OPF Models for Power System Security Control

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Index

Research topic

- Procedures to help system operators to guarantee power system security in the context of real-time operation

Power system security

- The ability of a power system to reach acceptable steady-state operating conditions after being subjected to sudden disturbances
- The power system should not be forced to uncontrolled cascading outages that can lead the system to a blackout

Power system security

To reduce the risk of blackouts:

- no equipment is overloaded
- all bus voltage magnitudes are within appropriate limits
- stable operation after plausible contingencies

Motivation

- Market clearing procedures do not explicitly consider security issues
- System operator must check system security and implement control actions if needed
  - Security assessment: state of the system under contingencies
  - Contingency filtering: identification of critical contingencies
  - Security control: design of control actions to improve the system security level

Motivation

- Control actions $\rightarrow$ adjustments with respect to the market solution:
  - Adjustments in the generator power outputs
  - Adjustments in the demand powers
  - Adjustments in the set points of system control devices
- Security control tool $\rightarrow$ Optimal Power Flow (OPF)

Motivation

- Market participants expect that the security control minimally modifies the market solution

- Security-constrained OPF requires:
  - To model the system behavior and stability constraints in detail
  - To deal with non-linear models and advanced stability concepts
  - To marry time-domain simulations and optimization

- Need to incorporate security constraints in the OPF problem

Proposed procedures

OPF-based control tools to assist system operators in avoiding security problems related to:

- Voltage instability
- Small-signal instability
- Transient instability

Proposed procedures

- Starting point → market dispatching solution adjusted by losses

- Security assessment procedures
- Contingency filtering procedures
- Security control procedures: OPF problems with stability constraints

Index

Definition of voltage stability

Voltage stability

The ability of a power system to maintain steady voltages at all buses throughout the system after suffering a disturbance from a given initial operating condition

Voltage collapse

The process by which the sequence of events accompanying voltage instability leads to a blackout or to abnormally low voltages in a significant part of the power system

Voltage stability analysis

System model:

$$\boldsymbol{g}(\boldsymbol{y}, \boldsymbol{p}) = \boldsymbol{0}$$

where

- $\boldsymbol{y}$: algebraic variables (e.g, voltage magnitudes at load buses)
- $\boldsymbol{p}$: control variables (e.g, generator power outputs)
- $\boldsymbol{g}$: power flow equations

Voltage stability analysis
Bifurcation theory

System model:

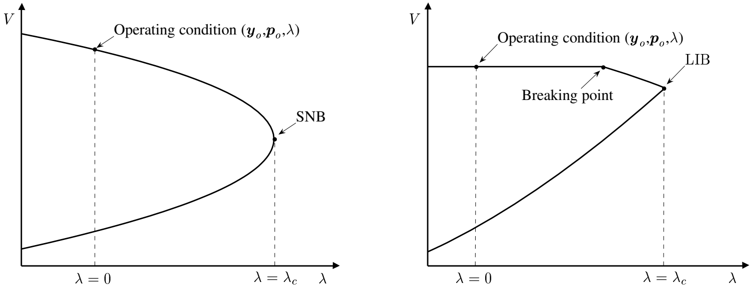
$$\boldsymbol{g}(\boldsymbol{y}, \boldsymbol{p}) \rightarrow \boldsymbol{g}(\boldsymbol{y}, \boldsymbol{p}, \lambda)$$

where λ usually represents changes in system load:

$$P_{\mathrm{D}i} = (1+\lambda) P_{\mathrm{D}i}^{\mathrm{A}}, \quad \forall i \in \mathcal{D}$$
$$Q_{\mathrm{D}i} = (1+\lambda) Q_{\mathrm{D}i}^{\mathrm{A}}, \quad \forall i \in \mathcal{D}$$

- Parameter λ changes “slowly”
- Voltage instability conditions:
  - Saddle-node bifurcations (SNB)
  - Limit-induced bifurcations (LIB)

Voltage stability analysis
Bifurcation theory



(a) Saddle-node bifurcation (b) Limit-induced bifurcation

Voltage stability assessment

Loading margin

Maximum amount of additional load that the system can provide until a voltage stability limit (SNB or a critical LIB) is reached

Loading margin λ^*

Maximum amount of additional load that the system can provide without exceeding a technical limit and ensuring that a voltage collapse does not appear within a given period of time

- Loading margin computation $\rightarrow$ Maximum loading condition problem

Security assessment related to voltage stability

- Security assessment $\rightarrow$ computation of the loading margin λ^* for post-contingency system configurations
- System operator specifies:
  - Initial set of contingencies $\rightarrow$ $N-1$ criterion
  - Time period Δt
- Loading margin λ^* is computed for each contingency of the initial set

Contingency filtering related to voltage stability

- System operator specifies:
  - Security margin λ^{SM}

- Contingency filtering criterion:
  - If $\lambda^* \leq \lambda^{\mathrm{SM}}$, the contingency is selected as critical. At the loading condition defined by λ^{SM} the system exhibits potential voltage instability.
  - If $\lambda^* > \lambda^{\mathrm{SM}}$, the contingency is filtered out

VSC-OPF problem

Minimize

- Cost of adjustments with respect to the base case solution

subject to

- Power flow equations for the adjusted operating condition
- Power flow equations under stressed operating conditions
- Technical limits
- Ramping constraints

