QuickStab®

Technical Background

ECI
Energy
Consulting
International, Inc.

General Concepts

- "Steady-state stability is the stability of the system under conditions of gradual or relatively slow changes in load" (S. B. Crary, 1945)
- Aperiodic (monotonic) steady-state instability
  - voltage collapse -- detected with dP/dV or dΔQ/dV criteria
  - units losing synchronism or instability when large blocks of MW are transferred across weak transmission corridors -- detected with dP/dδ criterion
- Voltage stability, load stability and steady-state stability are interrelated
  - conceptually under the "steady-state stability" umbrella where the load changes are small, gradual

General Concepts (cont'd)

- Steady-state instability is identified by the singularity of the <u>dynamic state</u> Jacobian
  - the singularity of any of its submatrices results in steady-state instability
    - ☞ *the singularity of dP/dδ, dP/dV or dQ/dV submatrices results in steady-state instability*
  - real power voltage stability criterion dP/dV
  - reactive power voltage stability criterion dQ/dV
  - angle stability criterion dP/dδ
- Steady-State Stability Limit (SSSL)
  - maximum total MW grid utilization (internal generation + imports) such that the system is stable in the presence of small load changes

General Concepts (cont'd)

- Steady-State Stability Limit (cont'd)
  - Steady-State Stability Reserve = "distance" from the current system state to the SSSL
    - stress (worsen) the base case until it becomes unstable
      - the "case worsening" scenario affects the SSSL
- The Transient Stability Limit (TSL) is a different concept altogether
  - difficult to determine (if not impossible)
  - intuitively it can be stated that
    - the Transient Stability Limit (TSL) and Steady-State Stability Limit (SSSL) are related
      - ☞TSL is always smaller than SSSL
      - ☞TSL and SSSL change in the same direction
    - a "safe operating margin" exists such that transient instability is unlikely at MW loadings below it

General Concepts (cont'd)

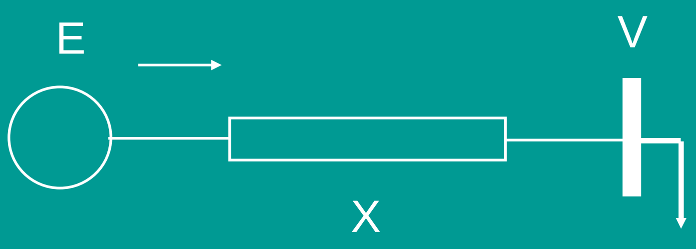
- **Safe Operating Margin**
  - ►system MW loading where there is no risk of transient instability
    - •implies no risk of aperiodic steady-state instability
  - ►always much smaller than SSSL
  - ►changes in the same direction with SSSL
  - ►conceptually similar to TTC

☞ *"any network that meets the steady-state stability conditions can withstand dynamic perturbations and end in a stable operating state"*

(Magnien, M., Rapport Spécial du Groupe 32 Conception et Fonctionnement des Réseaux, Conférence Internationale des Grands Réseaux Electriques à Haute Tension, CIGRE Session 1964)

General Concepts (cont'd)

Steady-State Stability Reserve Concept



conceptual model -- the solution algorithm represents ALL the machines

the power flows from generators to loads

E = generators' e.m.f.

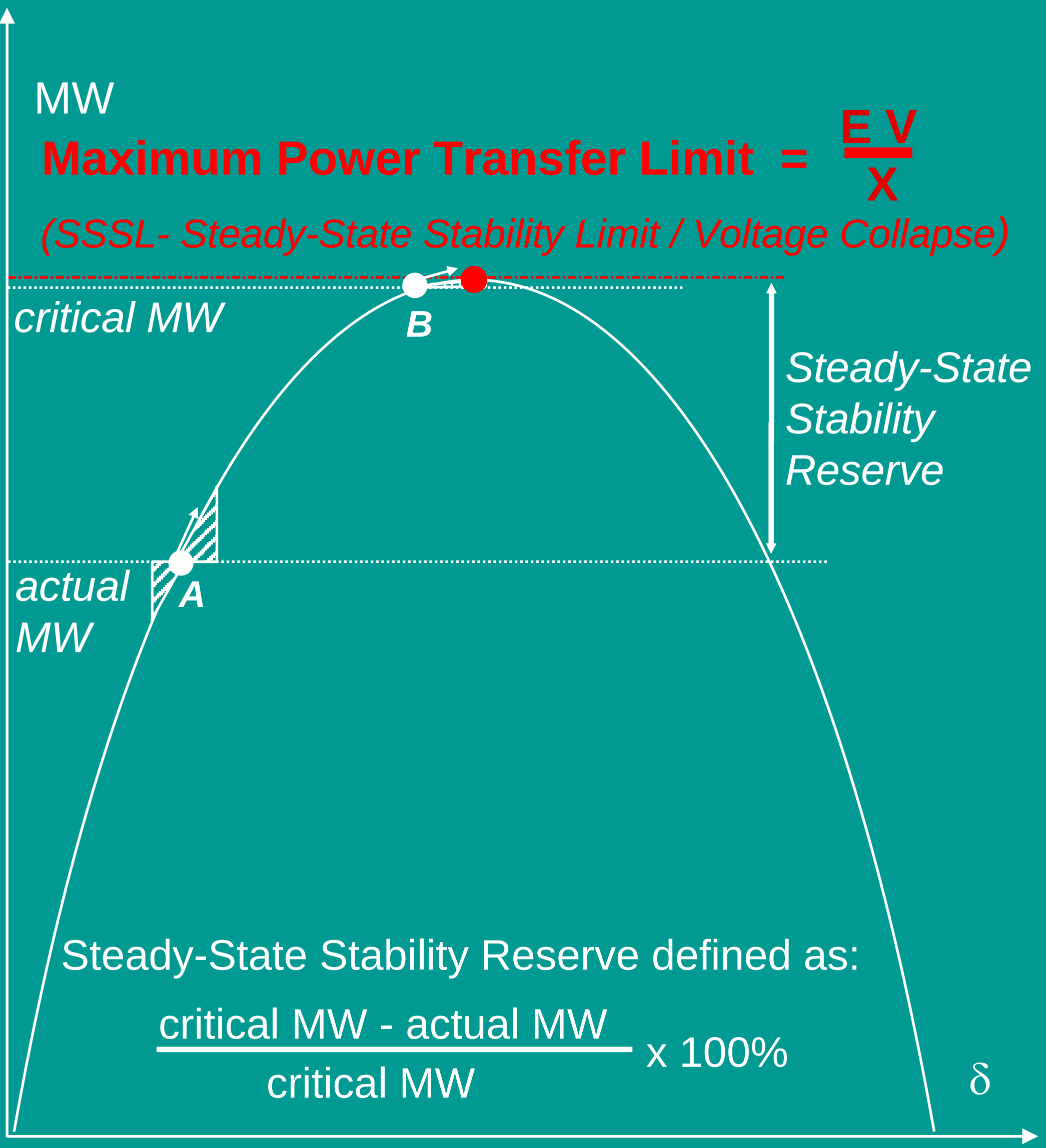
V = bus voltages at load buses

X = transmission system reactance (includes the generators)

Steady-state stability analysis by using a voltage stability criterion:

Point A -- a small load change does not cause instability

Point B -- a small load change causes voltage collapse and / or units out of synchronism



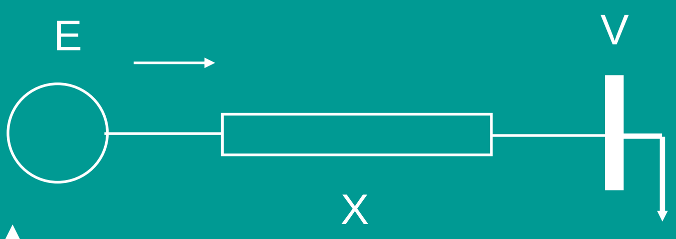
Steady-State Stability Reserve defined as:

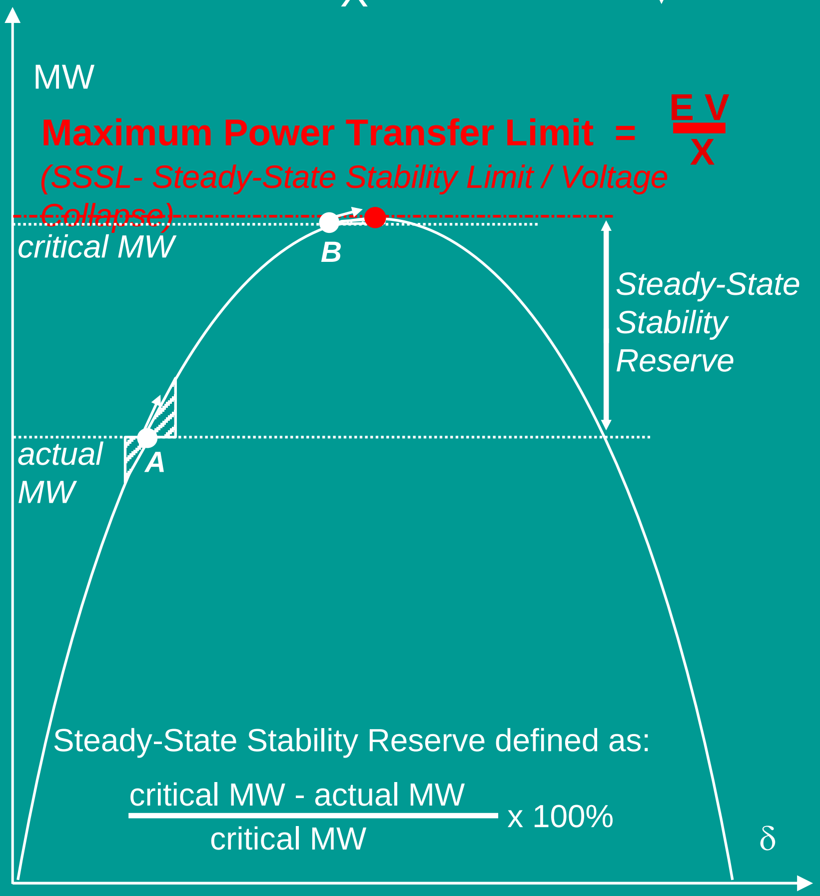
$$\frac{\text{critical MW} - \text{actual MW}}{\text{critical MW}} \times 100\%$$

