# Sustainable Electric Power Systems in the 21st Century: *Requirements, Challenges and the Role of New Technologies*

*Prabha Kundur*
*Powertech Labs Inc.*
*Surrey, B.C.  Canada*

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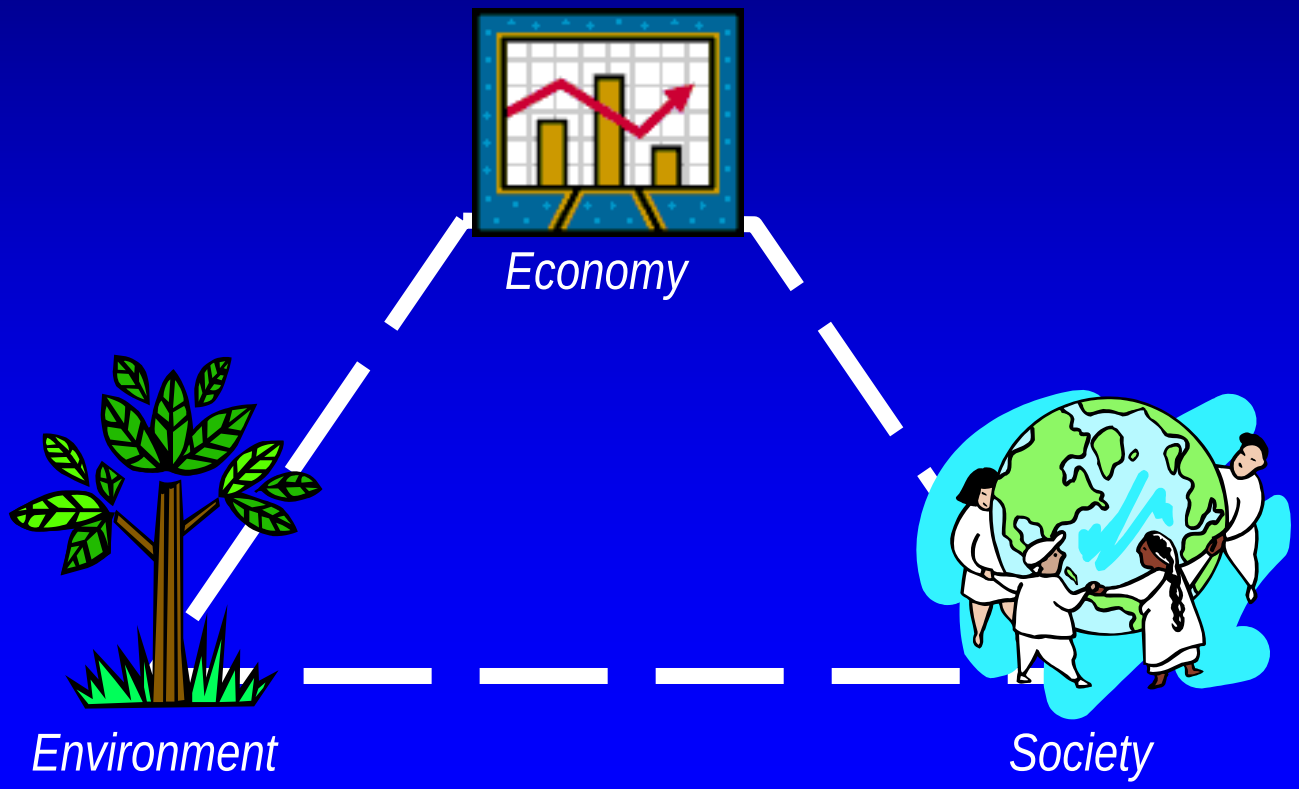
# Power Systems in the 21st Century

- The electric power industry:
  - humble beginning in the 1880s; grown into one of the largest industries
- Has done a good job of meeting the energy needs of the 20th century:
  - electricity has become a basic necessity in modern society
- Has had an adverse impact on the natural environment
- Industry now undergoing major restructuring
  - shift from monopolistic to competitive structure
  - new economic/social pressures
- Need to refocus business so as to meet energy needs of society in a way that is "sustainable" in the long run

# Sustainability

Requires balancing economic growth and social progress with the preservation of the natural environment



# Sustainability of Power Systems

- Business practices have to be built on "three pillars" of sustainability:
  - environmental sustainability
  - economic sustainability
  - social sustainability
- Our challenges, therefore, are to:
  - produce, transmit and utilize energy in an environmentally responsible manner
  - reduce cost by improving business practices and operating efficiency
  - enhance reliability and quality of power supply

# Environmental Sustainability

- The need to integrate "green thinking" into our way of life and business practices
- Minimize the environmental impact of power plants as well as other equipment
- Maximize resource conservation
  - leads to environmental as well as economic sustainability
- Efficient utilization of electricity

# Environmental Concerns Related to Power Generation

- Greenhouse gas emissions, global warming issues and local emissions
- Renewable sources unable to cover a substantial part of base load
- Use of natural gas is a step in the right direction
  - Available in abundance in most countries
  - What is the best form of its use?
- Opportunities for clean coal technologies
- Revival of nuclear option?
- Carbon-free electricity/hydrogen energy economy

# Distributed Generation (DG)

- Overall generating capacity will include a significant proportion of distributed generation
- Renewable sources of DG:
  - solar
  - geothermal
  - wind*
  - ocean*
- Non-renewable sources of DG:
  - micro turbines
  - fuel cells

# Wind Power

- Large wind farms being developed in many countries
- Integration of wind farms into existing power systems presents technical challenges
  - often located at points weakly connected to bulk transmission grid
  - wind power very cyclical and unpredictable
    - other complementary sources of generation
    - storage technologies
  - system stability and power quality
- Advanced power electronics and controls can assist in improving grid integration aspects

# Ocean Energy

- Forms of ocean energy
  - tidal current energy:  tides, currents, thermal, salinity gradient
  - wave energy
- Receiving much attention
  - many pilot projects worldwide
  - potentially a large source of clean, cheap primary source of energy
- Typical costs
  - capital costs = $700/kW to $2000/kW
  - energy costs = $0.35/kWh
- Integration with existing power systems presents technical challenges
  - not an insurmountable problem

# Microturbine-Generators (MTGs)

- Microturbines used for aircraft and other transportation applications for many years
- Now being developed for stationary applications
- MTGs are small high speed power plants
  - typically operate on natural gas; future units may use diesel or gas produced from landfill
- Technology has advanced rapidly in last 4 years
  - pre-commercial prototypes of 20-200 kW available
- Low efficiency (?); some NOx emissions

# Fuel Cells

- First demonstrated in 1839 by William Grove
  - combines hydrogen with oxygen from air to generate electricity with water and heat as by-products
- Hydrogen may be:
  - supplied from an external source, or
  - generated inside fuel cell by reforming a hydrocarbon fuel
- Used to power tractors since 1959; used by NASA for Gemini project in the 1960s
- Recent advances have reduced cost and size dramatically
- Wide range of potential applications
  - source of electric power in different sizes: micro FC for laptops to large units connected to power grids
  - automobiles: fuel cell vehicles

