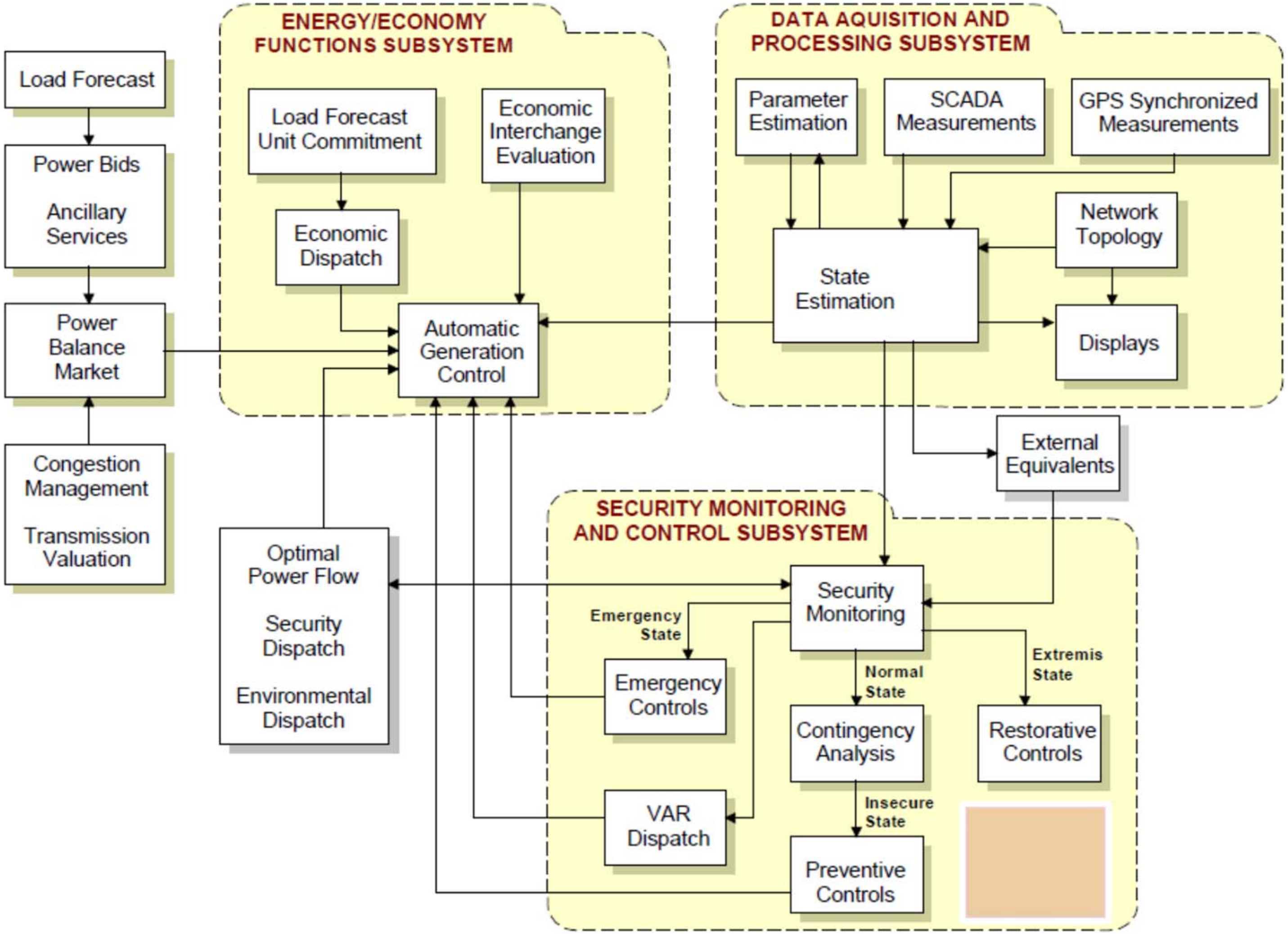
Dynamic Security Analysis


ENERGY/ECONOMY FUNCTIONS SUBSYSTEM
DATA AQUISITION AND PROCESSING SUBSYSTEM
Load Forecast
Power Bids
Ancillary Services
Power Balance Market
Congestion Management
Transmission Valuation
Load Forecast Unit Commitment
Economic Interchange Evaluation
Economic Dispatch
Automatic Generation Control
Parameter Estimation
SCADA Measurements
GPS Synchronized Measurements
Network Topology
State Estimation
Displays
External Equivalents
SECURITY MONITORING AND CONTROL SUBSYSTEM
Optimal Power Flow
Security Dispatch
Environmental Dispatch
Security Monitoring
Emergency State
Emergency Controls
Normal State
Extremis State
Contingency Analysis
Restorative Controls
VAR Dispatch
Insecure State
Preventive Controls

On-Line Dynamic Security Assessment

Dynamic Security Assessment (DSA)

- A challenging task
  - changing system conditions; complexity and size of power systems

- Historically based on off-line studies
  - system operated conservatively within pre-established limits

- On-line DSA essential in the new competitive environment
  - evaluation of available transfer capability (ATC)

On-Line Voltage Stability Assessment (VSA)