Total MW system grid utilization = internal generation + tie-line imports

General Concepts (cont'd)

Steady-State Stability Reserve Concept





Maximum Power Transfer Limit = $\frac{E\,V}{X}$

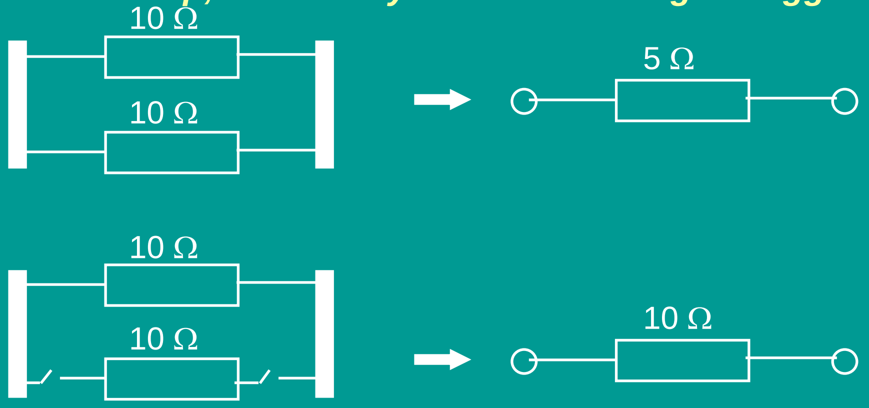
(SSSL- Steady-State Stability Limit / Voltage Collapse)

Steady-State Stability Reserve defined as:

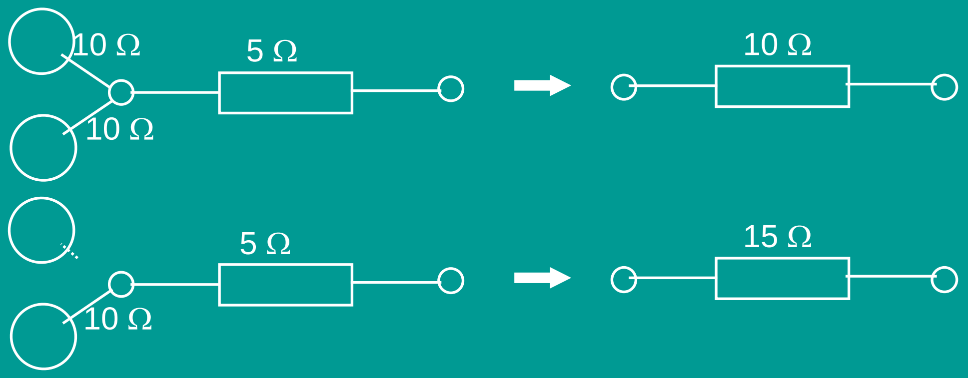
$$\frac{\text{critical MW - actual MW}}{\text{critical MW}} \text{ x } 100\%$$

Total MW system grid utilization = internal generation + tie-line imports

when lines trip, the total system reactance gets bigger



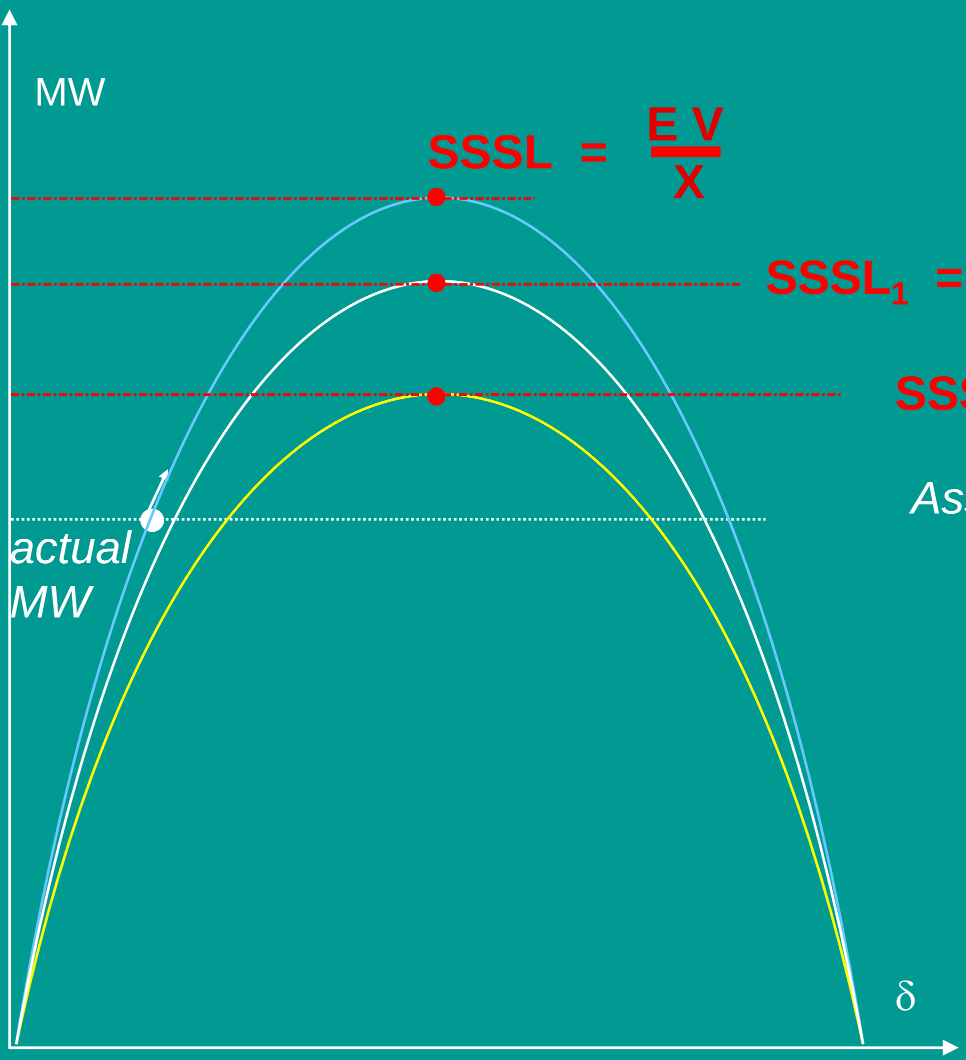
when generators trip, the total system reactance gets bigger



line and generator trips tend to reduce the maximum power transfer limit

General Concepts (cont'd)

Impact of Lower System Voltages



$$SSSL = \frac{E\,V}{X}$$

$$SSSL_1 = \frac{E\,V_1}{X}$$

$$SSSL_2 = \frac{E\,V_2}{X}$$

Assumptions:

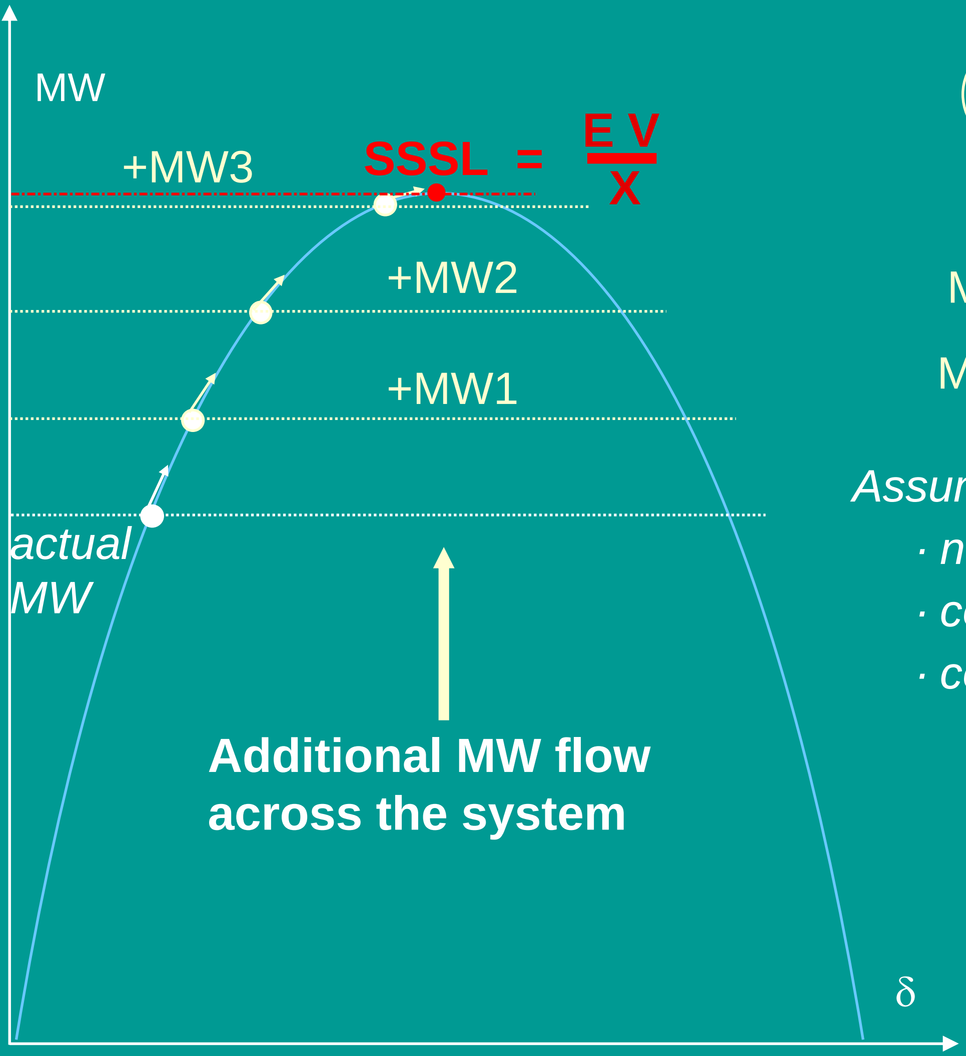
- *no topology changes*
- *same MW loading*
- *constant generator excitation currents*

decaying system voltages reduce the maximum power transfer limit

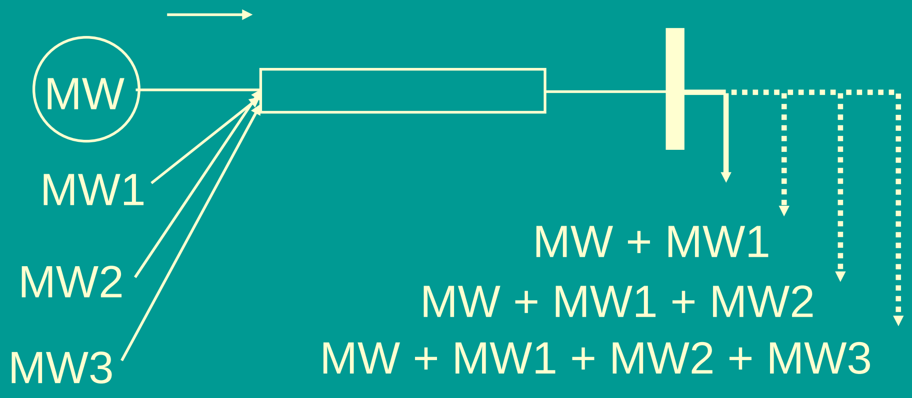
Total MW system grid utilization = internal generation + tie-line imports

