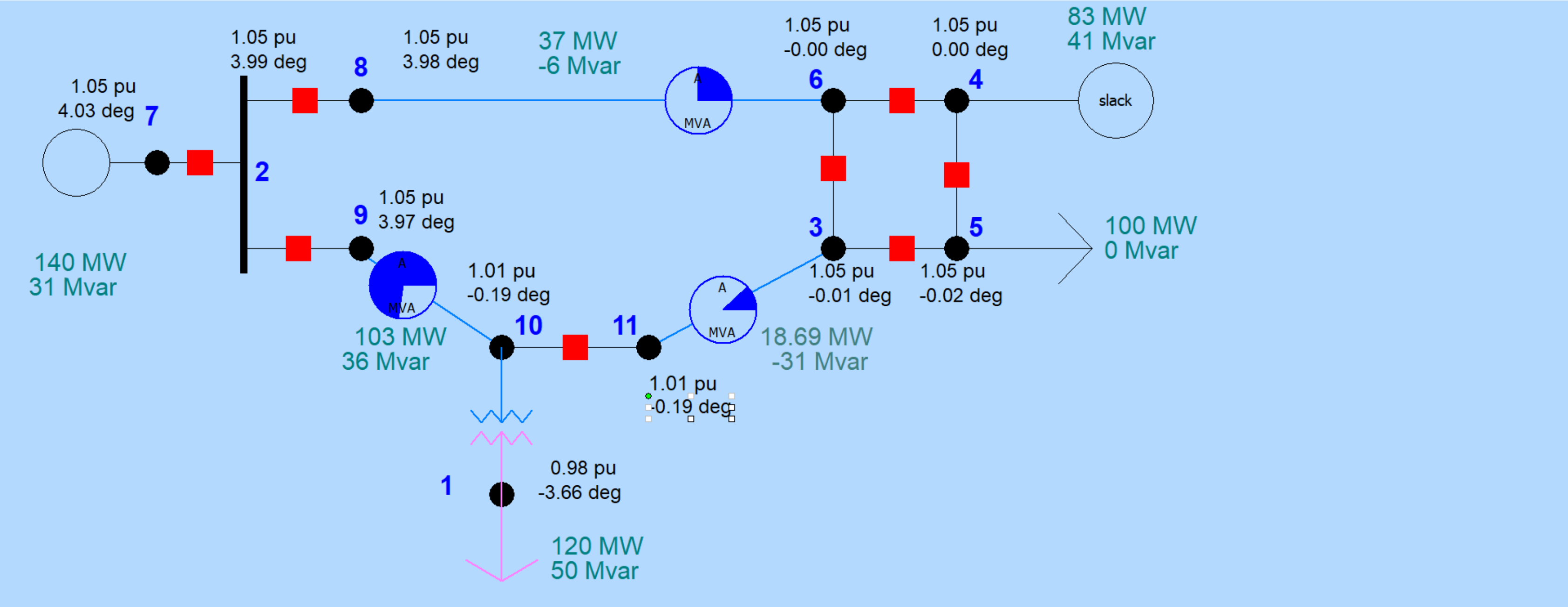




Node-Breaker Consolidation

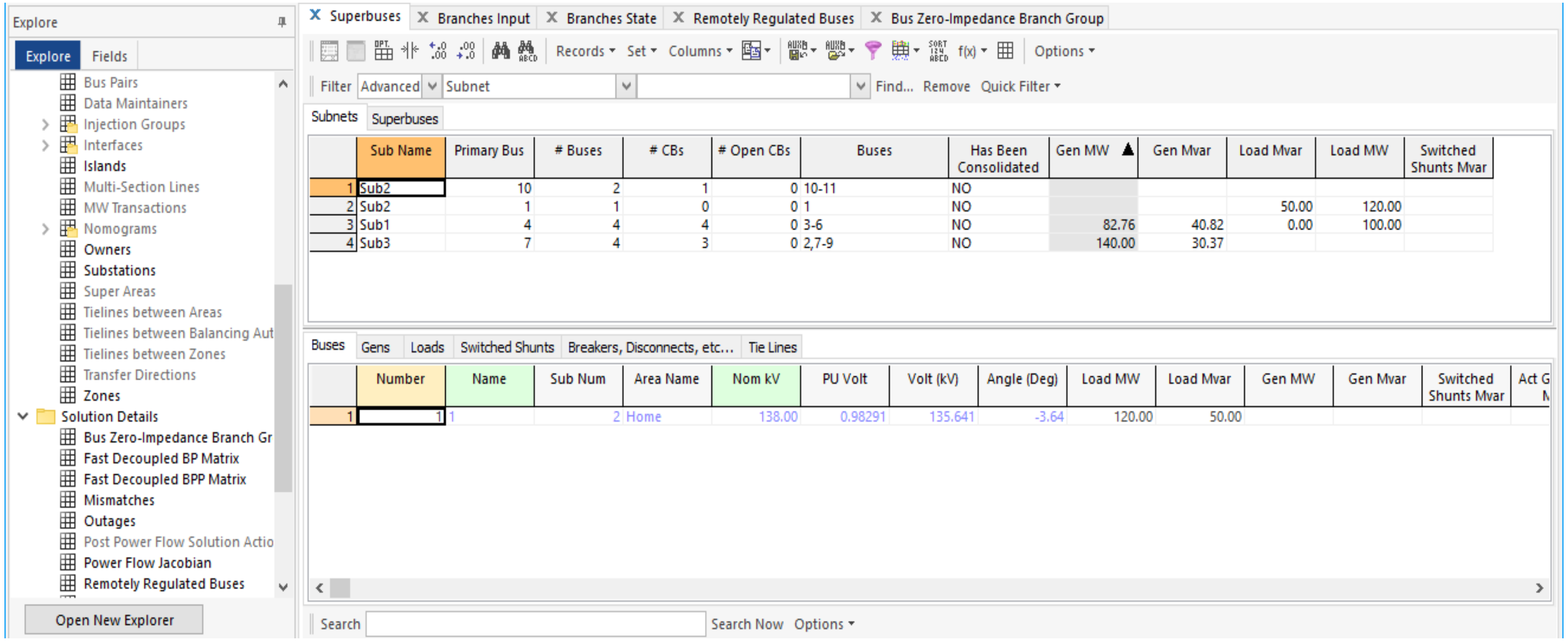
- One approach to modeling systems with large numbers of ZBRs (zero branch reactances, such as from circuit breakers) is to just assume a small reactance and solve
  - This results in lots of buses and branches, resulting in a much larger problem
  - This can cause numerical problems in the solution
- The alterative is to consolidate the nodes that are connected by ZBRs into a smaller number of buses
  - After solution all nodes have the same voltage; use logic to determine the device flows

Node-Breaker Example



Case name is **FT_11Node**. PowerWorld consolidates nodes (buses) into super buses; available in the Model Explorer: Solution, Details, Superbuses.