# Typical Operating Characteristics of Fuel Cells

| Type/Electrolyte | Efficiency | Temp | Capacity |
|---|---|---|---|
| Proton Exchange Membrane | 30-35% | 180°F | 5-250 kW |
| Phosphoric Acid | 35-40% | 400°F | 50-200 kW |
| Potassium/Lithium Carbonate | 45-57% | 1200°F | 250 kW-3 MW |
| Solid Oxide | 45-50% | 1800°F | 3 kW- 3 MW |

- Emissions (lbs/MWh):

| | NOx | $SO_2$ |
|---|---|---|
| Fossil fuel plant | 4.20 | 9.21 |
| Microturbine | 0.29 | 0.00 |
| Carbonate fuel cell | 0.013 | 0.00 |

# Fuel Cells (cont'd)

- With co-generation, a carbonate or solid oxide fuel cell can achieve an efficiency of 70% to 80%
  - can generate electricity directly from a hydrocarbon fuel by reforming the fuel inside to produce hydrogen
  - this compares with efficiency of 35% for coal plants and 40% for gas turbines
- Environmentally friendly alternative power generation source that can potentially yield lower cost electricity
  - non-combustion, non-mechanical power generation process
  - quieter and more efficient than conventional power plants
  - lower fuel and maintenance costs
  - high efficiency at even very small sizes
- With increased use and large scale production, costs will come down and reliability will improve

# Hydrogen Energy

- Hydrogen is an <u>energy carrier</u>
  - not a primary energy source
  - similarity with electrical energy
- Complementary use of electricity and hydrogen
  - hydrogen ideal for energy storage; offers more flexibility
- Hydrogen can be:
  - used just like conventional fuels, or
  - reacted with oxygen in a fuel cell to produce electricity
- The two most abundant hydrogen-containing compounds:
  - water ($H_2O$)
  - hydrocarbon fuels ($H_xC_y$), such as, oil, coal, natural gas and biomass

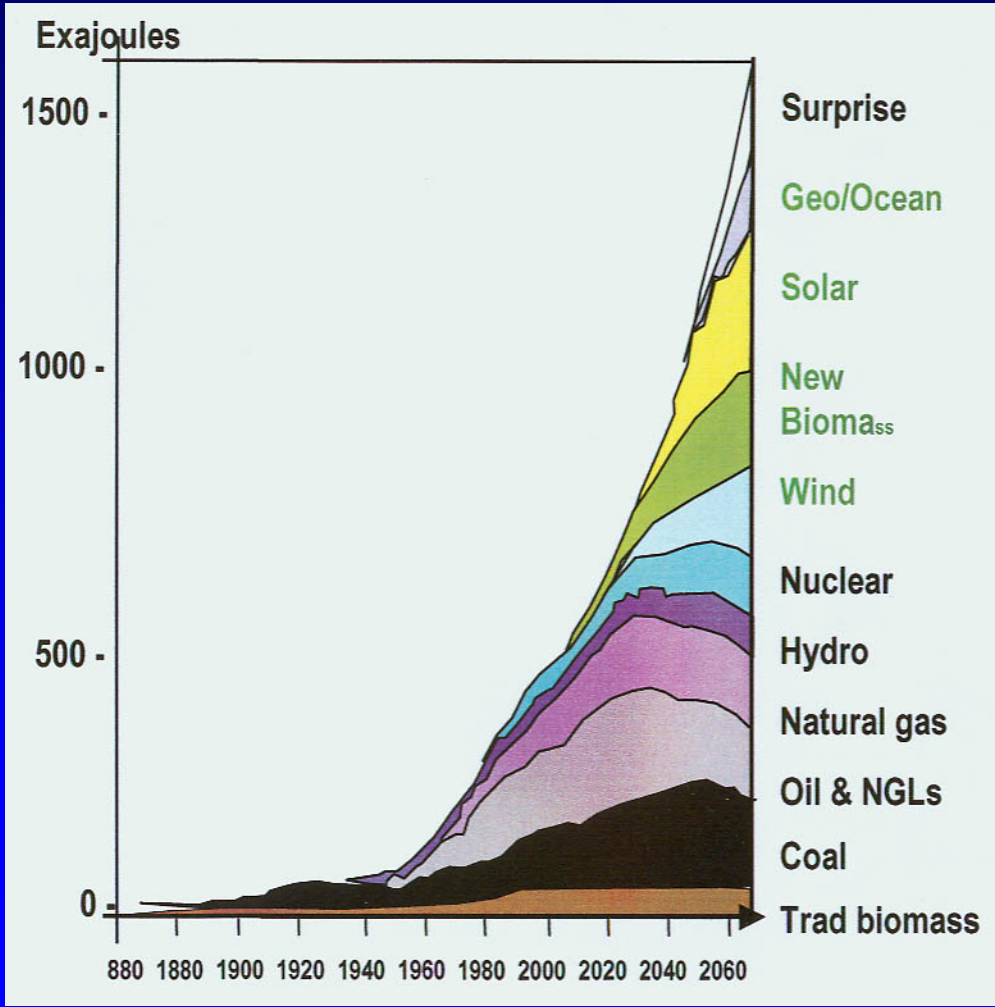
# Hydrogen Economy

- Significant changes in the energy field tend to occur at the turns of centuries
  - early 1800s - the rise of steam
  - early 1900s - the rise of electricity
  - early 2000s - the dawn of hydrogen age?
- Interest in hydrogen energy is not new!
- What are the major drivers leading to hydrogen economy now?
  - environmental concerns
  - technological developments
- Challenges to the use of hydrogen
  - reduction in cost of production
  - safe storage at the required high pressure
  - availability of appropriate primary energy source

# Formation of Hydrogen Infrastructure

- Production of hydrogen from hydrocarbons
  - reforming natural gas, methane, biomass, ...
  - development of decarbonization technologies
  - coal gasification: longer term, high potential option
- Production of hydrogen from water, using electrolysis
  - attractive in systems with surplus electricity and limited storage capability
- Development of renewable electric power resources for distributed hydrogen production: small hydro, solar, wind, wave
- Development of fuelling stations for hydrogen vehicles;
  - development of high pressure hydrogen storage and transportation technologies
- Hydrogen storage: high capacity and cyclable
  - metal hydrides, ceramics and conducting polymer

# Sources of Primary Energy



# Role of Electric Utility in Enabling the Hydrogen Economy

- Hydrogen and electricity are readily exchangeable
  - form an ideal “energy currency pair”
- Hydrogen and electricity will dominate the transportation and energy delivery systems of the 21st century
  - will link low-impact energy sources to end-users
- Electric utilities are well positioned to be key enablers of the hydrogen economy by producing, distributing and selling hydrogen to markets in:
  - transportation
  - industrial supply
  - portable power
  - stationary power