General Concepts (cont'd)

Impact of Wheeling MW Flows -- How "Transmission Congestion" Reduces the Stability Margin



Additional MW flow across the system



Assumptions:

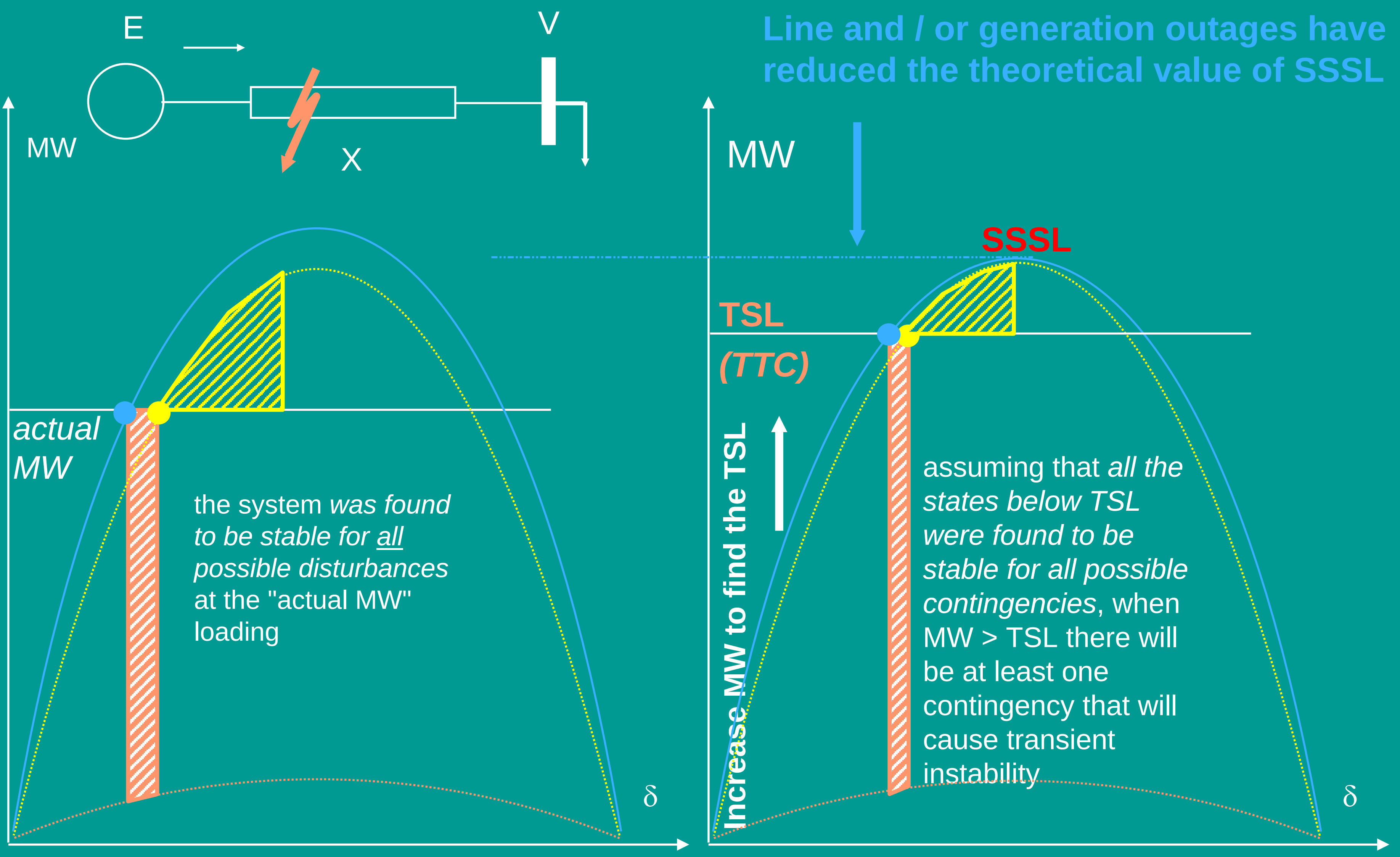
- *no topology changes*
- *constant generator excitation currents*
- *constant voltages at load buses*

external MW flows wheeled across the transmission network, also known as "congestion', push the system closer to its maximum power transfer limit

Total MW system grid utilization = internal generation + tie-line imports

General Concepts (cont'd)

Transient Stability Limit Concept



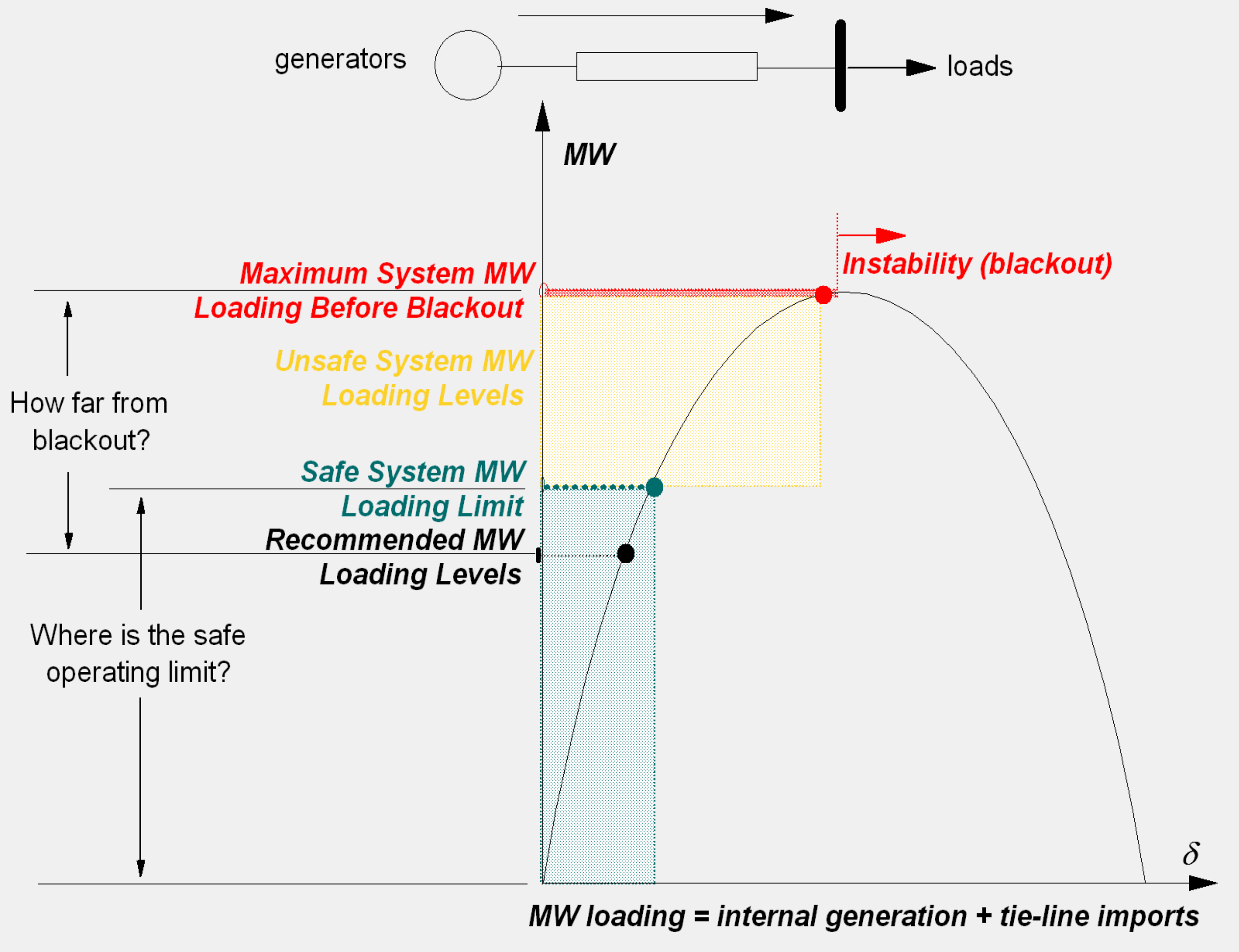
the system *was found to be stable for* *__all__* *possible disturbances* at the "actual MW" loading

Line and / or generation outages have reduced the theoretical value of SSSL

assuming that *all the states below TSL were found to be stable for all possible contingencies*, when MW > TSL there will be at least one contingency that will cause transient instability

Total MW system grid utilization = internal generation + tie-line imports

General Concepts (cont'd)