Node-Breaker Example



Note there is ambiguity on how much power is flowing in each device in the ring bus (assuming each device really has essentially no impedance)

Contingency Analysis

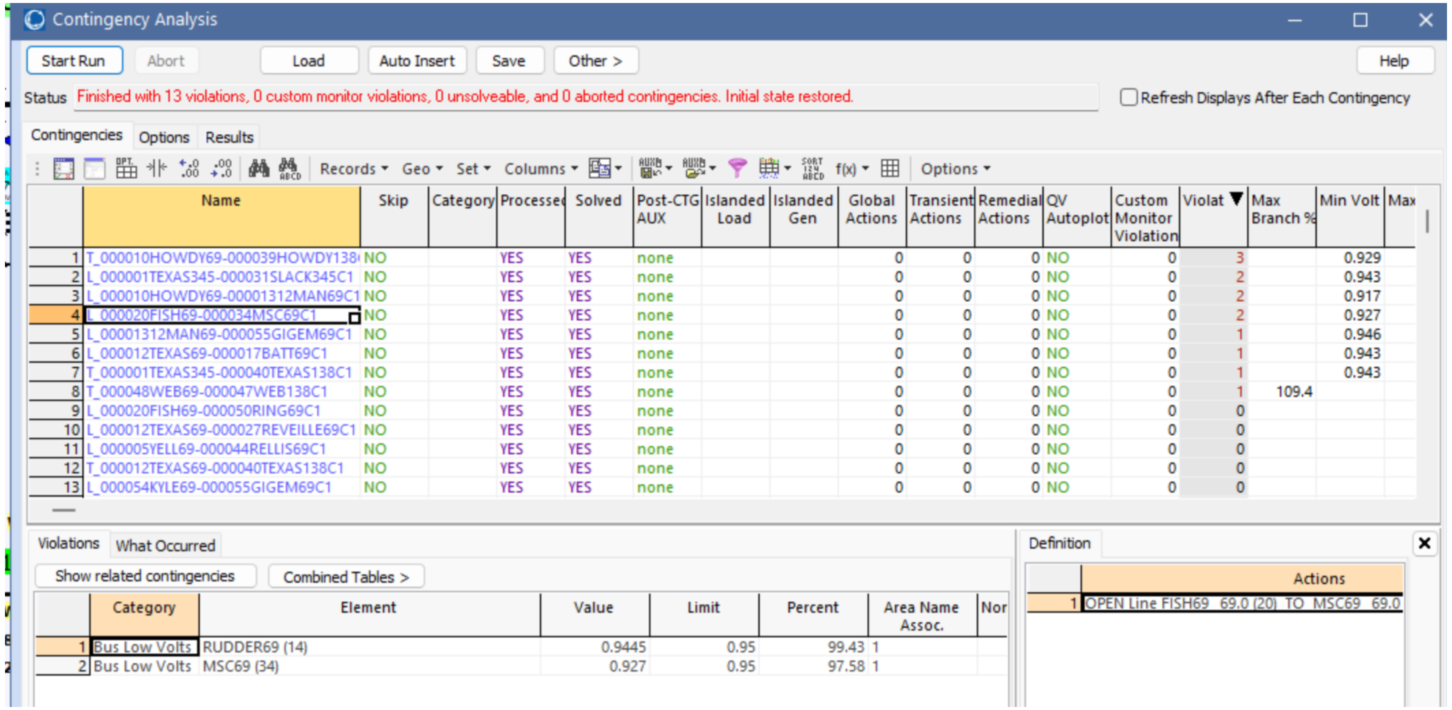
- Contingency analysis is the process of checking the impact of statistically likely contingencies
  - Example contingencies include the loss of a generator, the loss of a transmission line or the loss of all transmission lines in a common corridor
  - Statistically likely contingencies can be quite involved, and might include automatic or operator actions
- Reliable power system operation requires that the system be able to operate with no unacceptable violations even when these contingencies occur
  - N-1 reliable operation considers single elements

Contingency Analysis

- This process can be automated with the usual approach of first defining a contingency set, and then sequentially applying the contingencies and checking for violations
  - This process can naturally be done in parallel
  - Contingency sets can get quite large, especially if one considers N-2 (outages of two elements) or N-1-1 (initial outage, followed by adjustment, then second outage
- The assumption is usually most contingencies will not cause problems, so screening methods can be used to quickly eliminate many