Components of DSA

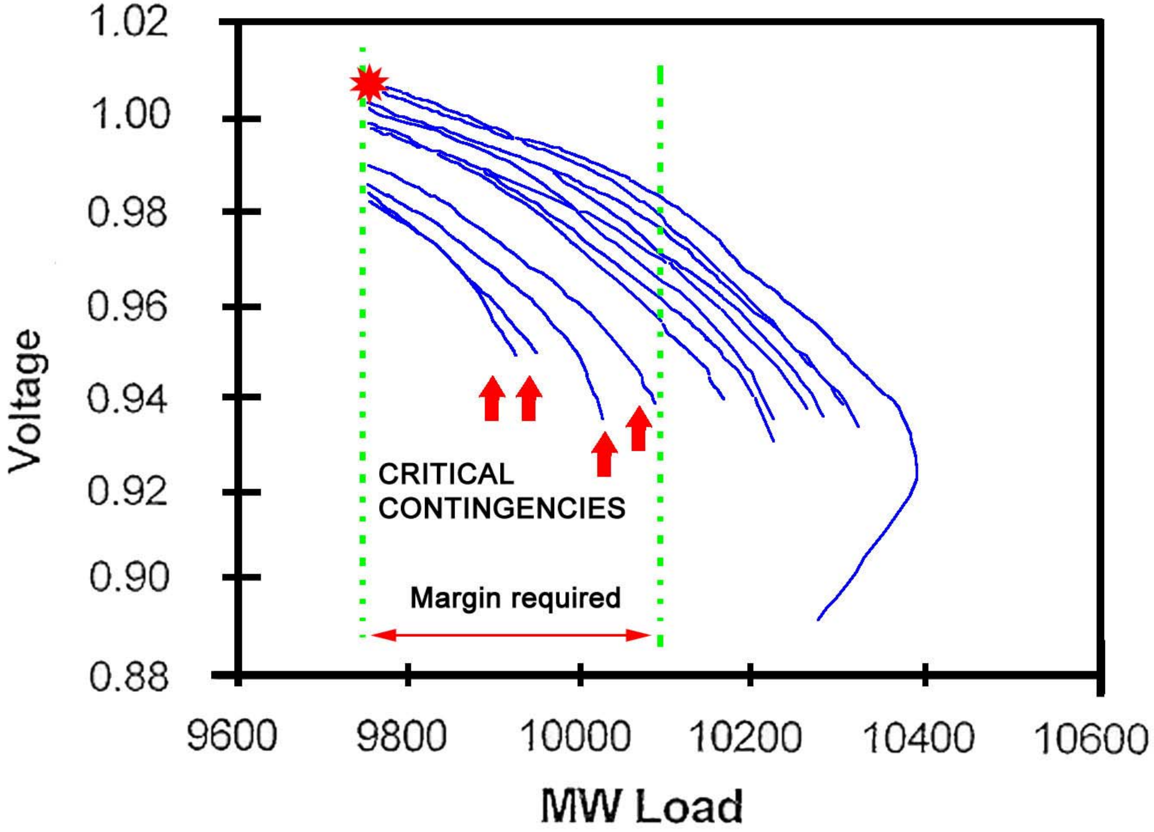
- All forms of system instability must be addressed
- Two categories important for on-line assessment
  - Transient (angle) stability
  - Voltage stability
- Small-signal (angle) stability
  - control problem addressed in system design
  - on-line assessment important for some systems

Key Elements of VSA

- Interface with EMS; Model Initialization
- Contingency screening and selection
- Determination of secure operating region
  - using static analysis
- Determination of remedial actions
- Fast time-domain simulation
  - validation and checking

Contingency Selection Module

- Impractical to consider every conceivable contingency
- A limited number (typically 20) critical contingencies determined for detailed studies
- Performance Indices based on a few power flow solutions and reactive reserve not reliable
- A fast screening method used:
  - based on exact margin to voltage collapse and full power flow solutions
  - number of power flow solutions 1.2 to 2.0 times number of contingencies
- Supplemented with user-specified contingencies



Automatic Critical Contingency Selection

Security Computation Module

- static analysis using detailed models
- Secure region is defined by a number of Coordinates
  - key system values: MW generation, area load, interface transfers, etc.
- Voltage stability determined by
  - existence of power flow solution
  - MVAr reserves of key reactive sources
  - post-contingency voltage decline
- Specialized power flow dispatcher and solver to quickly search for stability limit

Modelling:

  - generator capability curves
  - governor response, economic dispatch, AGC
  - nonlinear loads
  - control of ULTCs, switched shunts, etc.

Inputs and Outputs:

- Inputs
  - list of contingencies produced by screening and ranking (+user defined)
  - base case powerflow from state estimator
  - definition of SCRs
  - voltage security criteria and definition of parameter of stress
- Output
  - secure region in secure region space

Generator Capability Curve

- The loading capability of a synchronous generator is determined by its size and outlay. The major limiting factors:
  - Cooling limits of the rotor and stator windings,
  - Iron saturation,
  - The dimensioning of the excitation system, etc.
- Technical limits must be observed during operation.

Limit: Maximum permissible heating of the stator winding

- The maximum apparent power (S_{max}) is the determining factor for the maximum permissible heating of the stator winding
  - The machine must not supply more than its maximum apparent power S_{max} (for which the machine is built), i.e.
  - The boundary is represented by a circle in the P - Q diagram
  - The corresponding equation:

$$S^2 = P^2 + Q^2$$

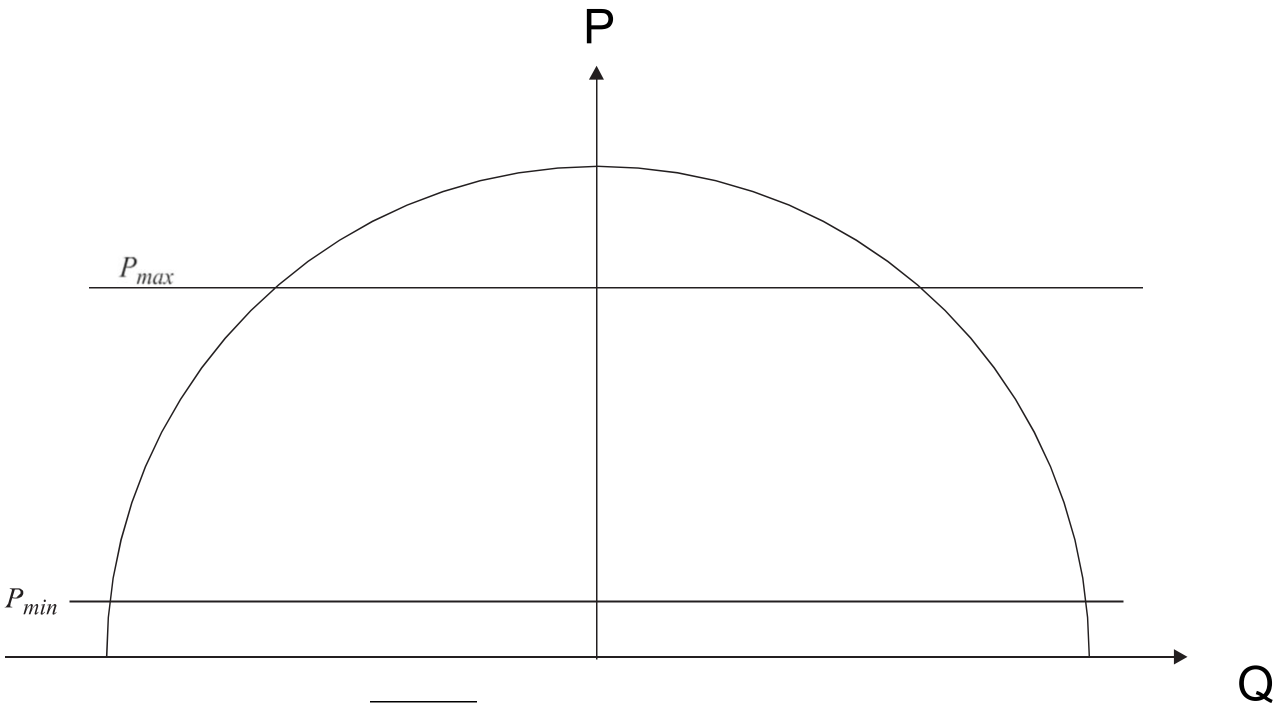
Equation of a circle in PQ plane

Limit: Minimum and maximum deliverable active power

- In the case of thermal power plants, these limit values (P_{min}, P_{max}) are determined by the minimum and maximum steam flow through the turbine
- For hydropower generators: $P_{min} = 0$, and P_{max} determined by the maximum flow rate of the water.
  - **The minimum and maximum deliverable active power, P_{min} and P_{max}, are shown as horizontal lines in the operating diagram.**

$P = P_{min}$ and $P = P_{max}$ straight lines in the PQ plane

Operational Diagram



Limit: Stability limit

$$\underline{I}_a = \frac{\underline{U}_p - U}{jX_d} = \frac{U_p\angle\delta - U}{jX_d} = \frac{U_p\angle\delta - \pi/2 + jU}{X_d}$$

$$\underline{S} = 3\cdot U\cdot \underline{I}_a^* = 3\cdot U\cdot\frac{U_p\angle-\delta+(\pi/2)-jU}{X_d} = \frac{3\cdot U\cdot U_p\cdot\sin\delta}{X_d} + j\frac{3\cdot U\cdot U_p\cdot\cos\delta - U^2}{X_d}$$

$$P = \frac{3\cdot U\cdot U_p\cdot\sin\delta}{X_d} = \omega_m\cdot M \qquad Q = \frac{3\cdot U\cdot U_p\cdot\cos\delta - U^2}{X_d}$$

- The theoretical stability limit is at δ = 90° .
  - Generally, however, an operational limit of $\delta_{max} = 70^0$ is chosen.

Limit: Stability limit (cont'd)

$$\sin\delta = \frac{P \cdot X_d}{3 \cdot U \cdot U_p}$$

$$\cos\delta = \frac{Q \cdot X_d + U^2}{3 \cdot U \cdot U_p}$$

$$\tan\delta = \frac{P \cdot X_d}{Q \cdot X_d + U^2} \rightarrow P = Q \cdot \tan\delta + \frac{U^2}{X_d} \cdot \tan\delta$$

$$P = 0 \rightarrow Q = -\frac{U^2}{X_d}$$

- The stability limit for $\delta_{max} = 70^0$ is a straight line with:

  The slope: tan $70^0 = 2.75$ and

  X - intercept at: $Q = -\frac{U^2}{X_d}$

Limit: Maximum permissible rotor heating

- Most generators have a voltage regulator.
- By changing the excitation current, the generated voltage and thus also the terminal voltage of the generator can be controlled.
- The voltage control specifies a minimum generated voltage $U_{p,MIN}$.
- The maximum generated voltage $U_{p,MAX}$ is specified by the maximum permissible heating of the rotor winding.
  - These two limit values can be represented in the operating diagram by two circles.

$$\sin\delta = \frac{P \cdot X_d}{3 \cdot U \cdot U_p} \qquad \cos\delta = \frac{Q \cdot X_d + U^2}{3 \cdot U \cdot U_p}$$

$$\left(\frac{3 \cdot U \cdot U_p}{X_d}\right)^2 = P^2 + \left(Q + \frac{U^2}{X_d}\right)^2$$