Energy is transferred from generators to loads across multi-area networks

MW loading = internal generation + tie-line imports

Foundation of the Methodology Used by QuickStab®

- **Field-proven steady-state stability analysis technique developed by Paul Dimo**
    - ☞ *not to be confused with Dimo's REI Equivalents!!*
  - ► **first published in Paris, France, RGE, November 1961**
  - ► **algorithm and equations described in detail in:**
    - ☞ **"Fast Assessment of the Distance to Instability. Theory and Implementation", in *Real Time Stability in Power Systems*, pp. 31-64, Springer Verlag, Norwell, MA, 2006**
  - ► **accuracy documented with detailed numerical example in:**
    - ☞ **"Dimo's Approach to Steady-State Stability Assessment: Methodology Overview and Algorithm Validation", in *Real-Time Stability Assessment in Modern Power System Control Centers*, pp. 320-353, Wiley-IEEE Press, New York, NY, 2009**
  - ► **predicated on the short-circuit currents transformation**
    - **replaces the actual meshed network with a radial network of "short-circuit" admittances**
    - **applied to individual load buses or to an equivalent load center**
    - **allows "seeing" the generators from the load bus (load-center)**

Foundation of the Methodology Used by QuickStab® (cont'd)

- equivalent load-center - Zero Power Balance Network
  - used <u>only</u> for system-wide stability analysis
  - mathematical transformation that merges <u>all</u> the loads (from load buses and generator buses) into a virtual bus where the
    - load is equal to the total system load
    - voltage represents the weighted average of the system bus voltages
  - Felix Wu (1978) demonstrated that this transformation is error free if the loads are "conforming"
- reactive power voltage stability criterion (Bruk-Markovic)
  - replaces eigenvalue calculations with simple computations to detect aperiodic instability
  - applied originally to generators radially connected to a load bus
  - extended by Paul Dimo to the network of short-circuit admittances
- modeling <u>all</u> the generators and tie-line imports
  - constant e.m.f. behind x'_d or x''_d if $Q_{gen} < Q_{max}$, or x_d if $Q_{gen} = Q_{max}$
- ”case worsening” procedure

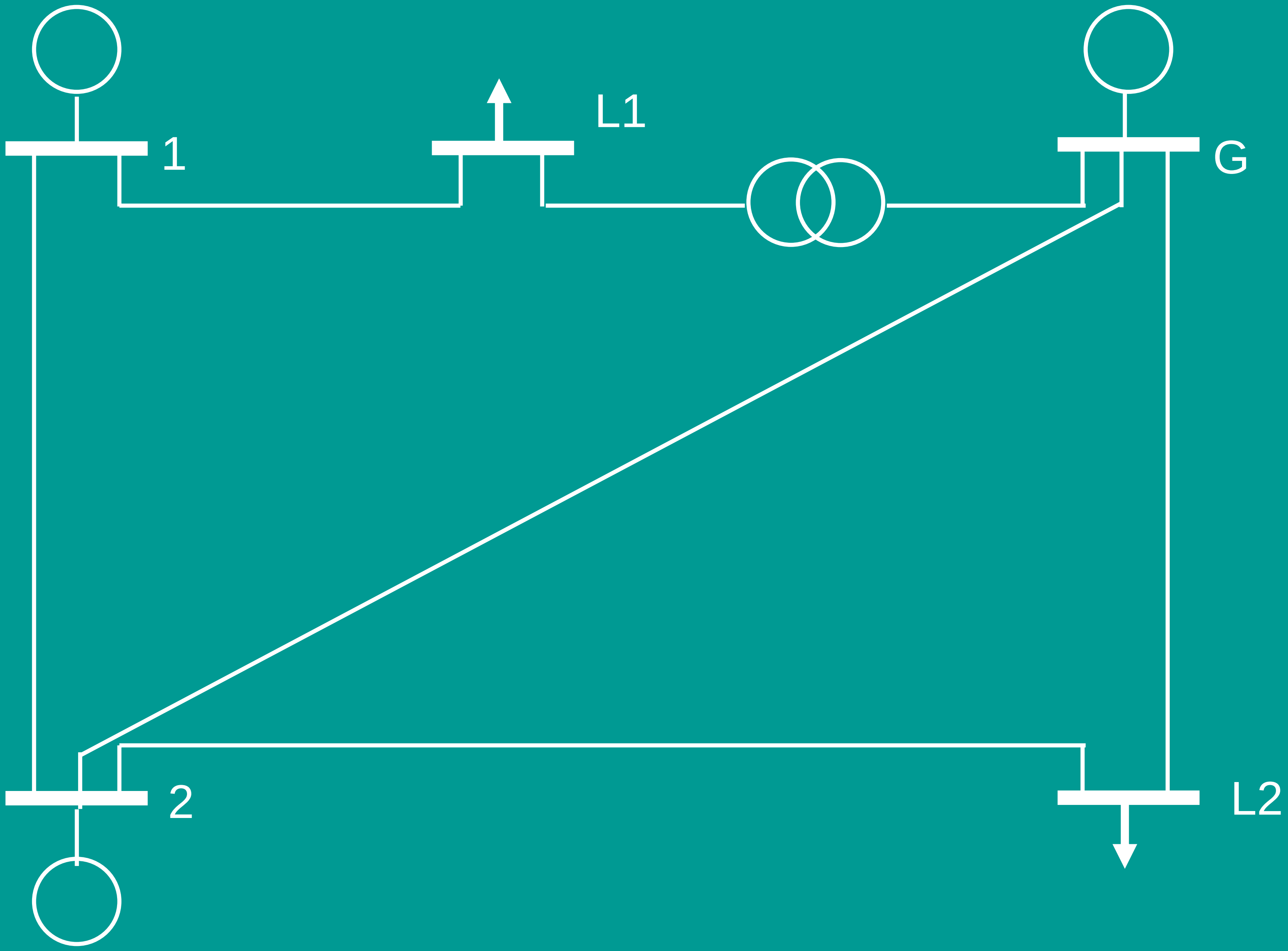
Short-Circuit Currents

- Barbier & Barret (1980)
  - used short-circuit currents to calculate the maximum power transfer from generators to any given load bus
- Paul Dimo (1961)
  - used short-circuit currents to formulate the <u>dQ/dV voltage stability</u> criterion used for
    - bus-level stability analysis
    - system-wide stability analysis
- The generators "seen" from a load bus
  - physically, the currents flow from generators to load
  - mathematically, the generators are connected to each load bus through short-circuit admittances

$I_{eq} = I_{sh\text{-}c} - Y_{sh\text{-}c} V_{load}$ (Barbier-Barret)

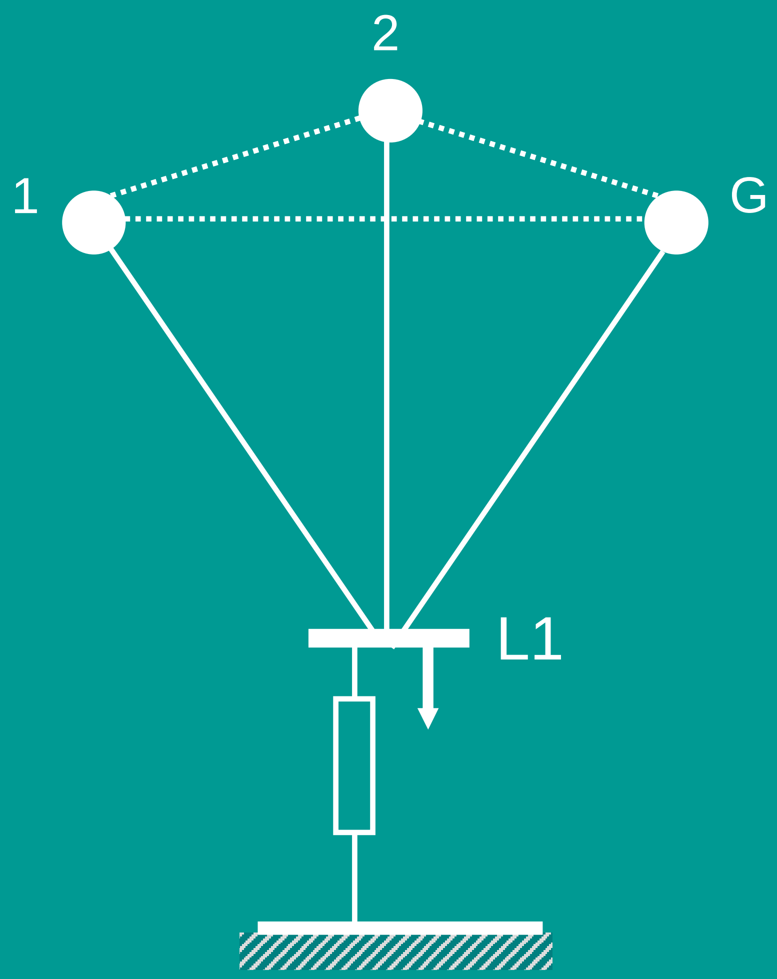
$I_{load} = I_{sh\text{-}c} - I_{sh\text{-}c\ no\text{-}load}$ (Dimo)