# Powertech's Hydrogen 700 Project

- Cooperative project sponsored by **six automobile manufacturers**
- Powertech is facilitating development of **700 bar (10,000 psi) hydrogen storage systems** for fuel cell vehicles
  - lightweight and safe storage system
  - performance tests on storage tanks, regulators, solenoid valves, pressure relief devices
  - tests include:
    - hydraulic pressure cycling
    - exposure to temperature and environmental extremes
    - vibration
    - bonfire and gunfire
  - ISO 15869 standard for compressed hydrogen storage for vehicles

# Powertech's Compressed Hydrogen Infrastructure Program ($CH_2IP$)

- Multi-year program initiated in 2001 to demonstrate the technical feasibility of hydrogen infrastructures for transportation and power generation markets
- Funded by the Federal Government and several industrial partners:
  - BC Hydro, Dynetek, Stuart Energy, BP, Shell Hydrogen, Chevron Texaco, BOC, JFE Container
- Design and construction of high pressure hydrogen fuelling stations
  - first 700 bar station in the world for fast-filling of hydrogen
- Lightweight mobile trailer for transporting hydrogen at 875 bars
- Supported testing 700 bar vehicle safety standards for hydrogen fuelling stations

BChydro
BCHydroGEN
Powertech
Stuart
Powertech
BCHydroGEN
Ford
fuel cell vehicle
zero emissions

# Future of Distributed Generation (DG)

- Offer significant economic, environmental and security benefits
- DG becoming increasingly cost competitive
  - 5.8 cents/kWh vs 8.9 cents/kWh for conventional central generation
  - Reduction of transmission costs in many cases
- DG will significantly reduce greenhouse gas emissions
- Less vulnerable to natural calamities and acts of terrorists
  - ice storm (Quebec and Eastern Ontario)
  - hurricane (France)
  - earthquakes
  - sabotage
  - power grid blackouts

# Other Aspects of "Greening of the Electric Power Business"

Minimizing the environmental impact of **all equipment**, not just generation.

The following projects underway at Powertech Labs serve as examples:

- Sulfur hexaflouride ($SF_6$) gas assessment and reclamation:
  - reduction of emission of an extremely potent greenhouse gas
- PCB in solids destruction plant
  - disposal of PCB contaminated fluorescent light ballast potting compound using a non-thermal environmentally benign process
- Continuous transformer oil decontamination
  - extends life of transformers, allows use of oil over longer periods

cont'd

# Other Aspects of Greening (cont'd)

- Environmentally friendly transformer oil:
  - vegetable-based oil as alternative to mineral-based oil; biodegradable and non-toxic to fish
- Environmentally benign wood pole preservatives:
  - evaluation of boron rods for groundline treatment of wood poles near waterways and sensitive areas
- Nondestructive techniques for assessment of coatings on structures
  - optimize coating costs and minimize environmental impact
- Environmentally-friendly fluids for use as lubricants in substation equipment and generating units
  - as substitutes for hydrocarbon oils

# Social Sustainability

- Ethical business practices*
- Governance and control
- Occupational safety and control
- Employee development
- Community development
- Partnerships/Networking*
- Support for universities and basic research*
- Equity of customer access

# Economic Sustainability

- Efficiency, economy and service quality
  - more important in the new environment
- Efficiency and economy achieved by
  - more effective use of individual equipment and the integrated power system
- Service Quality
  - Need to have an infrastructure that will support the reliability and service quality demands of a digital economy
- An increased focus will be on providing a "higher value service"

# Power Quality (PQ)

- Increasing importance of Power Quality
  - sensitive equipment and processes
- PQ problems are many
  - impulsive transients, voltage sags, flicker, harmonics, imbalance
  - frequency control problems
- Impact of new dispersed generation
- Analysis of measured data for diagnostics requires expertise in several areas
- Required new tools for diagnosis based on artificial intelligence (AI) techniques
  - large amount of data
  - imprecise data
- AI techniques: expert systems, ANN, adaptive neuro-fuzzy systems

# More Effective Use of Equipment

Much of the infrastructure and assets are 35 to 50 years old. The following technologies contribute to more effective use of equipment, operating efficiency and reliability:

- Automated pro-active monitoring systems for:
  - maintenance and prevention of failures
- "Intelligent systems" technology for equipment diagnostics
- New technologies for dynamic equipment rating
- New technologies for assessment of remaining life
- Improved methods of:
  - life extension, uprating and efficiency enhancement
- Reliability based asset management

# Effective Use of Integrated Power Systems

- Power systems are very large complex systems
  - cover large geographic areas: *continental power grids*
  - many processes whose operations need to be coordinated and optimized
  - millions of devices requiring harmonious interplay
- Role of system operators
  - increasingly complex
- Reliable and secure operation presents many challenges in a competitive "market" environment
  - many entities with diverse business interests
  - system expansion and operation driven by economic drivers
  - inadequate transmission and infrastructure enhancements
  - power systems are pushed harder

# Power System Security

- Ability to withstand disturbances:
  - *ensure stable operation*
  - *settle to operating conditions with no violation of physical constraints*
- Major concern since the infamous 9 November 1965 blackout of Northeast US and Ontario
- Presents new challenges in the present environment
- We had several wake up calls in recent years
  - July and August 1996 WSCC system disturbances
  - March 11, 1999 Brazil blackout
  - August 14, 2003 blackout of NE U.S.A. and Ontario
  - September 28, 2003 blackout of Italy
  - September 23, 2003 blackout of South Sweden and Eastern Denmark

# Traditional Approach to Power System Stability

- Focus primarily on only one aspect of stability:
  - "transient (rotor angle) stability"
- System designed and operated to withstand
  - loss of any single element
  - referred to as "N-1 criterion"
- Analysis of selected operating conditions
  - scenarios based on judgment/experience
- Operating limits based on off-line studies
  - system operated conservatively within pre-established limits
- Inadequate for dealing with present day power systems
  - complex modes of instability

# Case Study - A Complex Mode of Transient Instability

- North American Western Interconnected System
- A transmission line fault causes instability of a remote area
  - Sensitive to conditions in the faulted area
  - Nature of the stability problem is not readily apparent

# CASE A

- 4-cycle fault on Palo Verde - Devers line (Arizona-California)
- Alberta to B.C. transfer 500 MW
- East of River interface flow 7300 MW

*Note: power flow conditions considered for this study, do not represent present operating conditions.*