Contingency Example: Small System

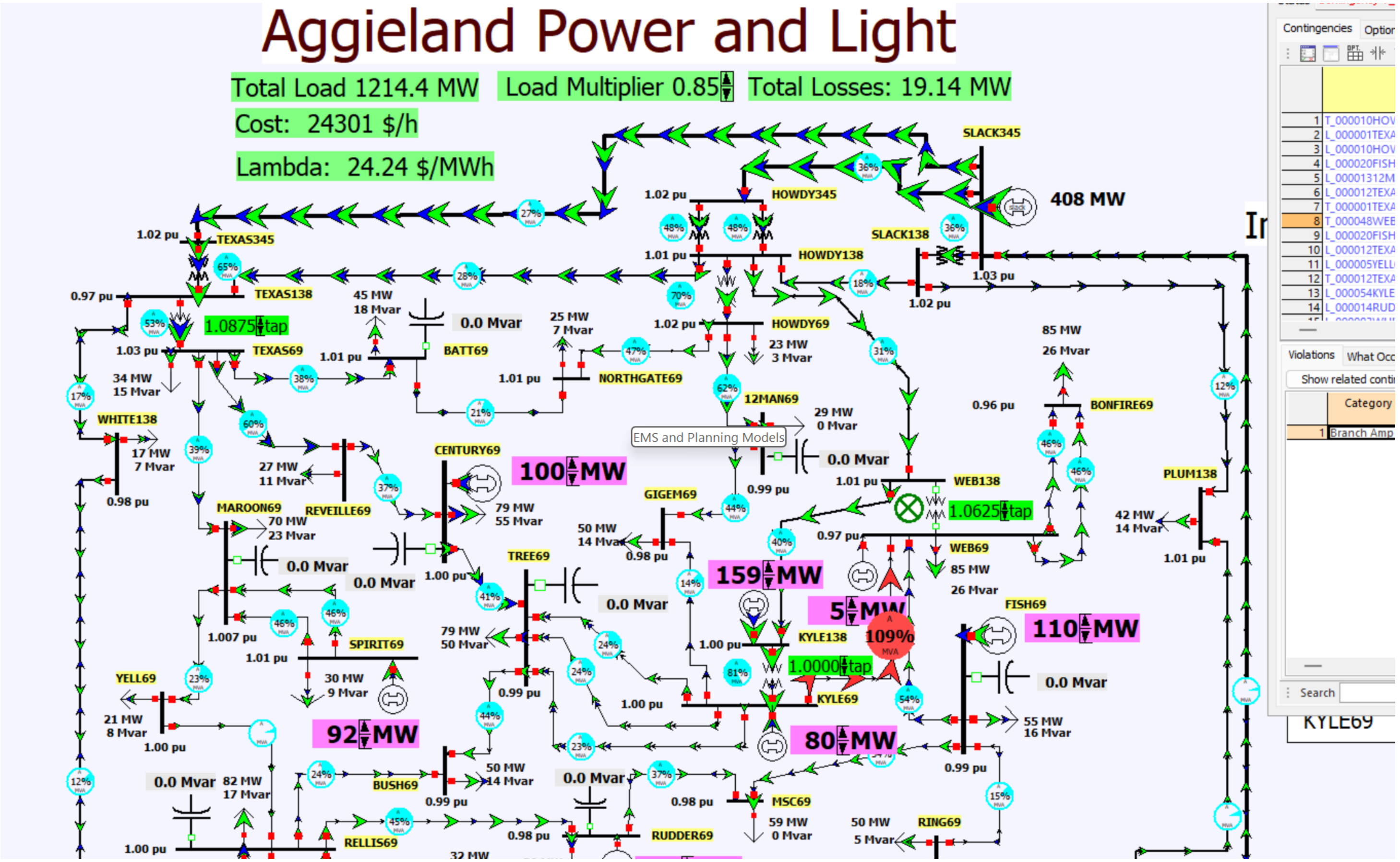
- The example here is the LabEcon_Bus37_Start case, which will be in Lab 5. To view contingency analysis select **Tools, Contingency Analysis**
  - The load has been increased to a multiplier of 0.85



While contingency analysis is simple to describe, many issues need to be considered in a contingent solution. For example, how much time is assumed for post-contingent control actions.

Contingency Example: Small System, cont.

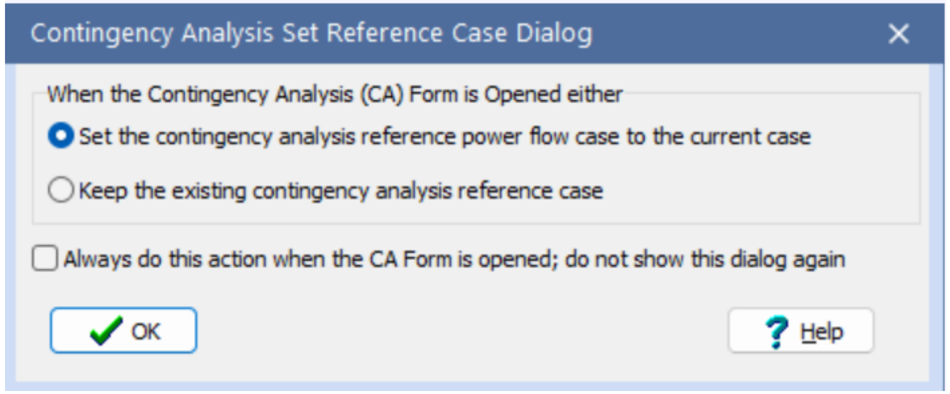
- To see a particular contingency, right-click on the desired contingency and select **Contingency Records, Solve Selected Contingency**



For the WEB138-WEB69 contingency, the single violation can be easily fixed by reducing the generation at WEB69

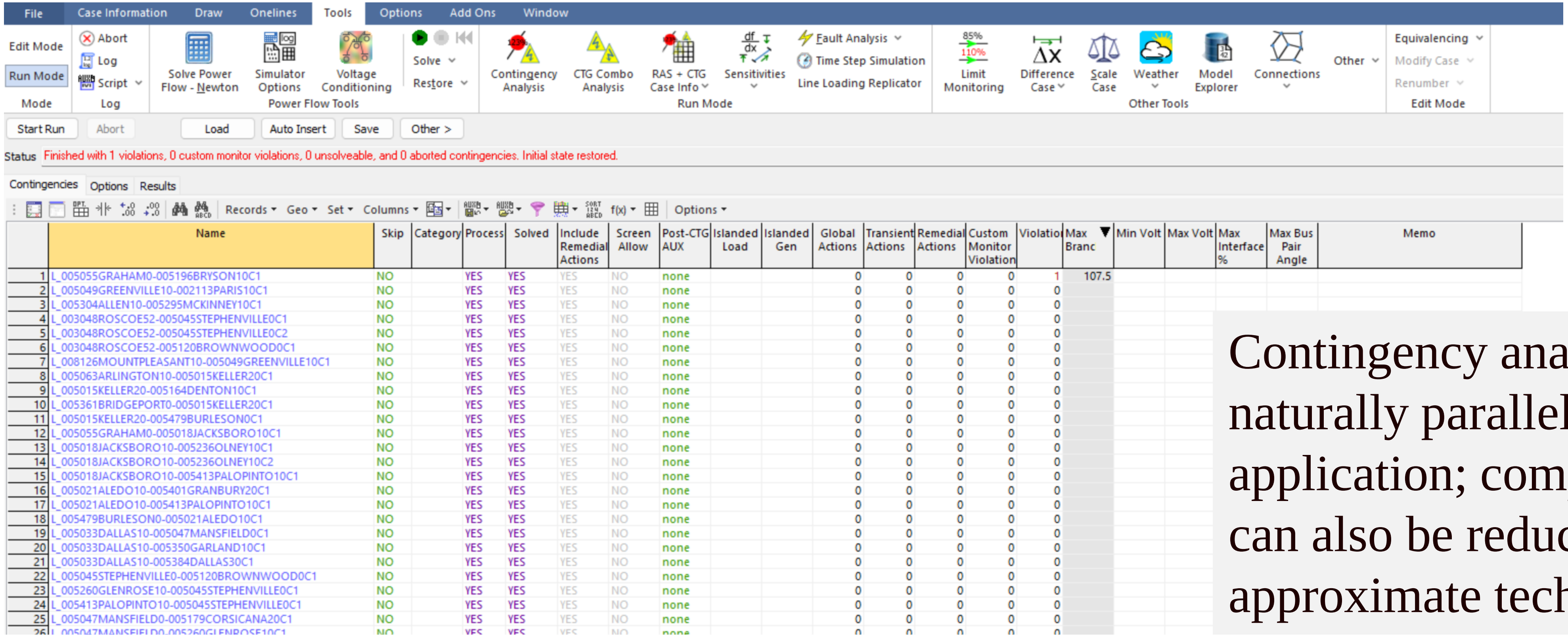
Contingency Analysis, cont.