Maximum/minimum Excitation

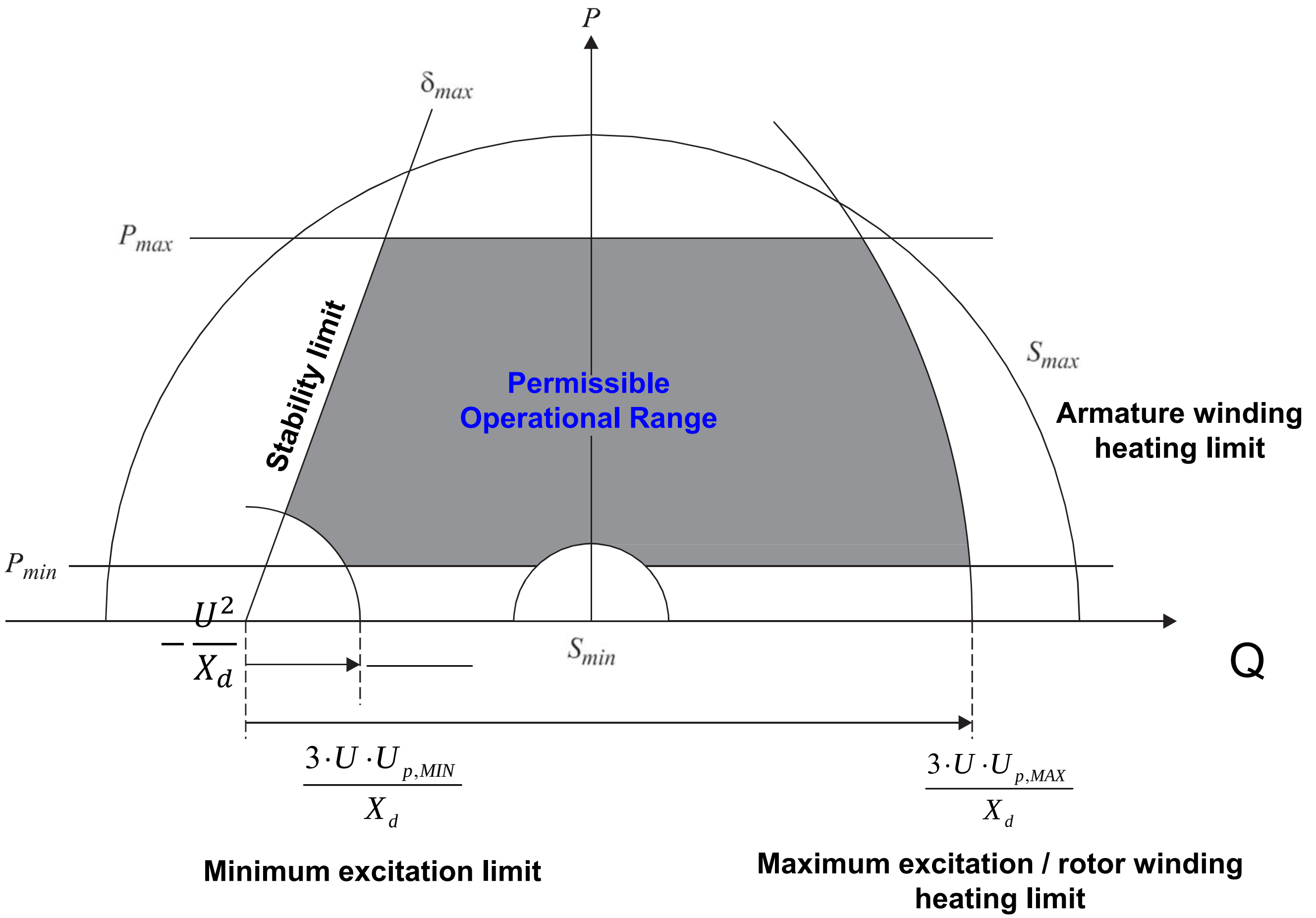
The locus

$$\boxed{\left(\frac{3\cdot U\cdot U_p}{X_d}\right)^2 = P^2 + \left(Q + \frac{U^2}{X_d}\right)^2}$$

A circle with the origin at: $\left(-\frac{U^2}{X_d}, 0\right)$ and the radius $\frac{3\cdot U\cdot U_p}{X_d}$

Minimum excitation: $\frac{3\cdot U\cdot U_{p,MIN}}{X_d}$ Maximum excitation: $\frac{3\cdot U\cdot U_{p,MAX}}{X_d}$