WILLISTON
KEMANO
VANCOUVER AREA
VANCOUVER ISLAND
WASHINGTON
CHIEF JOSEPH
GRAND COULEE
SEATTLE AREA
CENTRALIA
HANFORD
HOT SPRINGS
UNITED STATES
FT PECK
MONTANA
GREAT FALLS
ANACONDA
BILLINGS
COLSTRIP
YELLOWTAIL
WYODAK
BUCKLEY
BROWNLEE
IDAHO
BOISE
EUGENE
OREGON
PACIFIC INTERTIE
SUMMER LAKE
WYOMING
DAVE JOHNSON
JIM BRIDGER
NAUGHTON
LARAMIE RIVER
MALIN
PACIFIC HVDC INTERTIE 1000 kV
ROUND MTN.
TABLE MTN.
SALT LAKE CITY AREA
CRAIG
DENVER AREA
UTAH
HUNTINGTON
NEVADA
CABIN CREEK
CALIFORNIA
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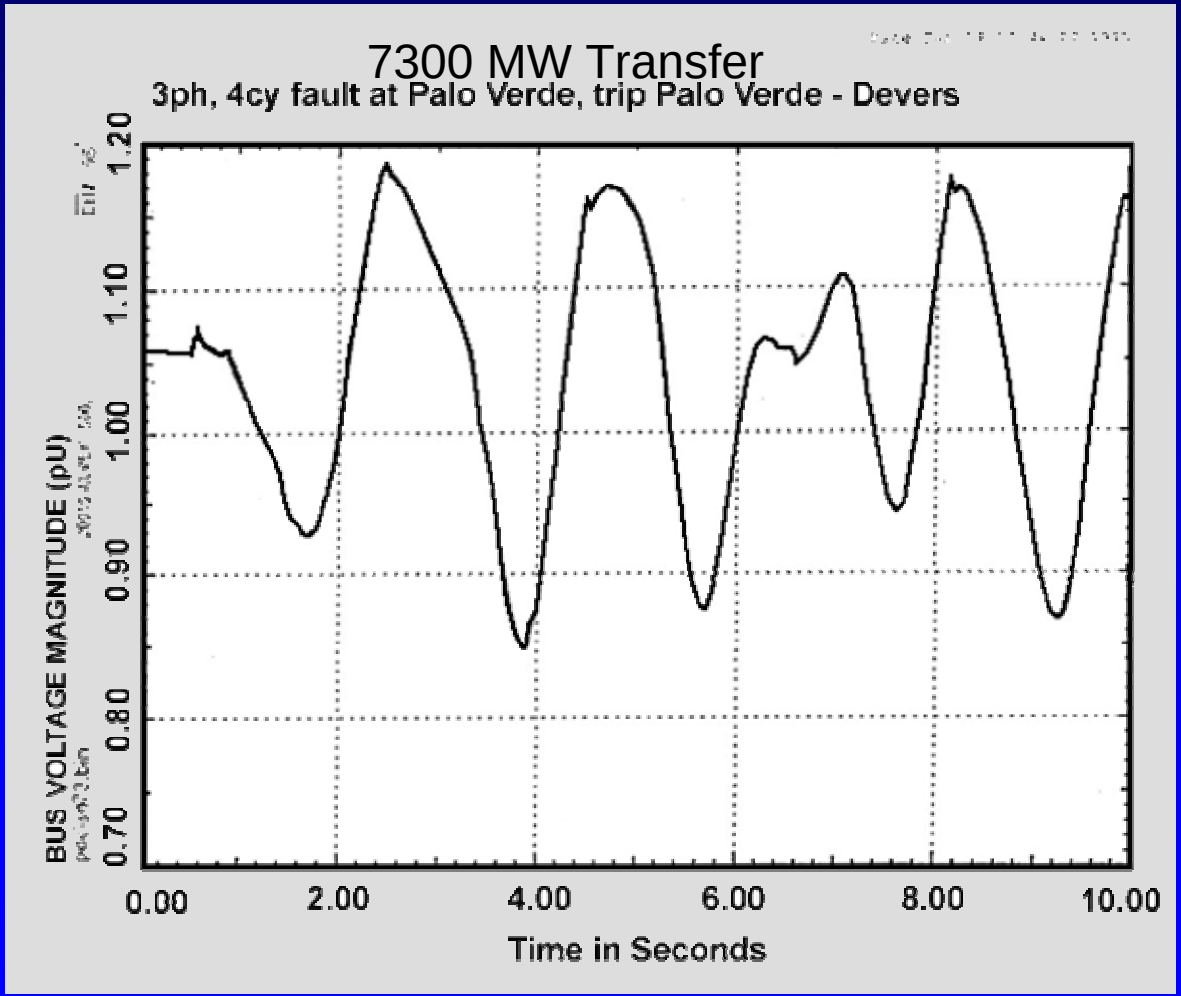
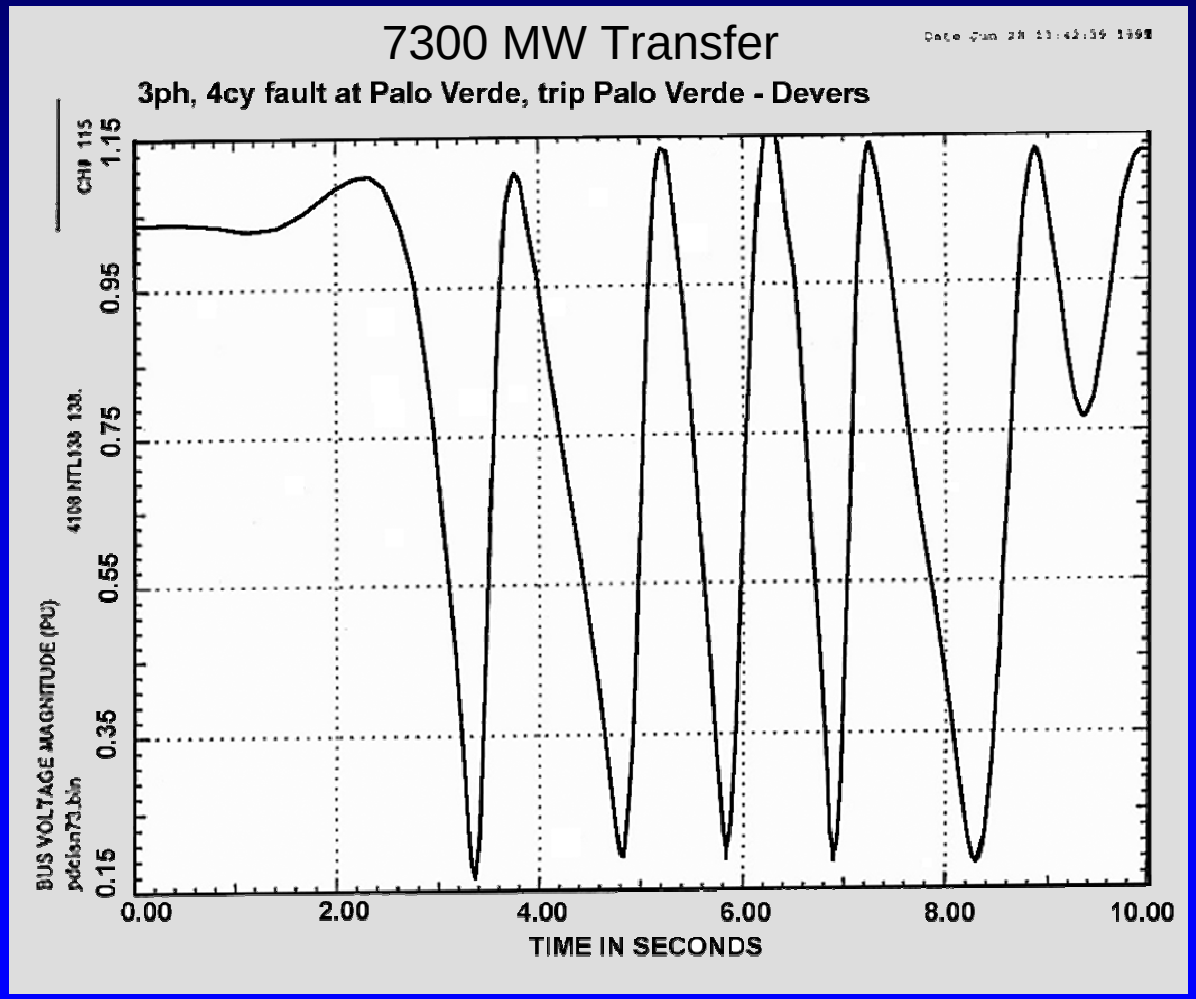
GLEN CANYON
PHOENIX
FOUR CORNERS
ALBUQUERQUE AREA
MOHAVE
LUGO
LOS ANGELES AREA
ARIZONA
NEW MEXICO
EL PASO AREA