- When doing contingency analysis in Simulator, the base case (starting case) is stored in memory, so it can be easily restored. This is known as the reference case
- This makes it easy to examine particular contingencies, but in can cause ambiguity when contingency analysis is restarted
  - When doing this the below dialog sometimes appears, asking which power flow case should be used as the contingency analysis reference case, either the current one, or the stored reference one



Contingency Example: 2000 Bus System

- Next, open the LabEcon_Texas_Start case, which has 77 contingencies defined



	Name	Skip	Category	Process	Solved	Include Remedial Actions	Screen Allow	Post-CTG AUX	Islanded Load	Islanded Gen	Global Actions	Transient Actions	Remedial Actions	Custom Monitor Violation	Violatio	Max Branc	Min Volt	Max Volt	Max Interface %	Max Bus Pair Angle	Memo
1	L_005055GRAHAM0-005196BRYSON10C1	NO		YES	YES	YES	NO	none			0	0	0	0	1	107.5					
2	L_005049GREENVILLE10-002113PARIS10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
3	L_005304ALLEN10-005295MCKINNEY10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
4	L_003048ROSCOE52-005045STEPHENVILLE0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
5	L_003048ROSCOE52-005045STEPHENVILLE0C2	NO		YES	YES	YES	NO	none			0	0	0	0	0						
6	L_003048ROSCOE52-005120BROWNWOOD0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
7	L_008126MOUNTPLEASANT10-005049GREENVILLE10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
8	L_005063ARLINGTON10-005015KELLER20C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
9	L_005015KELLER20-005164DENTON10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
10	L_005361BRIDGEPORT0-005015KELLER20C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
11	L_005015KELLER20-005479BURLESON0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
12	L_005055GRAHAM0-005018JACKSBORO10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
13	L_005018JACKSBORO10-005236OLNEY10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
14	L_005018JACKSBORO10-005236OLNEY10C2	NO		YES	YES	YES	NO	none			0	0	0	0	0						
15	L_005018JACKSBORO10-005413PALOPINTO10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
16	L_005021ALEDO10-005401GRANBURY20C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
17	L_005021ALEDO10-005413PALOPINTO10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
18	L_005479BURLESON0-005021ALEDO10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
19	L_005033DALLAS10-005047MANSFIELD0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
20	L_005033DALLAS10-005350GARLAND10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
21	L_005033DALLAS10-005384DALLAS30C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
22	L_005045STEPHENVILLE0-005120BROWNWOOD0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
23	L_005260GLENROSE10-005045STEPHENVILLE0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
24	L_005413PALOPINTO10-005045STEPHENVILLE0C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
25	L_005047MANSFIELD0-005179CORSICANA20C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						
26	L_005047MANSFIELD0-005260GLENROSE10C1	NO		YES	YES	YES	NO	none			0	0	0	0	0						

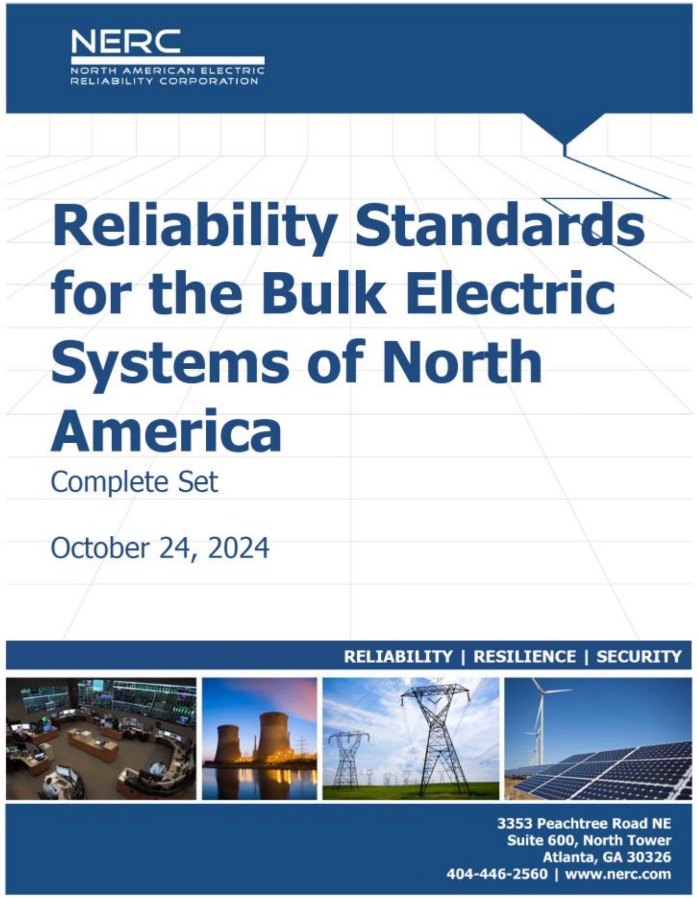
Contingency analysis is a naturally parallel application; computation can also be reduced using approximate techniques

NERC

- The North American Electric Reliability Corporation (NERC) is a nonprofit corporation that is charged with ensuring the reliability and adequacy of the North American electric grid
  - NERC formed in 2006, succeeding the North American Electric Reliability Council, which dates to 1968; it is now based in Atlanta, GA
  - The formation of the new NERC and the old NERC were both driven by blackouts (1965 and August 14, 2003)
- As a result of the Energy Policy Act of 2005 an entity (i.e., the new NERC) needs to develop and enforce mandatory reliability standards
- These standards cover many things, including operations and planning, and do require contingency analysis