Capabilty Curve / Operational Chart



Stability limit

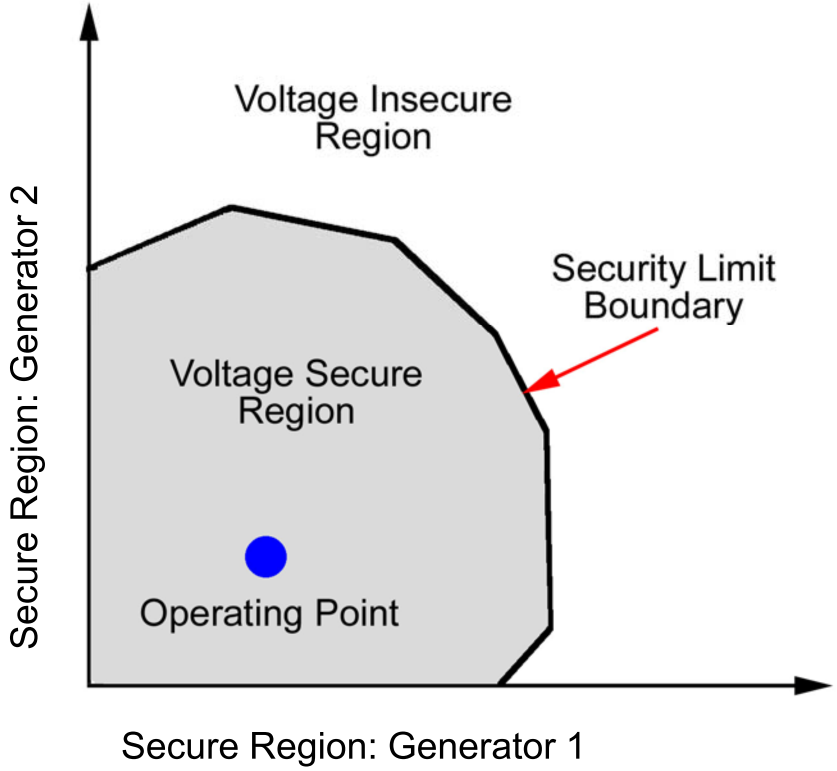
Permissible Operational Range

Armature winding heating limit

Minimum excitation limit

Maximum excitation / rotor winding heating limit

Secure Operating Region



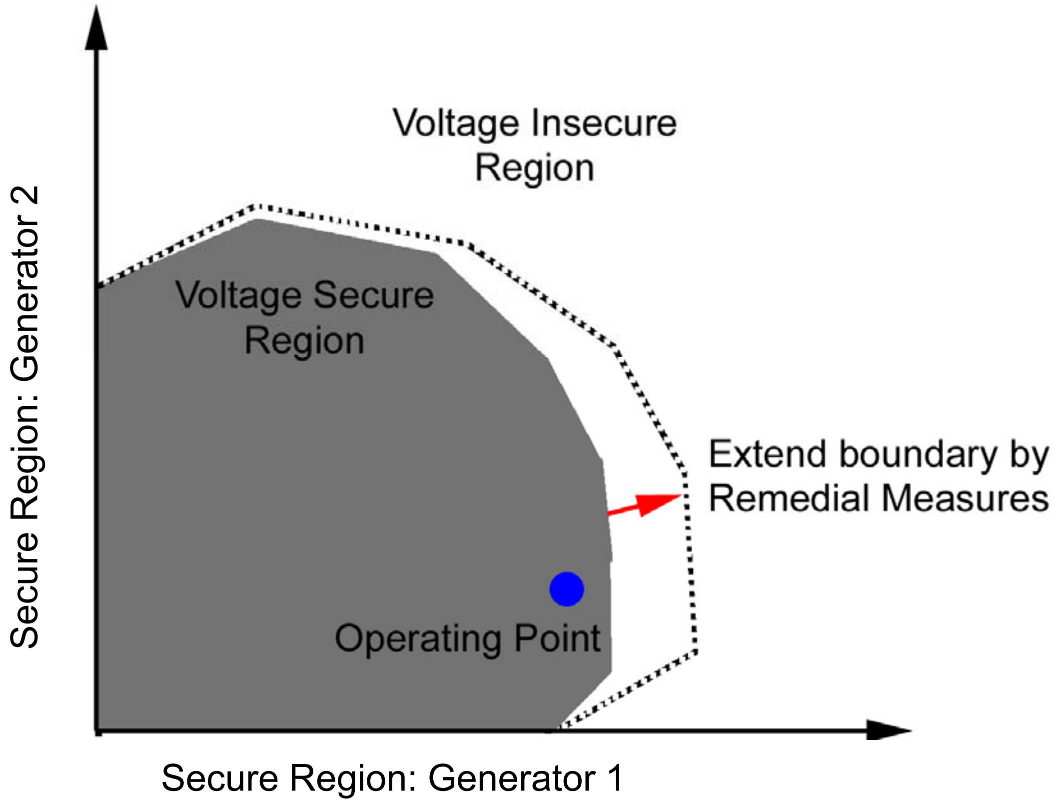
Remedial Measures Module

- Determines necessary remedial measures to
  - ensure sufficient stability margins
  - expand the secure region
- Preventative control actions:
  - taken prior to a contingency
  - caps/reactor switching, generation re-dispatch, voltage rescheduling
- Corrective (emergency) control actions:
  - applied following a contingency
  - load shedding, generator runback, transformer tap changer blocking
- Ranking of each remedial measure using sensitivity analysis