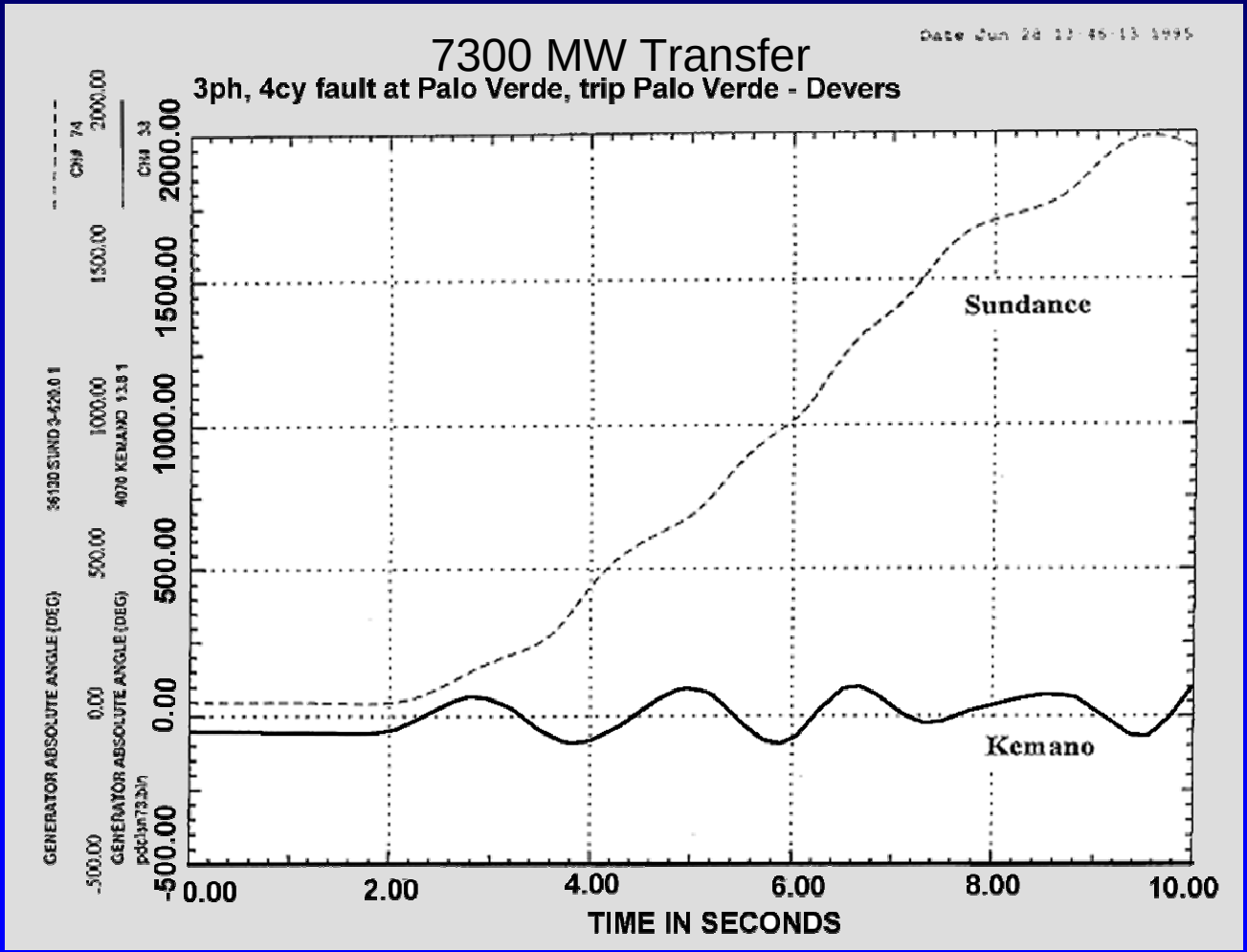
# BPA Bus Voltage



# BCH Bus Voltage Near Alberta Tie



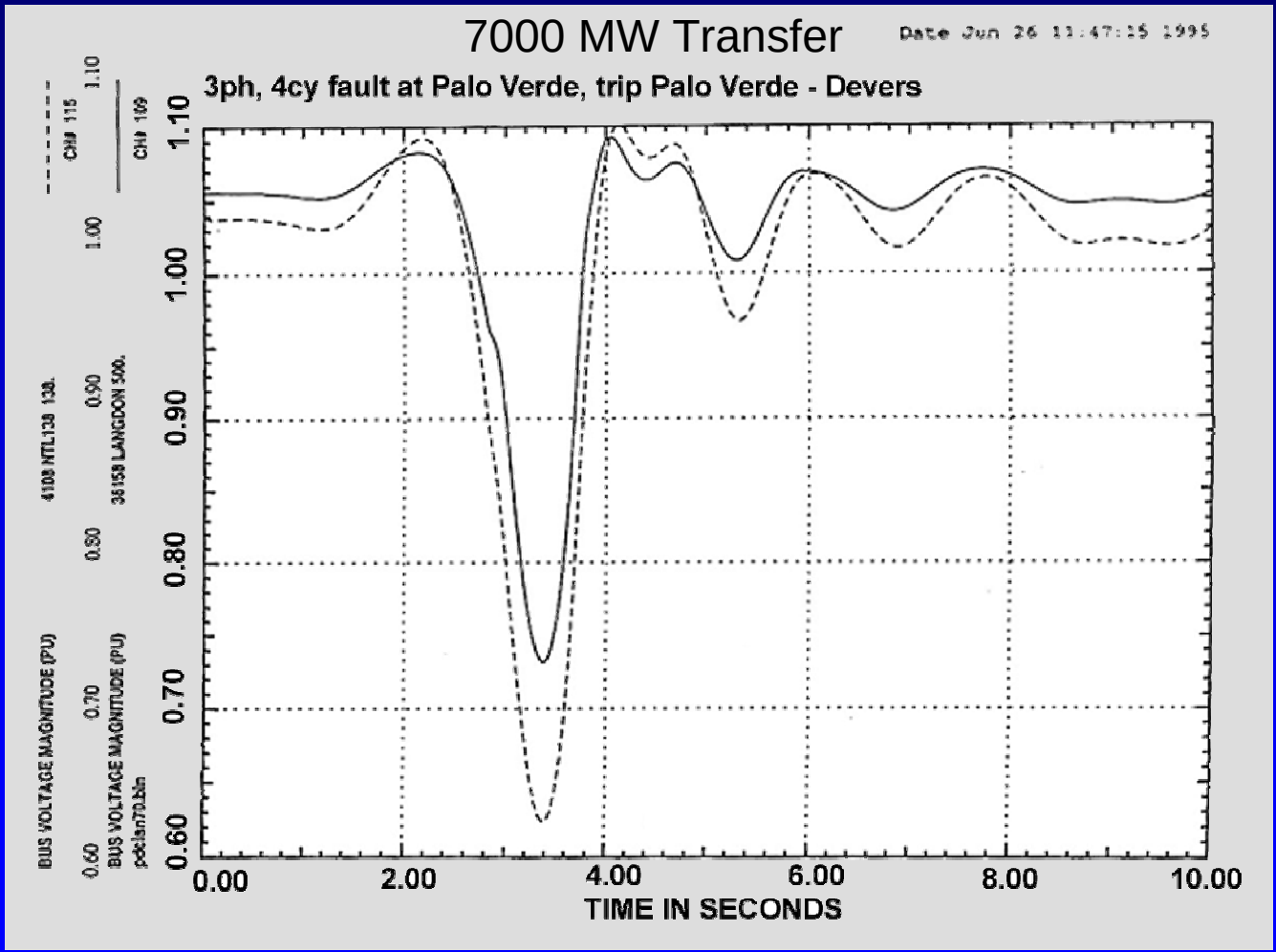