Sample Power System

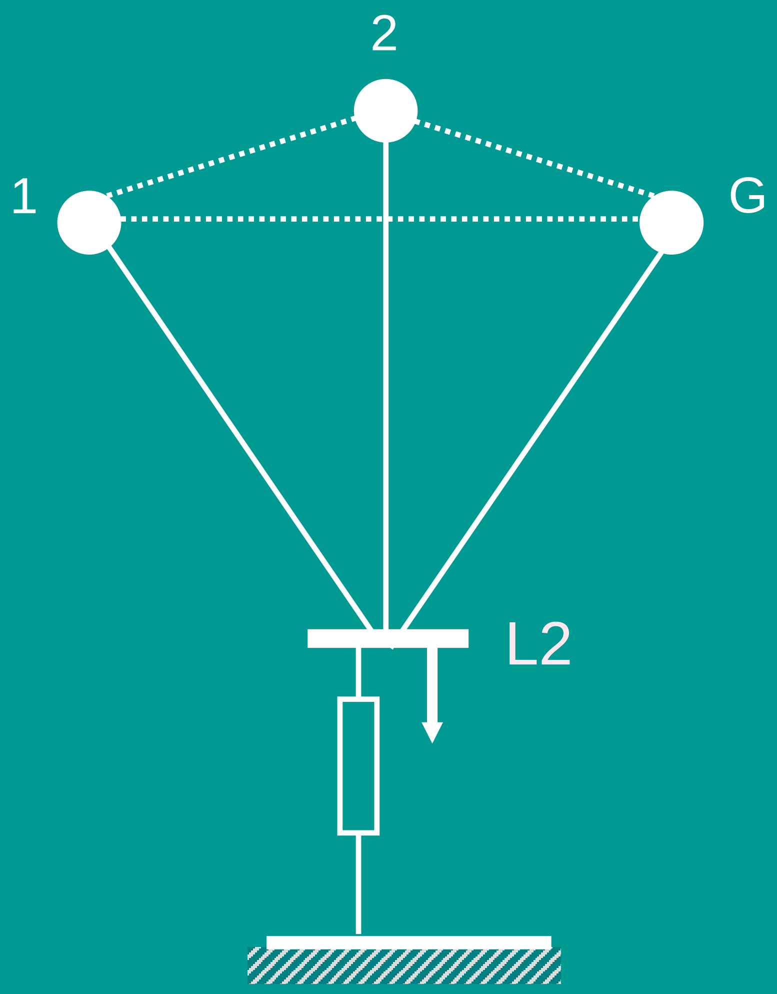


Sample Power System Replaced with the Short-Circuit Currents Model

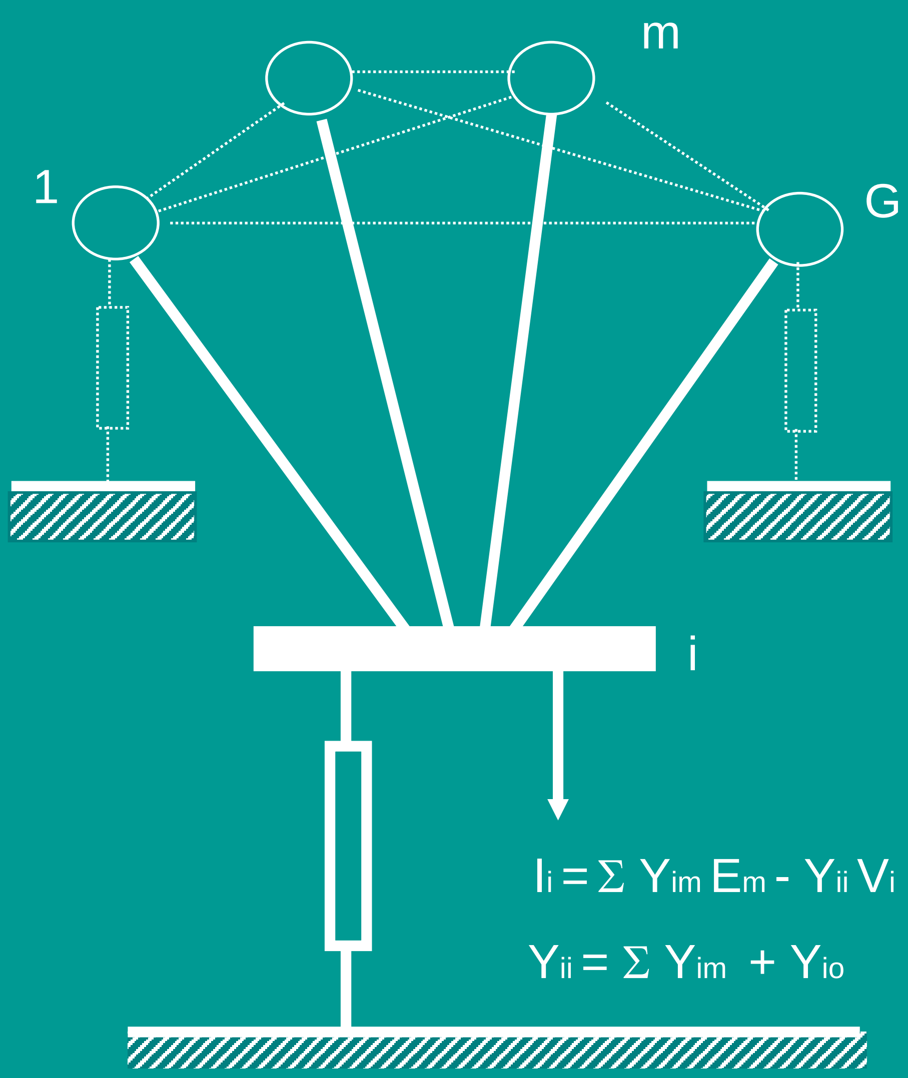
System "seen" from L1



System "seen" from L2

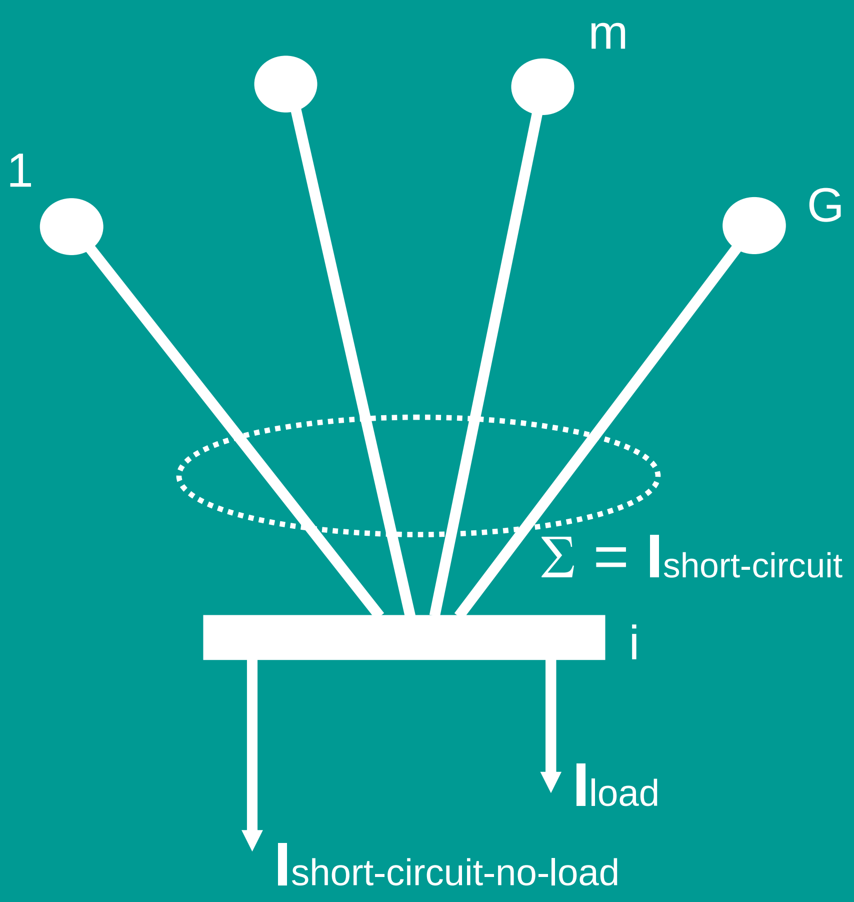


Another View of the
Short-Circuit Currents Model: the REI Net



$$I_i = \Sigma\, Y_{im} E_m - Y_{ii} V_i$$

$$Y_{ii} = \Sigma\, Y_{im} + Y_{io}$$



$$I_i = \Sigma\, Y_{im} E_m - (\Sigma\, Y_{ii} + Y_{io})\, V_i \quad \dashrightarrow$$

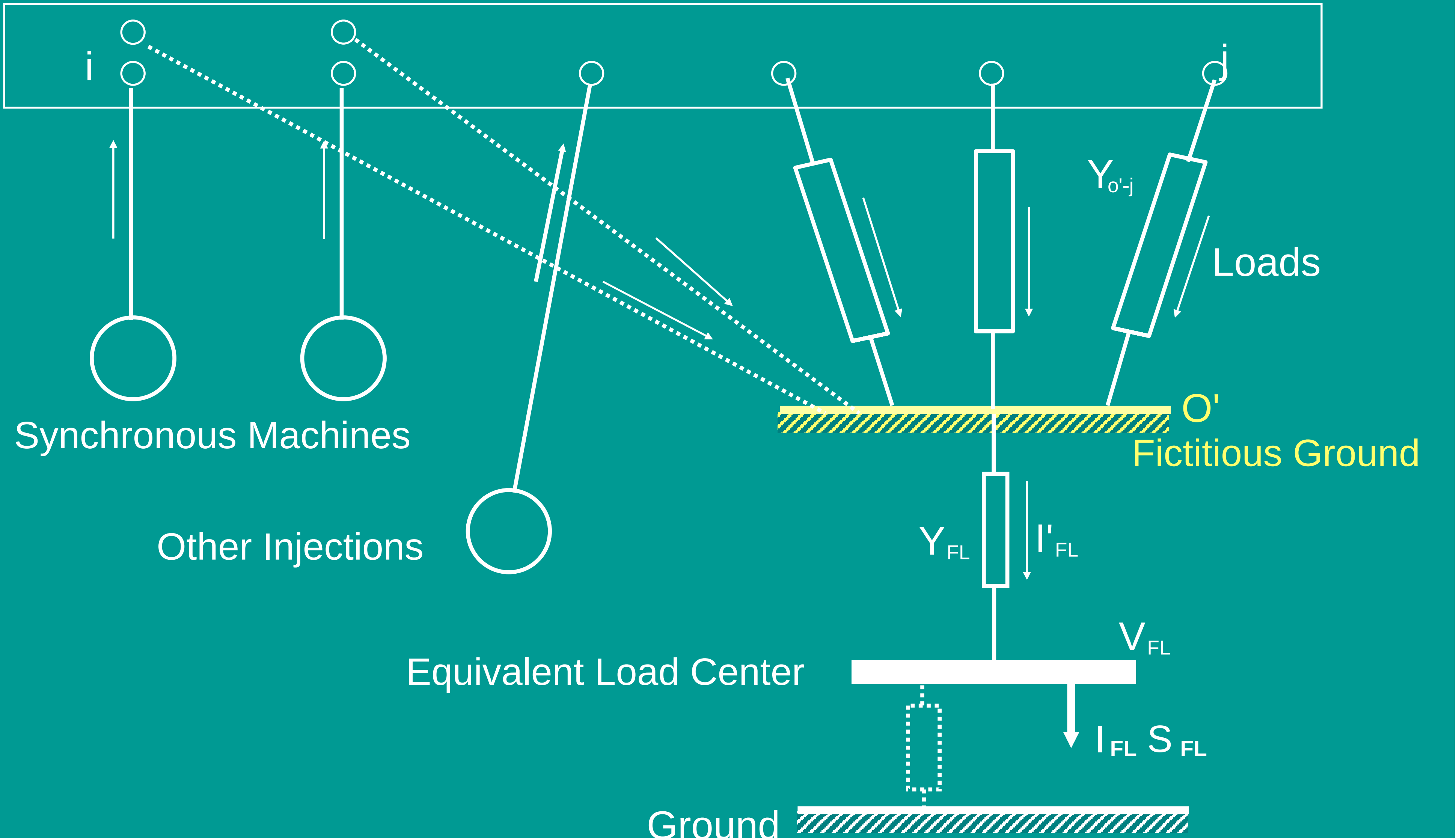
Fallou's Theorem:

$$I_{load} = I_{short\text{-}circuit} - I_{short\text{-}circuit\text{-}no\text{-}load}$$

The Zero Power Balance Network Concept

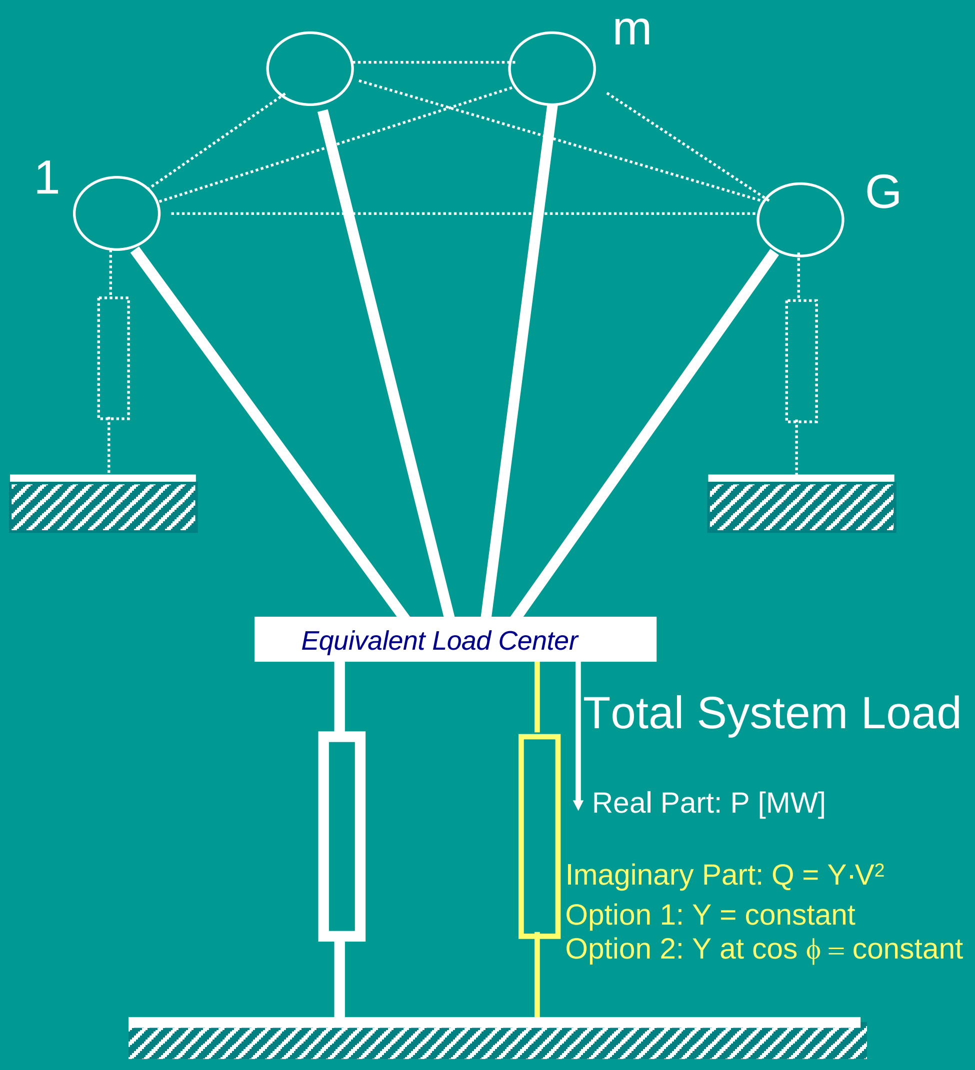
adding a network without losses to obtain an Equivalent Load Center

(used only for system-wide stability analysis)



Short-Circuit Currents Models Used by QuickStab®

System-Wide Stability Analysis



Equivalent Load Center

Total System Load

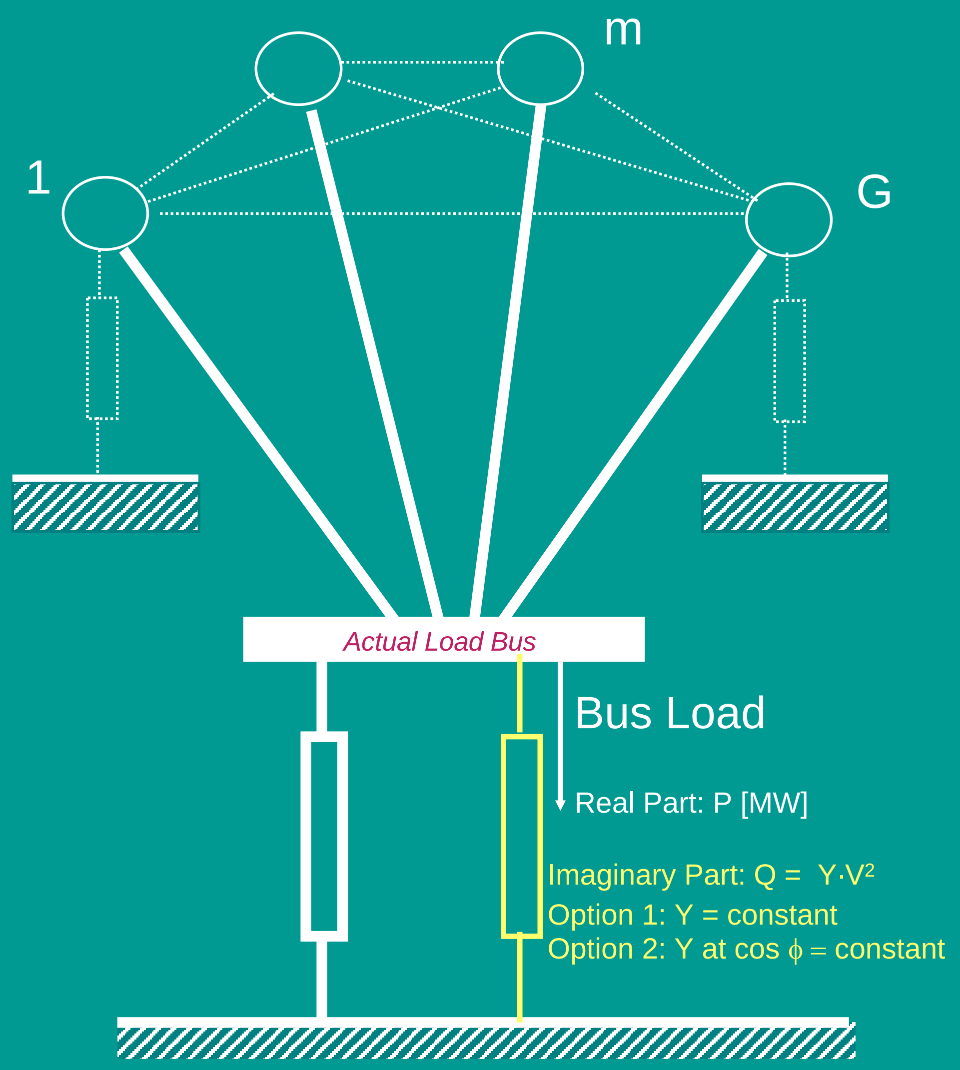
Real Part: P [MW]

Imaginary Part: $Q = Y \cdot V^2$

Option 1: Y = constant

Option 2: Y at $\cos \phi$ = constant

Bus-Level Stability Analysis



Actual Load Bus

Bus Load

Real Part: P [MW]

Imaginary Part: $Q = Y \cdot V^2$

Option 1: Y = constant

Option 2: Y at $\cos \phi$ = constant

Steady-State Stability Criteria

- **Steady-state stability analysis***
  - ▸ **describe the transient processes via nonlinear differential equations**
  - ▸ **obtain the characteristic (principal) determinant**
  - ▸ **determine the roots of the characteristic equation**
    - **if at least one real root > 0 -- <u>aperiodic</u> instability**
    - **if at least one complex root has the real part > 0 -- oscillatory instability (self oscillations)**
  - ▸ **necessary & sufficient condition for steady state stability**
    - ☞ ***for all the roots of the characteristic equation: real part < 0***
  - ▸ **solution is very laborious**
    - **replaced by determining relations between the roots and the coefficients of the characteristic equation**

** Further reading: V. A. Venikov, "Transient Processes in Electrical Power Systems", MIR Publishers, Moscow, 1977*

Steady-State Stability Criteria (cont'd)