Ranking Remedial Measures

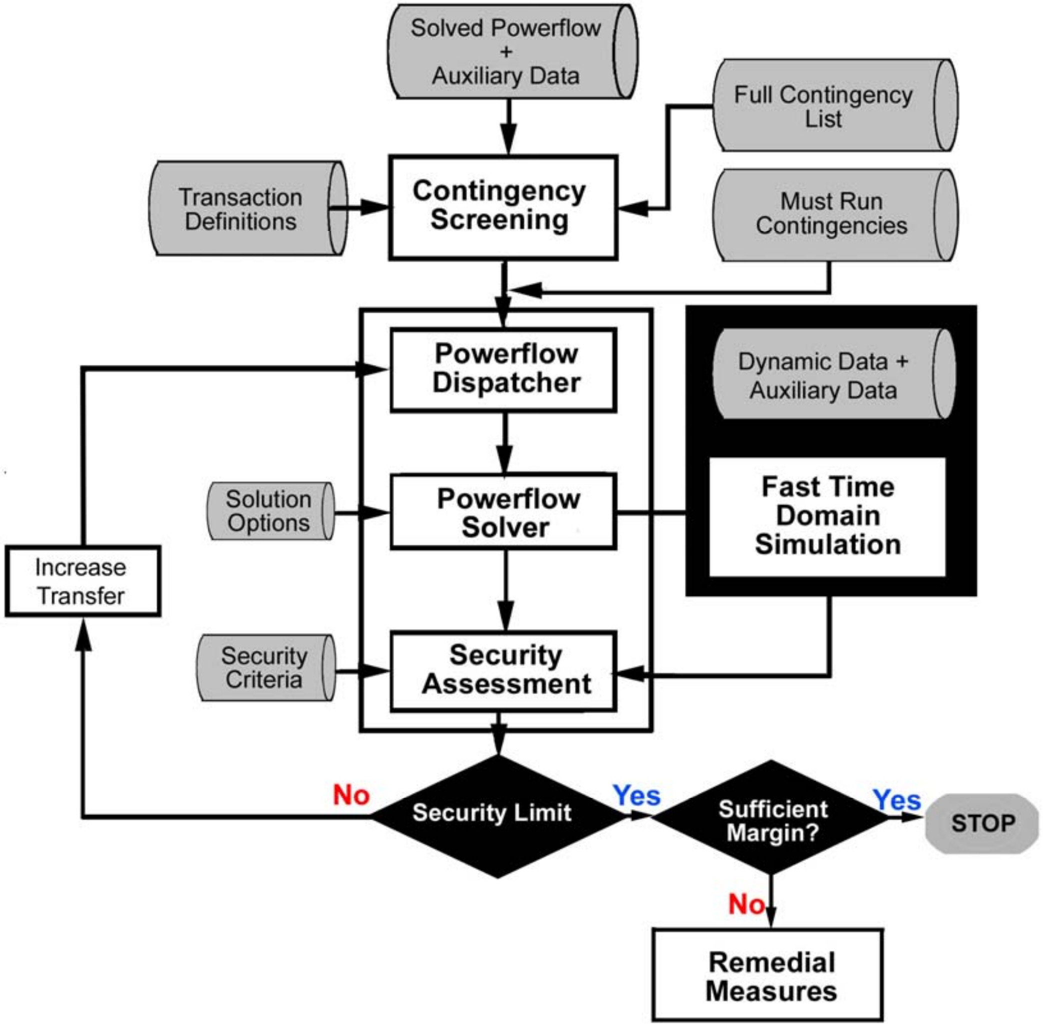
- Objective is to identify the most effective remedial measures to give the desired stability margin
- Obtain solved power flow case for the most severe contingency
  - gradually introduce the effect of the contingency
  - bus injection compensation technique
- Compute the sensitivities of reactive power (or bus voltage) to different control measures
  - rank the remedial measures
- Apply controls one at a time in order of ranking until power flow solves for the most severe contingency

Expanding the Secure Region



Fast Time-Domain Simulation

- Determines the essential dynamic phenomena without step-by-step numerical integration
  - when chronology of events significant
  - for validating the effect of remedial measures
- Focuses on the evolution of system dynamic response driven by slow dynamics
  - transformer tap changers, field current limiters, switched caps
- Captures the effects of fast dynamics by solving associated steady state equations



VSAT Structure

Transient Stability Assessment (TSA)

- Time-domain simulations essential
  - modeling detail and accuracy
- Sole dependence on time-domain simulations has severe limitations
  - high computational burden
  - no stability margin/sensitivity information
  - requires considerable human interaction
- Supplementary techniques for speeding up and automating overall process
- Methods available for deriving useful indices
  - Transient Energy Function (TEF)
  - Signal Energy Analysis
  - Extended Equal Area Criterion (EEAC)

Key Elements of TSA

- Interface with EMS; Model Initialization
- Contingency screening and selection
- Simulation engine
  - detailed modeling
  - time-domain simulation
  - speed enhancement
- Post-processing of detailed simulation
  - stability margin index using EEAC
  - power transfer limit search
  - remedial measures
  - damping calculation using PRONY

A Practical Tool for TSA

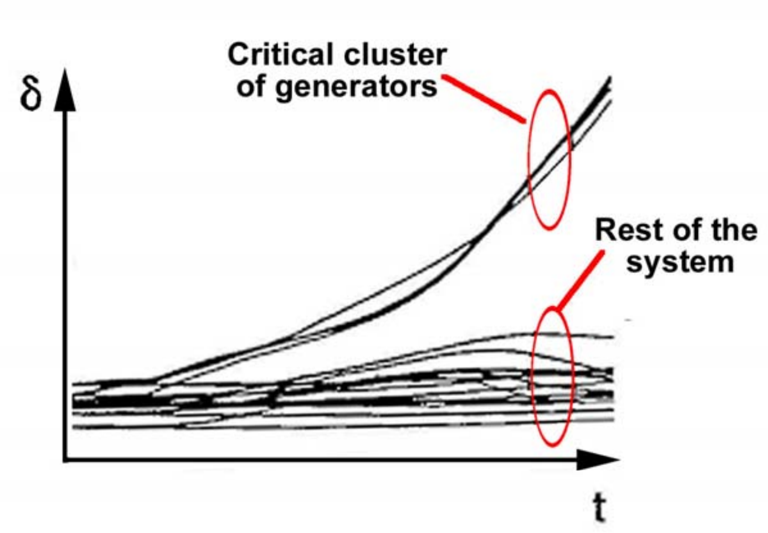
- Overall architecture similar to that of VSA
- Time-domain program, with detailed models and efficient solution techniques, forms simulation engine
- EEAC used for screening contingencies, computing stability margin, stability limit search, and early termination of simulation
- “Prony analysis” for calculation of damping of critical modes of oscillation
- A power flow dispatcher and solver for finding the stability limit
  - a fully automated process
- No modeling compromises;
  can handle multi-swing instability