# Rotor Angles in BC and Alberta



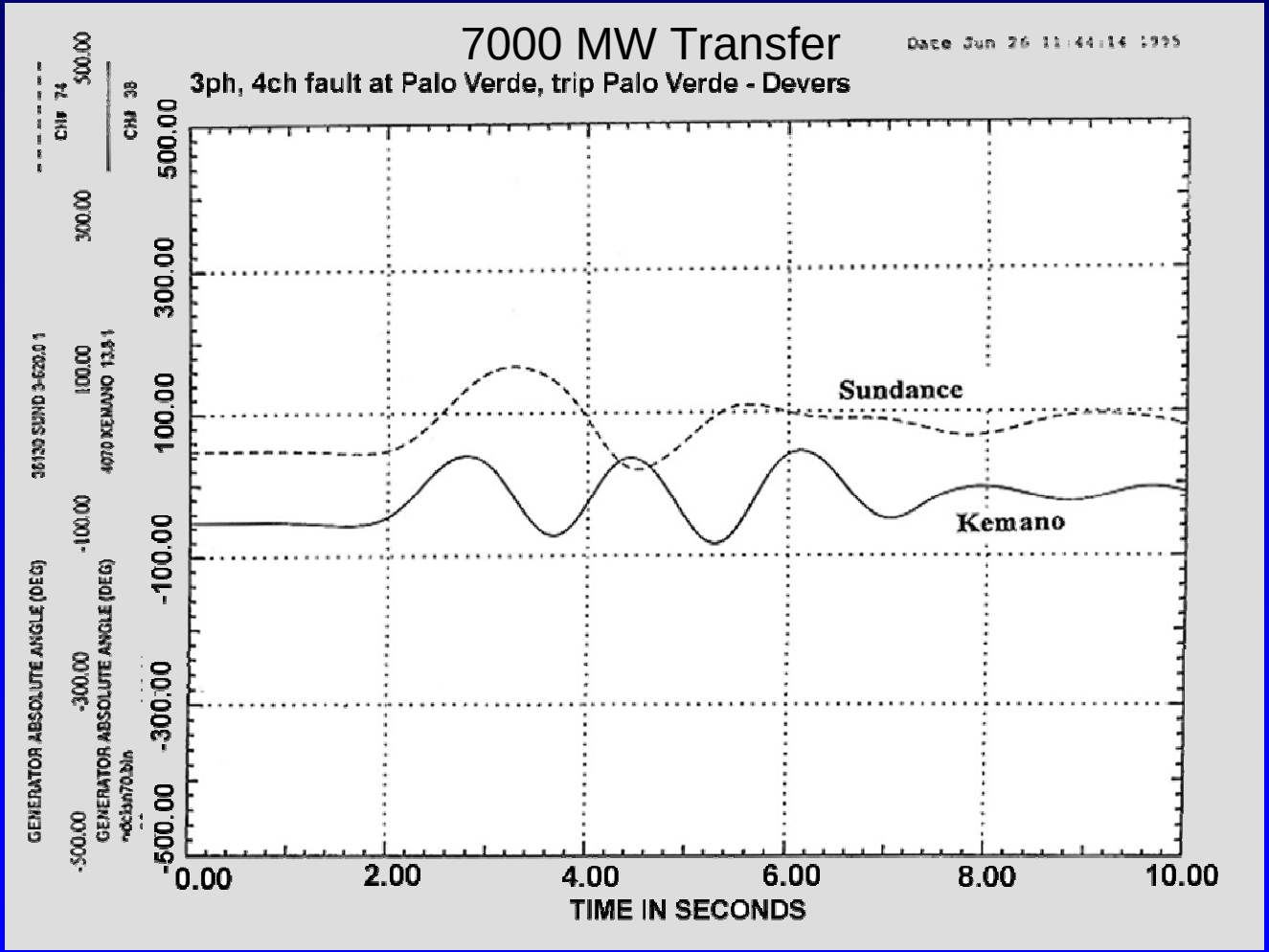
# CASE B

- East of River interface flow reduced to 7000 MW (from 7300 MW for Case A)