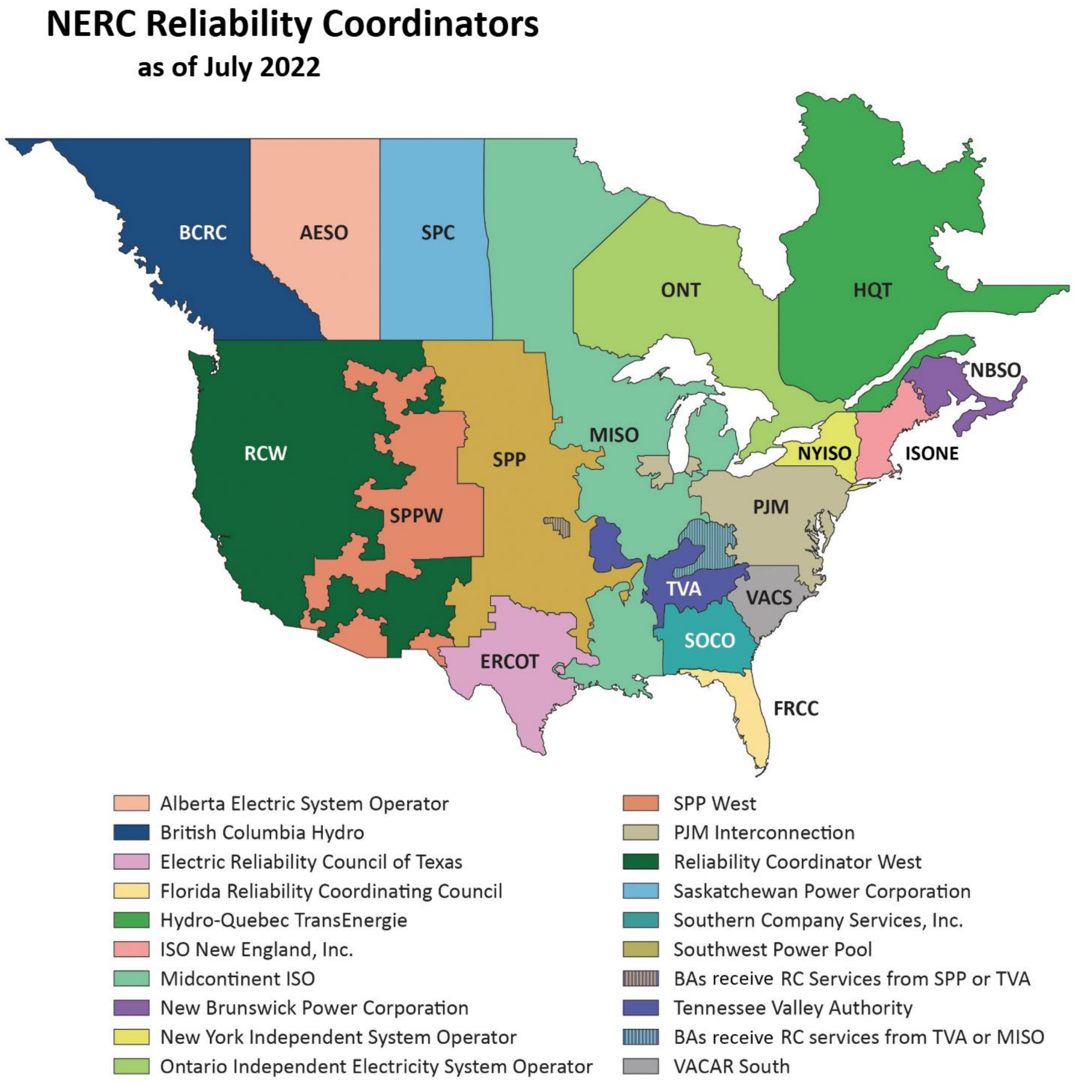
NERC and Reliability Standards

- You can download the full set at
  - www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf
  - This document has 3641 pages!
- TOP-001-3 covers Transmission Operations, with the purpose, "to prevent instability, uncontrolled separation, or Cascading outages that adversely impact the reliability of the Interconnection by ensuring prompt action to prevent or mitigate such occurrences."
  - Requirement R13 says the, "Each Transmission Operator shall ensure that a Real-time Assessment is performed at least once every 30 minutes."
  - This includes doing real-time contingency analysis



NERC Reliability Coordinators

- The Reliability Coordinator (RC) is the entity with the "highest level of authority who is responsible for the Reliable Opera tion of the Bulk Electric System (BES) and has the authority to prevent or mitigate emergency operating situations in both next-day analysis and real-time operations."



www.nerc.com/pa/Stand/Functional%20Model%20Advisory%20Group%20DL/FM_Technical_Document_V5-1_clean_10082019.pdf

Engineering Study Situational Awareness

- A common human factors term is “Situation Awareness” or “Situational Awareness” (SA)
- SA is formally defined as, “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future”
  - The informal definition is “knowing what’s going on” [1]
- The SA term started being used in the electric grid community after the August 14, 2003 blackout, with lack of SA noted as being two of the four primary causes of the event

[1] Quotes source: C.L. Wickens, “Situation Awareness: Review of Mica Endsley’s 1995 Articles on Situation Awareness Theory and Measurement,” Human Factors, Vol. 50, pp. 397-403, June 2008.

Engineering Study Situational Awareness, cont.

- While SA is mostly associated with operations, the same term certainly applies to engineering studies as well, such as with large grids
  - The models and software used in these studies have lots of parameters, and options; the engineer doing the studies needs to understand "what is going on"

Techniques for Maintaining Situational Awareness During Large-Scale Electric Grid Simulations

Thomas J. Overbye, Komal S. Shetye, Jess Wert, Wei Trinh, Adam Birchfield
Dept. of Electrical and Computer Engineering
Texas A&M University, College Station, TX, USA
overbye@tamu.edu, shetye@tamu.edu, jwert@tamu.edu, weit1@tamu.edu, abirchfield@tamu.edu

Tracy Rolstad
PSC Consulting
Spokane, WA, USA
tracy.rolstad@pscconsulting.com

James D. Weber
PowerWorld Corporation
Champaign, IL, USA
weber@powerworld.com

***Abstract*—Simulations of the dynamic response of high voltage, large-scale electric grids often generate large amounts of data. This can make it difficult for engineers to understand the overall system behavior. This paper presents various techniques to help with gaining situational awareness for electric grid simulations in the time frame of milliseconds to minutes. These techniques include the use of time-domain graphs, geographic data views in which geographic information embedded in the electric grid model is leveraged to create visualizations, contouring, animation loops, machine learning and modal analysis. Results are demonstrated on a 10,000 bus synthetic grid model and an actual electric grid model with 110,000 buses.**

I. Introduction

The design and operation of large-scale electric grid require a variety of different engineering studies and simulations. Some of these are static, such as power flow, contingency analysis and security constrained optimal power flow. And some are dynamic, usually involving time-domain simulations to determine the behavior of the electric grid following some disturbance (contingency). In all of these it is important that the person doing the study or simulation understand what is going on. A term that can be used to

accurate modeling of the much faster models associated with devices such as exciters, loads and some renewable generators.