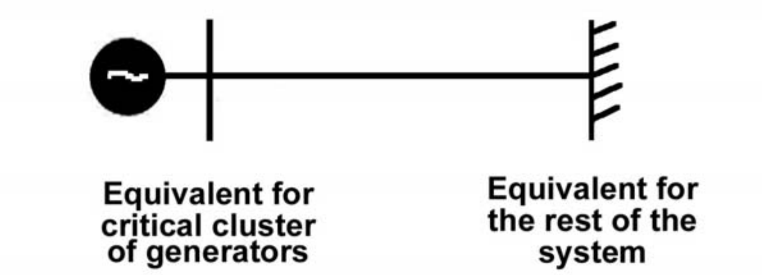
Extended Equal Area Criterion (EEAC)

- Integrates the dynamic response in the multi-machine space, and maps the resultant trajectory into a set of one-machine-infinite-bus planes
  - by applying complementary cluster center of inertia (CCCI) transformations
  - keeps all dynamic information in the multi-machine space
  - stability analysis can be quantitatively performed for the image OMIB systems
  - has the same accuracy and modeling flexibility
  - fast, quantitative

Extended Equal Area Criterion (EEAC)

- Loss of transient stability in a power system always starts in a binary splitting of generators:
  - critical cluster of generators
  - rest of the system





- **At any given point in the time-domain trajectory of the system, the system can be visualized as a one-machine-infinite-bus (OMIB) system**

Extended Equal Area Criterion (EEAC)

- The classical equal area criterion can be extended to the visual OMIB system

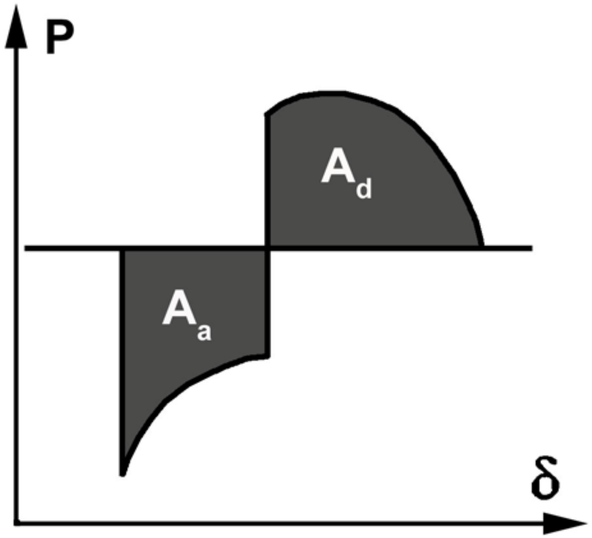
  Stability margin of the system is defined as

$$\eta = \begin{cases} 100\ x\ \dfrac{A_d - A_a}{A_d}\ \textit{if the system is stable}\ (A_d < A_a) \\ 100\ x\ \dfrac{A_d - A_a}{A_a}\ \textit{if the system is unstable}\ (A_a > A_d) \end{cases}$$