# BCH and Alberta Bus Voltages

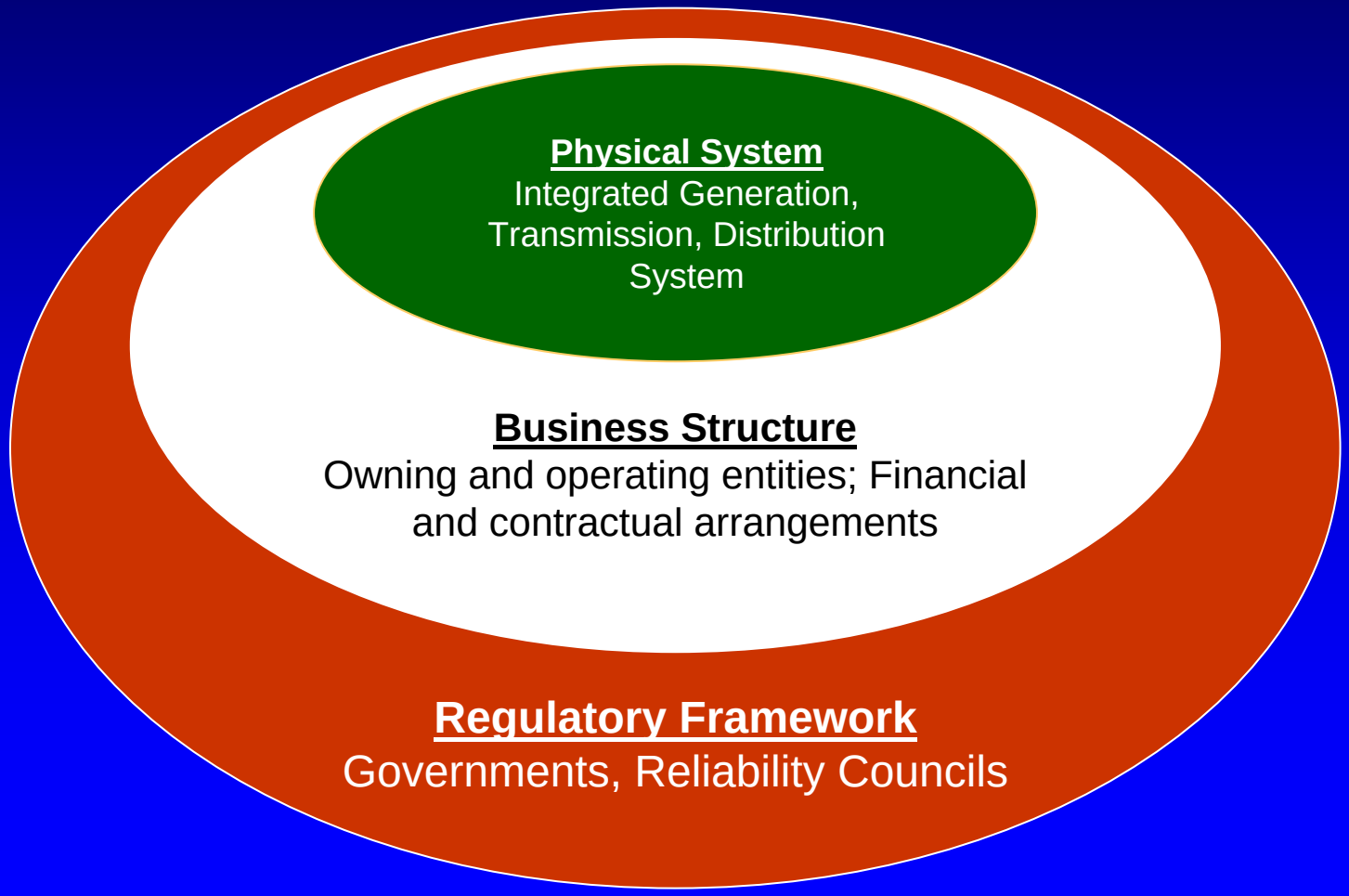


# Rotor Angles in BC and Alberta



# North American Western Interconnected System

# Factors Impacting on System Security



# Methods of Enhancing Security

- Impractical to achieve complete immunity to blackouts
  - need to strike a balance between economy and security
- Good design and operating practices could significantly minimize the <u>occurrence</u> and <u>impact</u> of widespread outages
  - Reliability criteria
  - On-line security assessment
  - Robust stability controls
  - Coordinated emergency controls
  - Real-time system system monitoring and control
  - Wide-spread use of distributed generation (✓)

# Reliability Criteria

- At present, systems designed and operated to withstand
  - loss of any single element preceded by single-, double-, or three-phase fault
  - referred to as "*N-1 criterion*"
- Need for using risk-based security assessment
  - consider multiple outages
  - account for probability and consequences of instability
- Built-in overall strength or robustness is the best defense against catastrophic failures!

# Management of System Reliability

- Roles and responsibilities of individual business and operating entities
  - well chosen, clearly defined and properly enforced
- Coordination of reliability management
- Need for a single entity with overall responsibility for security of entire interconnected system
  - real-time decisions
- System operates with high level of expertise in system stability
  - phenomena, tools

# State-of-the-Art On-Line Dynamic Security Assessment (DSA)

- Practical tools with the required accuracy, speed and robustness
  - a variety of analytical techniques integrated
  - distributed hardware architecture using low cost PCs
  - integrated with energy management system
- Capable of assessing rotor angle stability and voltage stability
  - determine critical contingencies
  - analysis with detailed models
  - security limits/margins for all desired energy transactions
  - remedial measures

# Computational Speed of DSA

Power System model with 4655 buses, 156 generators, using 1.7 GHz, Pentium 4 PC with 256 MB memory

## Voltage Stability Assessment:

| | |
|---|---|
| screening 300 contingencies | 20.0 secs |
| detailed security analysis with 20 critical contingencies | 1.2 secs |
| one transfer limit search | 12.0 secs |