- **Steady-state stability criteria***
  - **necessary and sufficient conditions for stability based on the analysis of the <u>coefficients</u> of the characteristic equation (rather than solving it)**
    - **algebraic (Routh-Hurtwitz)***
      - **sets up relations between the coefficients of the characteristic equation in the form of inequalities**
        - **all Routh-Hurwitz determinants have positive signs**
      - **necessary condition: all the coefficients of the characteristic equation be positive**
      - **<u>aperiodic instability</u>: the last (free) term changes the sign with further loading**
    - **frequency-domain (Nyquist)***

** Further reading: <u>V. A. Venikov</u>, "Transient Processes in Electrical Power Systems", MIR Publishers, Moscow, 1977*

<u>P.M. Anderson, A. A. Fouad</u>, "Power System Control and Stability", The Iowa State university press, Ames, IA, 1986

Steady-State Stability Criteria (cont'd)

- **Practical steady-state stability criteria***
  - **derived from simplifying assumptions**
  - **reveal only aperiodic instability**
    - **oscillatory instability undetected**
  - **dP/dδ > 0 -- synchronizing power criterion (Crary)**
    - **constant frequency**
    - **constant turbine power**
    - **constant voltage at nodal point**
  - **dP/dV < 0 -- active power voltage stability (load stability) criterion**
    - **constant e.m.f. of generators**
    - **loads represented as complex impedances**

** Further reading: V. A. Venikov, "Transient Processes in Electrical Power Systems", MIR Publishers, Moscow, 1977*

Steady-State Stability Criteria (cont'd)

  - $d\Delta Q/dV < 0$ -- reactive power voltage stability criterion (Bruk-Markovic)
    - applies when analyzing the stability of a system with a nodal point*
    - constant frequency
    - active power balance maintained at the load node
    - constant e.m.f. behind x'_d or x''_d of generators
- Paul Dimo applied the $d\Delta Q/dV$ voltage stability criterion to the short-circuit currents model
  - radial network of short-circuit admittances, thus matching the requirement of "a system with a nodal point"
  - during the "case worsening procedure", the reactive component of the load varies proportionally with V^2

** Further reading:* *V. A. Venikov, "Transient Processes in Electrical Power Systems", MIR Publishers, Moscow, 1977*

Savulescu, S.C., "Fast Assessment of the Distance to Instability. Theory and Implementation", in Real Time Stability in Power Systems, Springer , 2006

Paul Dimo's Formulation of the Reactive Power Voltage Stability Criterion

*For m generators connected radially to a load bus through short-circuit admittances, dQ/dV can be computed with the formula developed by Paul Dimo**

$$dQ/dV = \Sigma(Y_m E_m / \cos\delta_m) - 2(\Sigma Y_m + Y_{load})V$$

Y_{load} $= Q_{load} / V^2$

E_m = e.m.f. behind transient or synchronous reactance of the machine m

δ_m = internal angle of machine m

Y_m = admittance between machine m and the single-load bus

V = voltage magnitude at the single-load bus

** Further reading: Savulescu, S.C., "Fast Assessment of the Distance to Instability. Theory and Implementation", in Real Time Stability in Power Systems, Springer , 2006*

Representation of Generators

- Machines are modeled via x'_d or x''_d reactances
  - synchronous machine models (V.A. Venikov)
    - *FAVC - fast action voltage controllers*
      - constant voltage on machine's terminals
      - internal reactance = 0 (power-flow model)
    - *PAVC - proportional action controllers*
      - constant E' (E") behind transient reactance x'_d (x''_d)
      - classical machine theory
- Monitor the MVAr output of each generator
  - units on the maximum excitation current when the generated MW = P_{max} may cause instability *
    - ☞ ***replace x'_d (x''_d) with x_d for generators where $Q = Q_{max}$ and $P = P_{max}$***

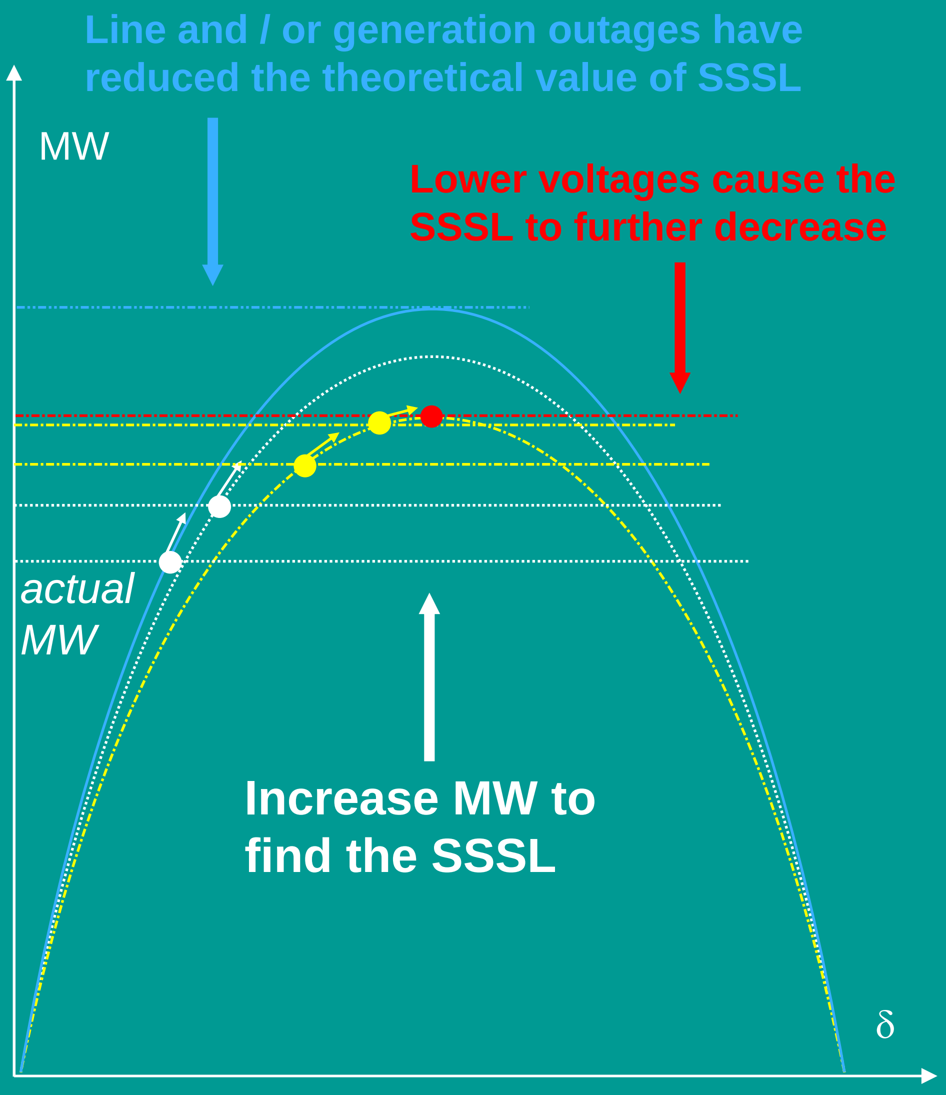
- *Further reading:* *Barbier & Barret (1980)*
  Dobson & Liu (1993)
  Van Cutsem (1993)

Case Worsening Procedure

Algorithm:

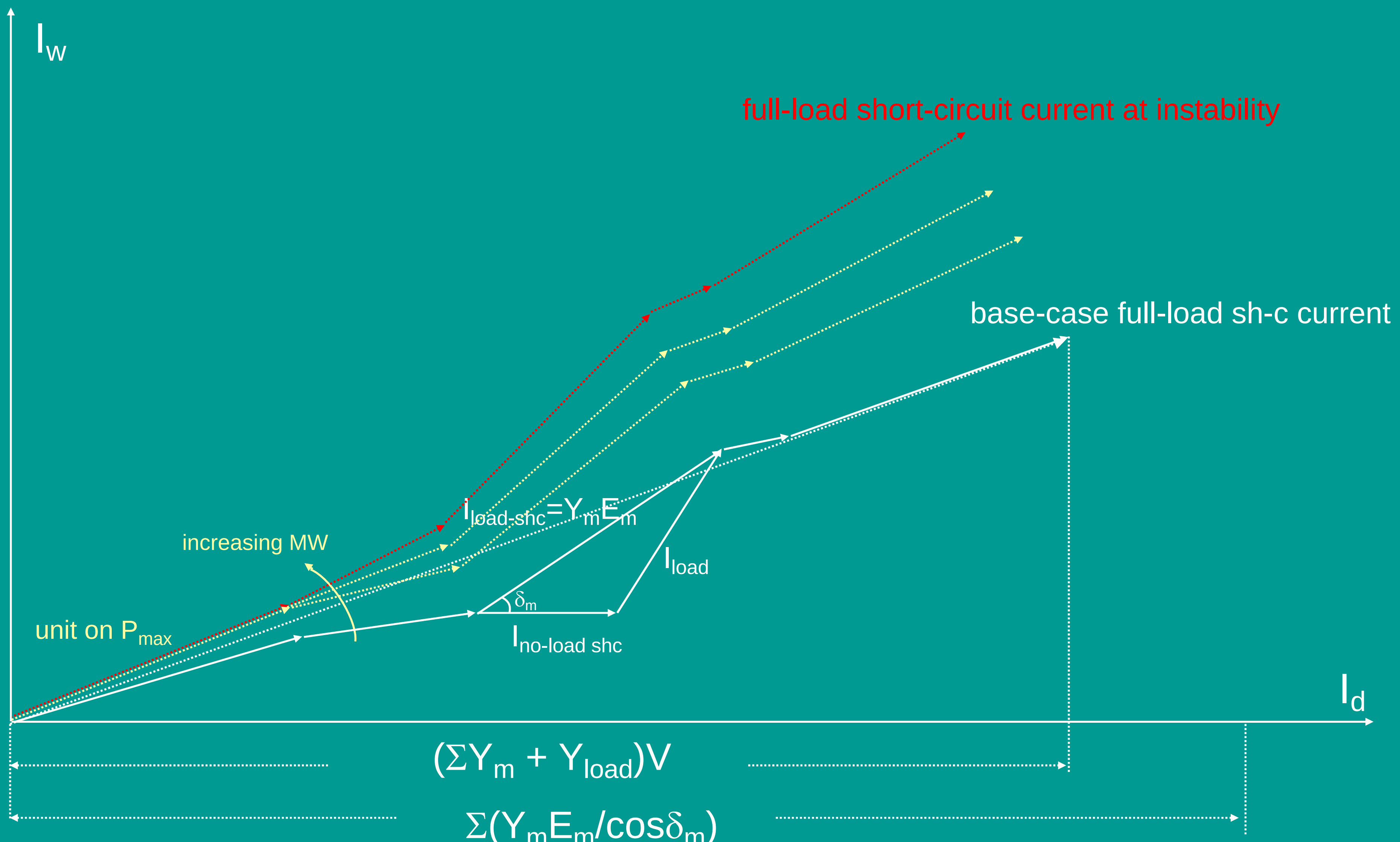
- evaluate "steady-state stability" for the current system state (base case)
  - reactive power criterion for voltage stability
- "worsen the case" by increasing the MW (generation + tie-line imports) while allowing the
  - voltages to decay
  - generators to increase the MVAr
- monitor generators to identify machines on max MVAr (maximum excitation limit) and /or on max MW
- reapply the reactive power stability criterion for the degraded case
- continue to alternate <u>case worsening calculations</u> and <u>voltage stability checks until SSSL has</u> been reached
- developed originally by Paul Dimo in Europe in early 1960s
- used by QuickStab® Professional