Thus, $-100 \le \eta \le 100$, and

$\eta > 0$ if the system is stable
$\eta \le 0$ if the system is unstable

η can be used as a *stability index*



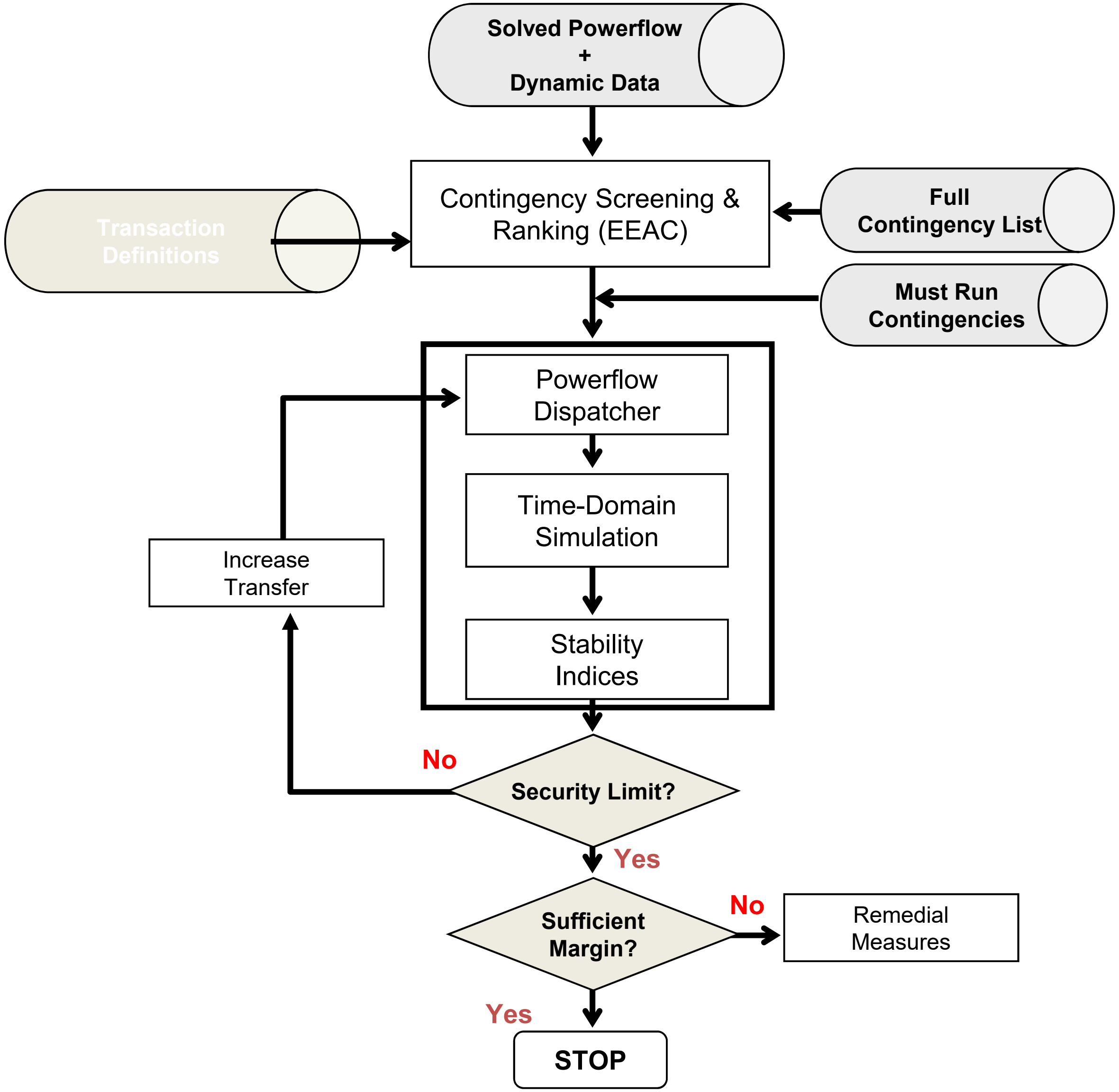
Use of EEAC Theory

- Contingency screening
  - stability margin gives an indication of the relative severity
- Corrective measures for maintaining secure system operation
  - critical cluster of generators (CCG) provides valuable information
- Power transfer limit search
  - stability limit can be determined in four iterations using stability margin
  - each iteration involves a detailed simulation and computation of stability index

Speed Enhancement: Parallel Processing

- Code parallelization
  - differential equations easily parallelized, but not network equations
  - speed-ups limited by serial slowdown effect
  - up to 7 times speed-up can be achieved with 20-30 processors
  - not an effective way
- Conventional serial computers offer much faster computational per-CPU
- Best approach is to use multiple processors
- Perform TS analysis and VS analysis in parallel
- For multiple contingencies
  - perform initialization only once
  - run contingencies on multiple processors

TSAT Structure



Computational Performance of DSA

- Target cycle time from capture of state estimation to completion of security assessment for all specified transactions:
  - 20 minutes
- TSA and VSA functions performed in parallel
  - distributed processing on separate CPUs
- This can be readily achieved with low cost PCs

Summary

- On-line DSA is a complex problem
- It is a challenge to provide comprehensive analysis with the required
  - accuracy, speed, and robustness
- A practical tool for use with large complex systems has been built by
  - drawing on techniques developed over many years;
  - enhancement and integration of these techniques;
  - use of specialized software designs and distributed hardware architectures
- May be used for real time application, or previous day to post ATC

New and Emerging Technologies

- Real-Time Monitoring and Control
- Risk-Based Security Assessment
- Intelligent Control

Real-Time Monitoring and Control

Real-Time Wide Area Monitoring

- Advances in communications technology have made it possible to:
    - monitor power system over a wide area
    - remotely control many functions
- Wide Area Monitoring:
    - phasor measurement units (PMUs) provide time synchronized measurements with an accuracy of 1 microsecond, utilizing Global Position System (GPS)
    - PMUs send measured voltage and current phasors to a Centralized Monitoring System, typically at 100 millisecond intervals
    - Data stored and processed for various applications
    - Results displayed on a Graphical User Interface
- Examples of Wide Area Monitoring Systems:
    - North American Western Interconnected System's Wide Area Measurement System (WAMS) project; BPA, EPRI, DOE as participants
    - ETRANS Wide Area Monitoring (WAM) project for the Swiss Power Grid; developed by ABB

Wide Area Monitoring Current Applications

- On-line monitoring of transmission corridors for loading
- Fast detection of critical situations
  - voltage stability
  - power system oscillations
  - transmission overloading
- Additional input values of system variables for state estimator
- Disturbance recording
  - for calibration of power system model
  - validation of stability analysis software

WAM Potential Future Applications: Wide Area Emergency Control

- Prevention of partial or total blackout of power systems
  - trigger emergency controls based on system response and measurements
- Research into the application of "Multisensor Data Fusion" technology
  - process data from different monitors and integrate information
  - determine nature of impending emergency
  - make intelligent control decisions in real time
- A fast and effective way to predict onset of emergency conditions and take remedial control actions

Risk-Based
Dynamic System Assessment

Dynamic Security Assessment Current Practice

- The utility practice has been to use deterministic approach
  - build strong systems and operate with large security margins
  - overly conservative, but cost could be passed on to captive customers
- The deterministic approach has served the industry well
  - high security levels
  - study effort minimized
- In the new environment, with a diversity of new participants, the deterministic approach not readily acceptable
  - need to account for the probabilistic nature of conditions and events
  - need to quantify and manage risk

Risk-Based Dynamic Security Assessment

- Examines the <u>probability</u> of power system becoming unstable and its <u>consequence</u>
- Computes indices that measure security level or degree of exposure to failure
  - capture all cost consequences
- Notion of security posed in a language and form understood by marketers and financial analysts
- Possible with today’s computing and analysis tools

Intelligent Control

Power System Control

- Overall control functions highly distributed
  - several levels of control
  - involve complex array of devices
- Human operators provide important links at various levels
  - acquire and organize information
  - make decisions requiring a combination of deductive, inductive, and intuitive reasoning
- “Intuitive reasoning” allows quick analysis of unforeseen and difficult situations and make corrective decisions
  - most important skill of an operator

Intelligent Control of Power Systems

- Future power systems more complex to operate
  - less structured environment
- Current controls do not have
  - “human-like” intelligence
- Add intelligent components to conventional controls
  - learn to make decisions quickly
  - process imprecise information
  - provide high level of adaptation
- Overall control of power systems
  - utilize both conventional methods and decision making symbolic methods
  - intelligent components form higher level of control