While historically such studies were known as transient stability simulations [11], here we'll use the generic term "simulations." Usually these simulations are initialized from a power flow solution, then a contingency scenario is applied to the grid and the goal is to determine the time-domain response. The simulations considered here are assumed to have a fixed duration ranging from seconds to minutes. Such simulations are extremely common throughout the electric power industry.

The SA challenges with these simulations depend upon the electric grid size, the complexity of its models, the simulation contingency scenario complexity, and the desired application. For example in many educational and some research simulations the grid size, model complexity, scenario complexity and desired application are similar to the 96-bus angular stability study presented in [11]; SA can usually be adequately maintained just using a graph or two (e.g., Figure 8 of [11] showing the rotor angles for the 20 generators). Similarly even with a large system with complex models and

Paper: T.J. Overbye, K.S. Shetye, J.L. Wert, W. Trinh, A. Birchfield, Tracy Rolstad, Jamie Weber, "Techniques for Maintaining Situational Awareness During Large-Scale Electric Grid Simulations," IEEE Power and Energy Conference at Illinois (PECI), Champaign, IL, April 2021. Available at overbye.engr.tamu.edu/publications/

Color Contouring Power System Information

- Jamie Weber and I popularized color contouring in the power system community starting in 1998
  - A few years prior to our work, EPRI had looked at contouring, and concluded it was not a useful approach
  - There are some valid objections to using on contouring, but we concluded the benefits out weighted the problems

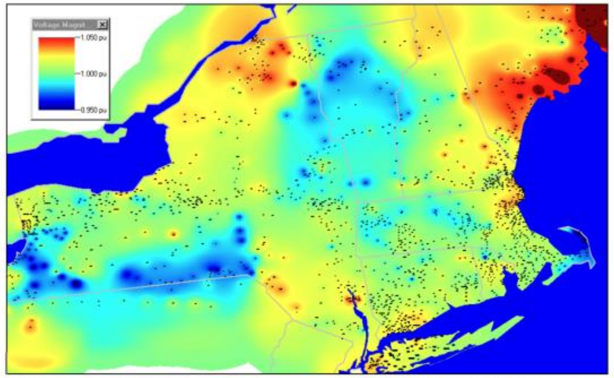


Figure 3: Voltages Magnitudes at 115/138 kV Buses in New York and New England

Finally, contouring need not be restricted to bus voltage magnitudes. Electricity markets are increasingly moving towards spot-market based market mechanisms [14] with the United Kingdom, New Zealand, California Power Exchange in the Western US, and PJM Market in the Eastern US as current examples. In an electricity spot-market, each bus in the system has an associated price. This price is equal to the marginal cost of providing electricity to that point in the network. Contouring this data could allow EMS operators and market participants to quickly assess how prices vary across the market. As an example, Figure 5 plots the actual locational marginal prices (LMRs) in the PJM

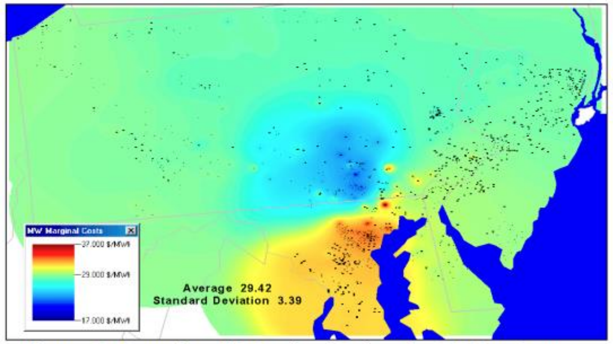


Figure 5: Locational Marginal Prices in PJM at 2pm on August 20, 1999.

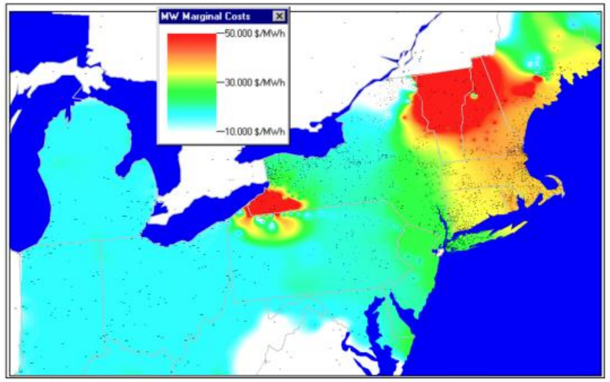


Figure 6: Locational Marginal Prices for Northeast U.S.

Images from: T. J. Overbye and J. D. Weber, "Visualization of power system data," *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, Maui, HI, USA, 2000, pp. 7 pp.-, doi: 10.1109/HICSS.2000.926744

Book Chapter 7 Photo

- This is our utility control center test facility out at the Texas A&M RELLIS campus, Center for Infrastructure Renewal (CIR) building