The "Case Worsening" Concept



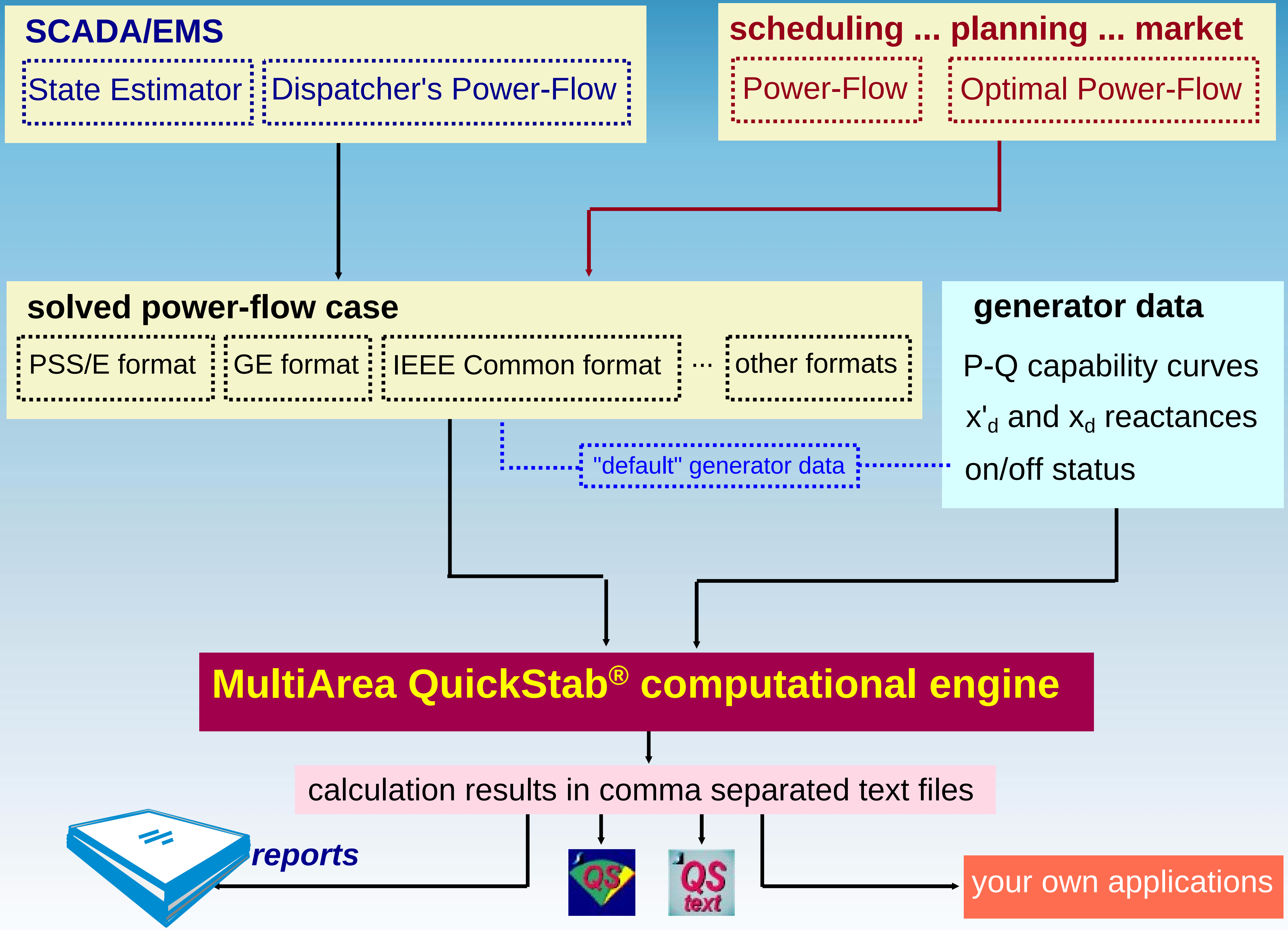
Total MW system grid utilization = internal generation + tie-line imports

Case Worsening Procedure (cont'd)



$$dQ/dV = \Sigma(Y_m E_m/\cos\delta m) - 2(\Sigma Y_m + Y_{load})V$$

QuickStab® Implementation



SCADA/EMS

State Estimator

Dispatcher's Power-Flow

scheduling ... planning ... market

Power-Flow

Optimal Power-Flow

solved power-flow case

PSS/E format

GE format

IEEE Common format

···

other formats

generator data

P-Q capability curves

x'_d and x_d reactances

on/off status

"default" generator data

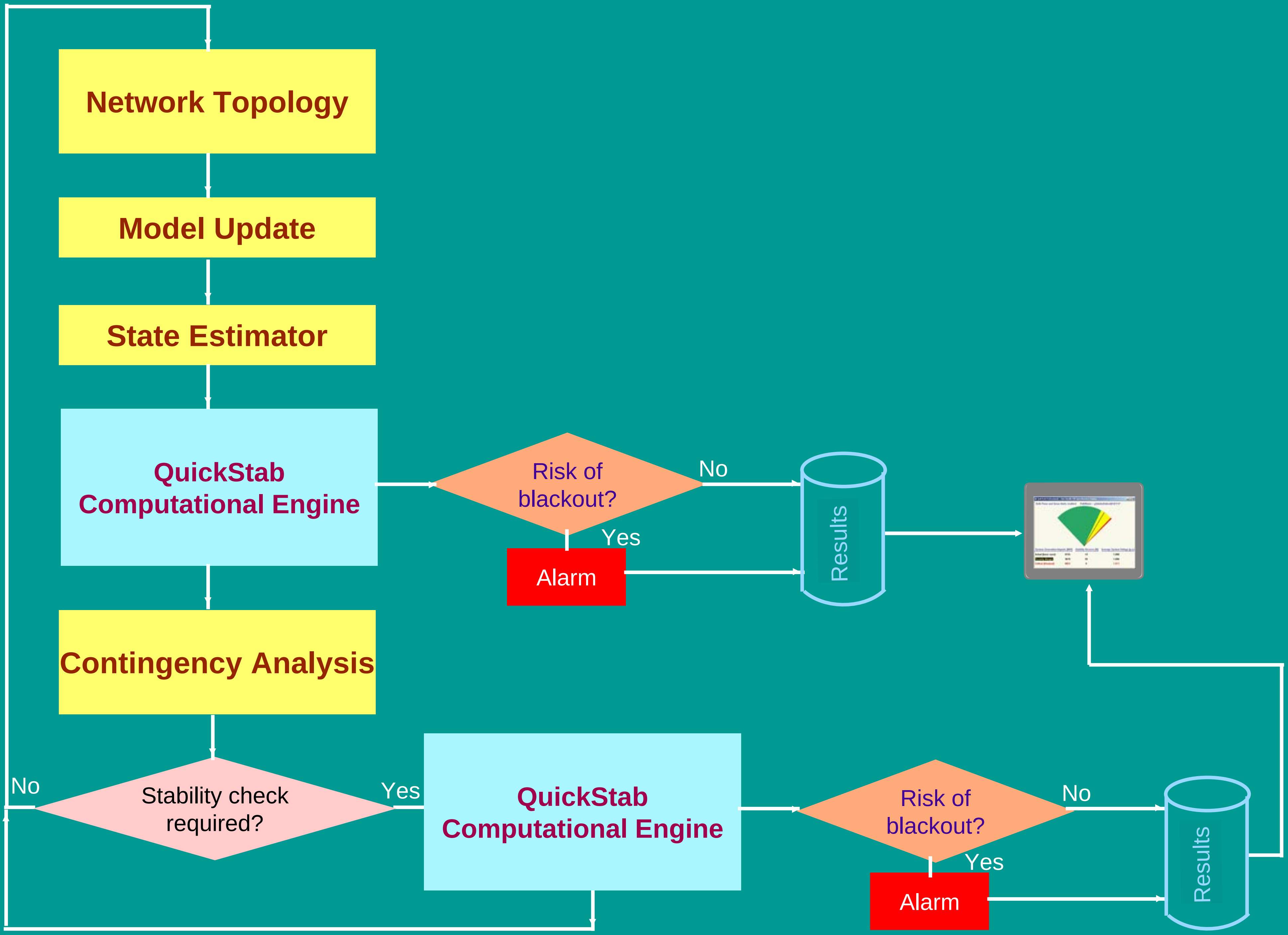
MultiArea QuickStab® computational engine

calculation results in comma separated text files

reports

your own applications

QuickStab® Implementation in Real-Time



Network Topology

Model Update

State Estimator

QuickStab Computational Engine

Risk of blackout?

No

Yes

Alarm

Results

Contingency Analysis

Stability check required?

No

Yes

QuickStab Computational Engine

Risk of blackout?

No

Yes

Alarm

Results