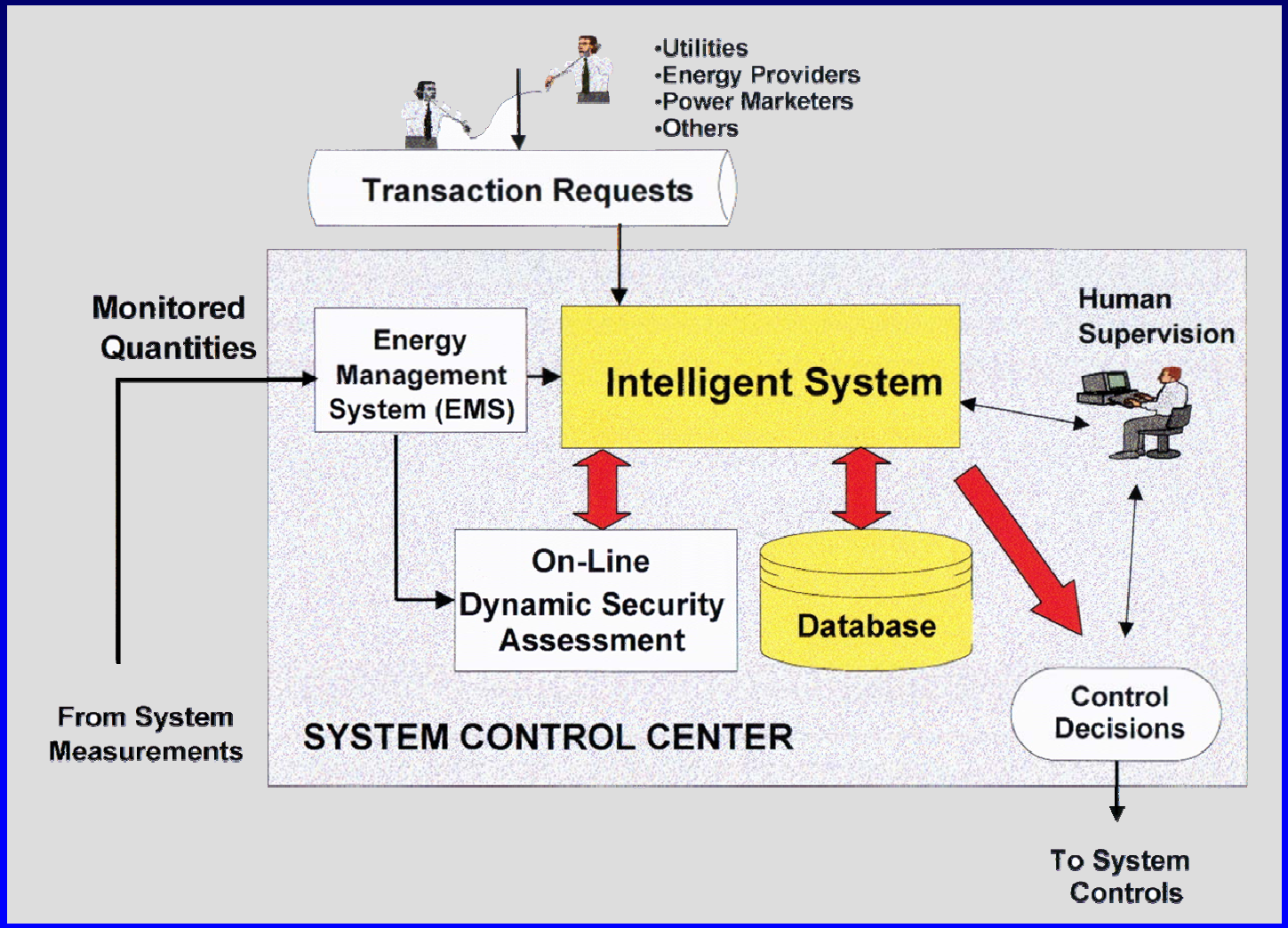
## Transient Stability Assessment:

| | |
|---|---|
| screening 100 contingencies | 75.0 secs |
| 10 second simulations with 10 critical contingencies | 75.0 secs |
| one transfer limit search | 120.0 secs |

# Future Trends in DSA: *Intelligent Systems*

- Knowledge base created using simulation of a large number cases and system measurements
- Automatic learning, data mining, and decision trees to build intelligent systems
- Fast analysis using a broad knowledge base and automatic decision making
- Provides new insight into factors and system parameters affecting stability
- More effective in dealing with uncertainties and large dimensioned problems
- At Powertech, we recently completed a PRECARN project for power system security assessment using intelligent systems technology: POSSIT

# DSA Using Intelligent Systems



# Enhancement of Stability: *Controls*

- Greater dependence on stability controls
  - excitation control (PSS), FACTS, HVDC, secondary voltage control
  - multi-purpose controls
  - multiple controllers
- Coordination, integration and robustness present challenges
  - good control design procedures and tools have evolved
- Hardware design should provide
  - high degree of functional reliability
  - flexibility for maintenance and testing
- Industry should make better use of controls!

# Need for Safeguarding Against Multiple Contingencies

- Most major blackouts are the results of multiple contingencies
  - brought about by combination of events: multiple outages, protective relay misoperation

- Examples of major system upsets caused by multiple outages

  a) 2 July 1996 WSCC disturbance:
     - two 345 kV lines, two 230 kV lines
     - voltage instability

  b) 10 August 1996 WSCC disturbance:
     - four 500 kV lines
     - unstable 0.23 Hz inter-area oscillation

  c) 11 March 1999 Brazil disturbance:
     - five 440 kV lines
     - transient instability

# Development of a Good "Defense Plan" against Multiple Contingencies

- Judicious choice of emergency controls
  - protection against different scenarios
  - identification of scenarios based on past experience, knowledge of unique characteristics of system, probabilistic approach
- Coordination of different emergency control schemes
  - complement each other
  - act properly in complex situations
- Response-based emergency controls should generally be preferred
  - "self-healing" power systems
- Need for advancing this technology!

# Example of Self-Healing System: Prevention of Voltage Collapse in Eastern Ontario

- Coordinated scheme consisting of:
  - shunt capacitor switching: 36 banks
  - transformer tap-changer block: 14 TS's
  - load rejection: 9 blocks, 750 MW
- Triggered by voltage drop <u>magnitude</u> and <u>duration</u>
- Following a contingency, depending on the severity (power flow, line outage)
  - only the required level of control action is provided

# Real-Time Monitoring and Control: *An Emerging Technology*

- Advances in communications technology have made it possible to
  - monitor power systems over a wide area
  - remotely control many functions
- Research on use of <u>multisensor data fusion</u> technology
  - process data from different monitors, integrate and process information
  - identify phenomenon associated with impending emergency
  - make intelligent control decisions
- A fast and effective way to <u>predict</u> onset of emergency conditions and take <u>remedial actions</u>

# Efficient Utilization of Energy

- Leads to environmental as well as economic sustainability
- Enormous opportunities exist in this area
- Examples of "smart" use of power:

(a) "Buildings for Sustainability"

- David and Lucile Packard Foundations Los Altos Project
- "Living Building": designed for use of energy from renewable "clean" energy sources locally  minimal reliance on the grid, efficient use of energy

(b) "Better Buildings Through Integrated Intelligent Systems"

- Project commissioned by Industry Canada, coordinated by Continental Automated Buildings Association (CABA) and PRECARN
- Reduced energy consumption and greenhouse gas emissions, improved safety and security of occupants, and reduced life cycle costs

(c) BC Hydro Power Smart program

# Future Organizations and Workforce

- Good organization and workforce critical to sustainability
  - the fourth pillar of sustainability
- Prof. Peter Senge, Sloan School of Management MIT:
  - the Command and Control Corporate model will not carry us into the 21st Century
- Companies that will excel in the future will be "learning organizations" with five disciplines:
  - systems thinking, personal mastery, mental models, team learning, shared vision
- Workforce will be required to interact with others and respond quickly
  - highly skilled, well informed, and empowered
- An added concern for electric power industry:
  - Power Engineering Education programs have been on the decline for many years

# Sustainable Power Systems in the 21st Century

## Summary

- Challenge is to produce electricity that is:
  - greener, cheaper, reliable and of higher quality
  - responsive to growing consumer needs
- Greater dependence on dispersed generation
- Increased emphasis on "smart" use of electricity
- New technologies will play a critical role in meeting the challenges and shaping the industry
- Hydrogen and electricity form an ideal "energy currency pair"
  - likely to dominate the energy delivery and transportation systems