Power System Economic Dispatch

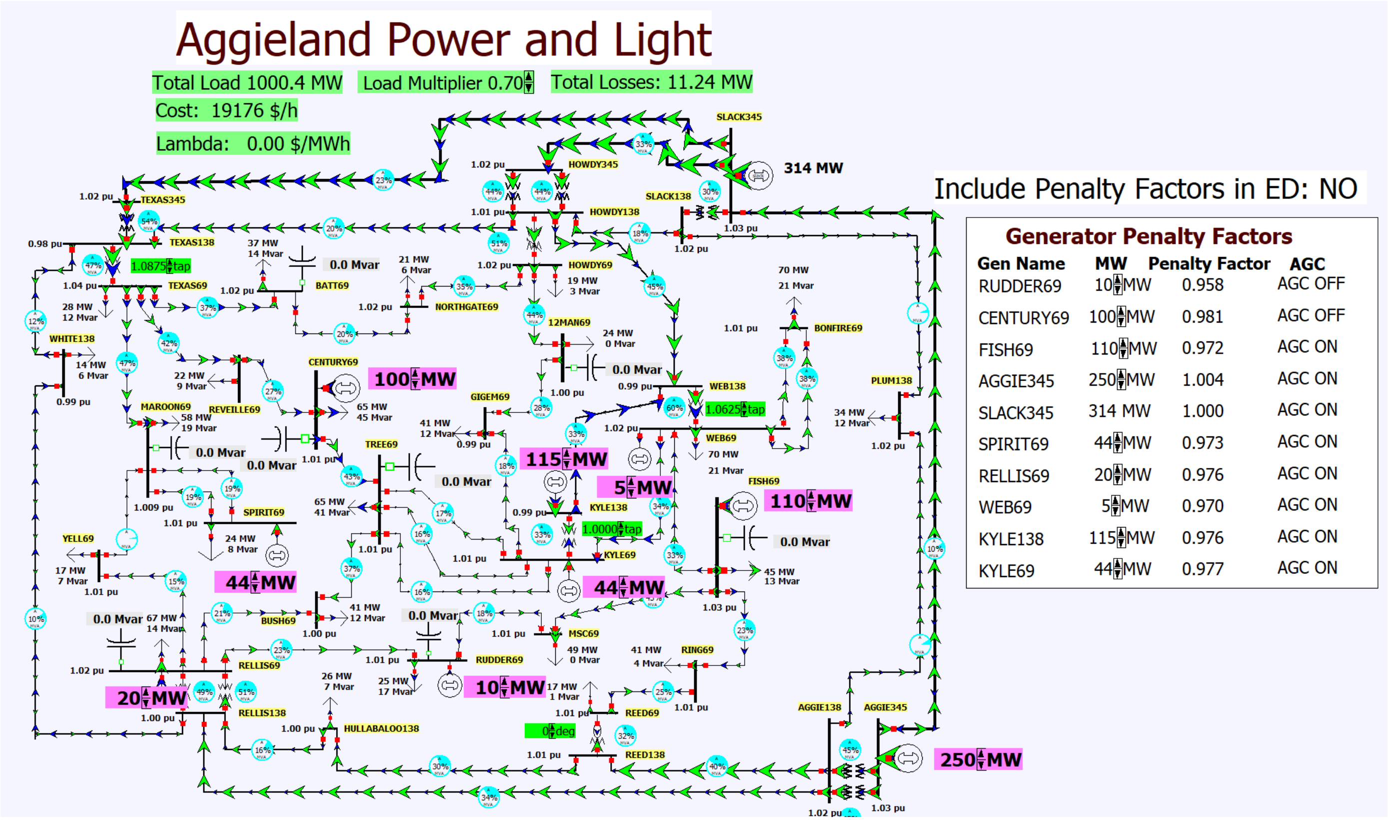
- Generators can have vastly different incremental (also called marginal) operational costs
  - Some are essentially free or low cost (wind, solar, hydro, nuclear)
  - Because of the large amount of natural gas generation, electricity prices are very dependent on natural gas prices
- Marginal cost is a general economic concept
  - When there are multiple sources for a product (electricity here), and each has an increasing marginal production cost, the optimal solution (dispatch) is when all the sources have equal marginal cost
- Economic dispatch is concerned with determining the best dispatch for generators that minimizes cost without changing their commitment

Lab 5 Intro: Economic Dispatch in PowerWorld

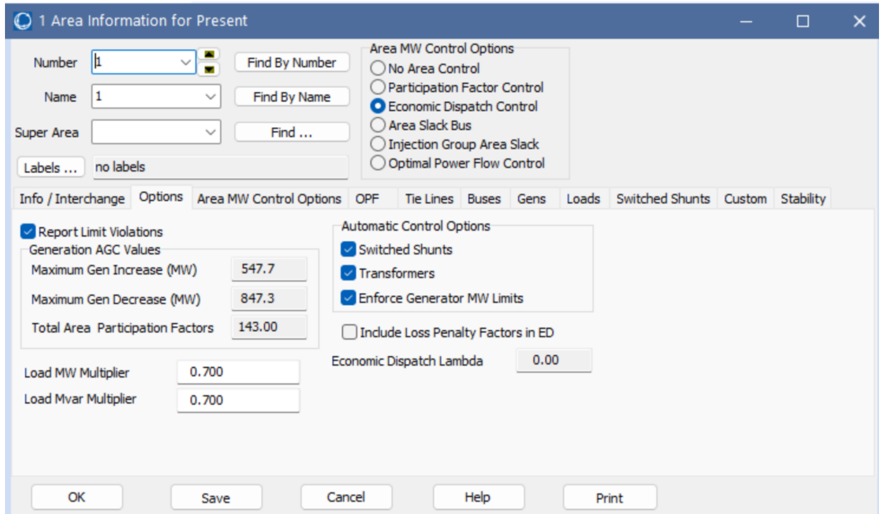
- In power systems economic dispatch has mostly been replaced by a more general optimal power flow (OPF) solution, which we'll cover next. However, we'll cover economic dispatch first since 1) it is simpler, and 2) sets the stage of OPF
- Economic dispatch in power systems uses the standard economics concept of equal marginal cost, but with two main caveats
  - Economic dispatch is done on each balancing authority area (areas in the power flow)
  - Economic dispatch usually considers system losses, recognizing that as the generation dispatch is changed the losses also change; this is represented by penalty factors applied to the generator marginal cost curves
- Since it is used in Lab 5, I'll first show you how to do it in PowerWorld, and then present the modeling and solution algorithms

Lab 5 Intro: Economic Dispatch in PowerWorld

- Lab 5 37-bus case, showing turning on/off inclusion of the penalty factors



Gen Name	MW	Penalty Factor	AGC
RUDDER69	10 MW	0.958	AGC OFF
CENTURY69	100 MW	0.981	AGC OFF
FISH69	110 MW	0.972	AGC ON
AGGIE345	250 MW	1.004	AGC ON
SLACK345	314 MW	1.000	AGC ON
SPIRIT69	44 MW	0.973	AGC ON
RELLIS69	20 MW	0.976	AGC ON
WEB69	5 MW	0.970	AGC ON
KYLE138	115 MW	0.976	AGC ON
KYLE69	44 MW	0.977	AGC ON



Electric Grid Economic Operation

- Electric grid operations have been optimized for many decades!

1928

Progress and Problems

From Interconnection in Southeastern States

BY W. E. MITCHELL[1]

Fellow, A. I. E. E.

Synopsis.—Great progress has been made. Interconnection between independent systems is primarily a protective measure. The greatest economic benefits have been realized when the interconnections have been made by subsidiary companies of one holding company. The capacity of tie lines and the amount of power interchanged has increased greatly. The size of generating units has increased, as has the size of power plants, resulting in lowered cost per kw. The problem of satisfactory voltage and power factor control has increased in complexity as has that of system load dispatching. While much improvement has been made in oil circuit breakers, they still leave much to be desired. Interconnection has made possible more economical operation of existing plants and has resulted in the use of a larger proportion of the available water on systems combining steam, storage, and run-of-river hydroelectric plants.

Long-time forecasting of load and rainfall conditions is important in economical system planning. The 110-kv. and 154-kv. line construction is discussed, also the value of ground wires and lightning arresters. The growing importance of carrier current for supervisory control and communication and their application are discussed.

* * * * *

IN 1924 in a paper on Interconnection of Power Systems in the Southeastern States, the author suggested that our great problem for the next 10 years would be to increase the capacity of the interconnecting links between different systems, to develop water power distant from the power market, and to construct the mine mouth or other strategically located (from an economic standpoint) high capacity steam plants, and connect them with the great load centers by means of high-capacity networks. He also suggested that we should plan for at least 10 years in the future.

Less than four years have passed, yet tremendous strides have been taken along these very lines. The economic possibilities of interconnection are being clearly realized. One of the results has been the coordination in a number of instances of the various individual operating companies under one holding company, thus deriving the benefit of massed capital, data, load, rainfall, storage reservoir conditions, and other problems of mutual interest. This has proved of the greatest value to all concerned. Getting better acquainted and the resultant better understanding, together with a greater knowledge of each others' systems and their points of strength or weakness, have facilitated the prompt handling of the exchange of power in emergencies. Frequently, improved operating economies through interchange have resulted from a greater knowledge of conditions throughout the entire territory.

Unquestionably the greatest benefits are derived, however, (and this applies both to the general public as well as to the individual companies), when the interconnected companies while maintaining their independent corporate identity are subsidiaries of one holding company. It is practically impossible to have a unified development program for five independent

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Theory of Economic Operation of Interconnected Areas

R. H. KERR
ASSOCIATE MEMBER AIEE

L. K. KIRCHMAYER
MEMBER AIEE

THIS PAPER extends the theory and the co-ordination equations[1] previously derived for optimum economy for a single area to obtain the co-ordination equations for optimum economic operation of a pool operated as a multiple-area system. Multiple-area operation of the pool is defined to be operation for which the interchanges between the areas are directly determined and controlled. The theory of this paper forms the basis for obtaining automatic economic operation of interconnected areas as well as the basis for multiarea dispatching computers.

The equations whose solution result in minimum cost operation for a given area are given by:

$$\frac{dF_n}{dP_n}+\lambda\frac{\partial P_L}{\partial P_n}=\lambda \qquad (1)$$

where

$\frac{dF_n}{dP_n}$ = incremental production cost of plant n in \$/mwhr (dollars per megawatt-hour)

$\frac{\partial P_L}{\partial P_n}$ = incremental transmission loss of plant n
= ratio of change in transmission loss to change in particular P_n when delivering an increment of power from P_n to the hypothetical load of the area

λ = incremental cost of received power in \$/mwhr

These equations state that, for optimum economy, the incremental cost of received power should be the same from all sources. These equations would be applicable if all of the areas were treated as a single area and would involve the use of a computer representing the entire pool. This computer would require a knowledge of all plant loadings and tie-line flows to companies external to the pool, and the control system would require as a minimum a control channel to each plant.

Another approach would involve application of computer-controllers to the individual areas with means of determining automatically the most economic interchange between the areas. It would be desirable for each area to require only a knowledge of the plant loadings within the area and interconnection flows out of the area in addition to control information as to whether the area should increase or decrease its delivery to the pool. Such a decentralized approach will offer the following advantages over a centralized or single-area approach.

1. The telemetering channel requ are reduced as this method does no as much information at any given the system.

2. Smaller decentralized comp trollers are required rather than one centralized computer.

3. Pertinent information for accounting between areas is readily available.

The basis for such decentralized arrangements follows from the theory to be presented here. This theory has been directly applied to the design of the multiarea dispatching computer shown in Fig. 1 which has been recently installed by the Niagara Mohawk Power Corporation. Also, the General Electric automatic dispatching system may be readily extended to obtain automatic economic operation of interconnected areas according to the theory presented here.

Review of Single-Area Co-ordination Equations

The physical interpretation of the equations for a single area will be reviewed by consideration of a 2-plant system with two ties as shown in Fig. 2. The co-ordination equations become:

$$\frac{dF_1}{dP_1}+\lambda\frac{\partial P_L}{\partial P_1}=\lambda \qquad (2A)$$

$$\frac{dF_2}{dP_2}+\lambda\frac{\partial P_L}{\partial P_2}=\lambda \qquad (2B)$$

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R. H. KERR and L. K. KIRCHMAYER are with the General Electric Company, Schenectady, N. Y.

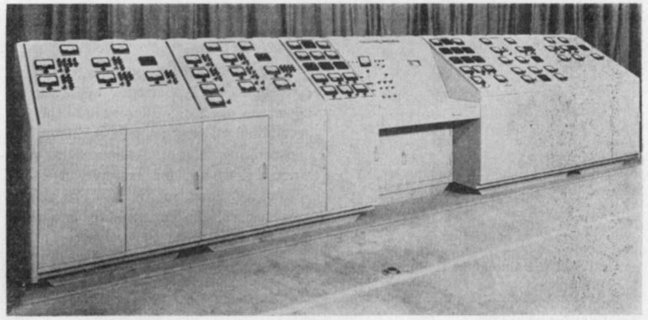

Fig. 1. Niagara Mohawk multiarea dispatching computer

Unit Commitment: Quick Coverage

- Before covering economic dispatch, we'll first touch on unit commitment
- Unit commitment is used to determine which generator units should be committed to meet the load
- The electric load varies substantially so there is almost always more generator capacity available than load
- Units have availability constraints
  - Minimum up time, time to start, cost to start
  - Minimum down time, time to shutdown, cost to shutdown
  - Ramp rates, minimum MW output
  - Scheduled and unscheduled outages
- System constraints including load, reserve, emissions, network

Solving Unit Commitment

- Unit commitment involves a potentially large number of integer and continuous variables
  - Not just the status of each unit, but also the amount of time it has been in a particular state (i.e., off or on)
- Solved for a set of discrete time periods, which at each time period there are lots of different potential states
- Solution approaches include
  - Dynamic programming
  - Lagrangian relaxation
  - Mixed Integer Programming (MIP) (currently state-of-the-art)
    - the idea is some or all of the variables are restricted to being integers; it is widely used in many applications, with a power application looking at generator statuses (on=1, off=0)