VSC-OPF - Constraints

Power flow equations for the adjusted operating condition

- Power balance at all system buses
- Generator powers:

$$P_{\mathrm{G}j} = P_{\mathrm{G}j}^{\mathrm{A}} + \Delta P_{\mathrm{G}j}^{\mathrm{up}} - \Delta P_{\mathrm{G}j}^{\mathrm{down}}, \quad \forall j \in \mathcal{G}$$

with

$$\Delta P_{\mathrm{G}j}^{\mathrm{up}} \geq 0, \quad \forall j \in \mathcal{G}$$
$$\Delta P_{\mathrm{G}j}^{\mathrm{down}} \geq 0, \quad \forall j \in \mathcal{G}$$

Superscript “A” indicates base-case solution

VSC-OPF - Constraints

Power flow equations for the adjusted operating condition

- Demand powers:

$$P_{\mathrm{D}i} = P_{\mathrm{D}i}^{\mathrm{A}} - \Delta P_{\mathrm{D}i}, \quad \forall i \in \mathcal{D}$$
$$Q_{\mathrm{D}i} = P_{\mathrm{D}i} \tan(\psi_{\mathrm{D}i}), \quad \forall i \in \mathcal{D}$$

with

$$\Delta P_{\mathrm{D}i} \geq 0, \quad \forall i \in \mathcal{D}$$

Superscript “A” indicates base-case solution

VSC-OPF - Constraints

Power flow equations under stressed operating conditions

As many stressed operating conditions are included in the VSC-OPF problem as critical contingencies identified in the contingency filtering procedure

- Power balance at all system buses
- The line that corresponds to the critical contingency is removed
- The demand is increased according to the security margin λ^{SM}

$$P_{\mathrm{D}i}^{s} = (1+\lambda^{\mathrm{SM}})P_{\mathrm{D}i} \quad \forall i \in \mathcal{D}, \quad \forall s \in \mathcal{S}$$
$$Q_{\mathrm{D}i}^{s} = (1+\lambda^{\mathrm{SM}})P_{\mathrm{D}i}\tan(\psi_{\mathrm{D}i}), \quad \forall n \in \mathcal{D}, \quad \forall s \in \mathcal{S}$$

where $P_{\mathrm{D}i}$ corresponds to the adjusted operating condition

VSC-OPF - Constraints

Power flow equations under stressed operating conditions

- Generator powers:

$$P_{\mathrm{G}j}^{s} = P_{\mathrm{G}j} + \Delta P_{\mathrm{G}j}^{\mathrm{up},s} - \Delta P_{\mathrm{G}j}^{\mathrm{down},s}, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}$$

with

$$\Delta P_{\mathrm{G}j}^{\mathrm{up},s} \geq 0, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}$$
$$\Delta P_{\mathrm{G}j}^{\mathrm{down},s} \geq 0, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}$$

where $P_{\mathrm{G}j}$ corresponds to the adjusted operating condition

VSC-OPF - Constraints
Technical limits

For the adjusted and stressed systems:

- Maximum and minimum power output of generators
- Maximum and minimum reactive power limit of generators
- Maximum and minimum voltage magnitude at system buses
- Maximum current magnitude through system branches

VSC-OPF - Constraints
Ramping limits

- Ramping limits for generators:

$$P_{\mathrm{G}j}^{s} - P_{\mathrm{G}j} \leq R_{\mathrm{G}j}^{\mathrm{up}} \Delta t, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}$$

$$P_{\mathrm{G}j} - P_{\mathrm{G}j}^{s} \leq R_{\mathrm{G}j}^{\mathrm{down}} \Delta t, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}$$

Proposed redispatching procedure

1 - Base case operating condition:
- Market dispatch solution adjusted by losses

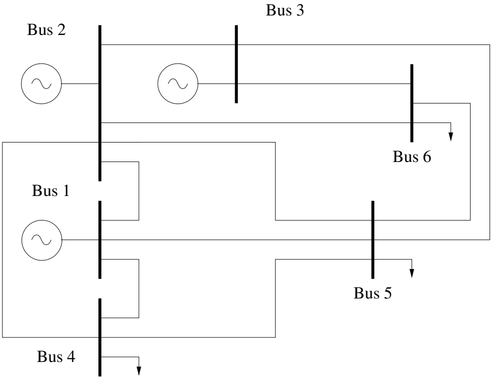
2 - Security assessment:
- Initial set of contingencies: $N - 1$ contingency criterion
- Computation of loading margins λ^*

3 - Contingency filtering:
- Comparison of loading margins λ^* with the required security margin λ^{SM}

4 - Stressed operating conditions for the VSC-OPF problem:
- One stressed condition per critical contingency
- The system load is increased by λ^{SM} for all stressed systems

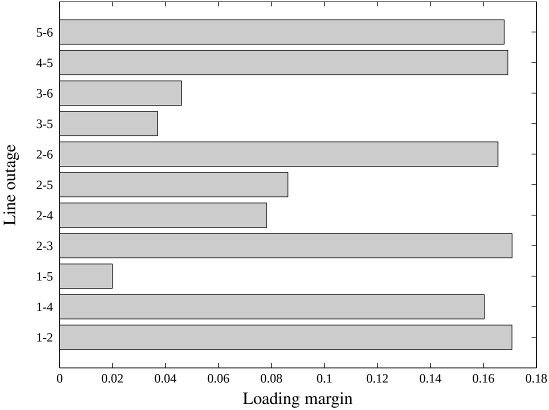
5 - Solve the VSC-OPF problem

Illustrative example: W&W 6-bus system



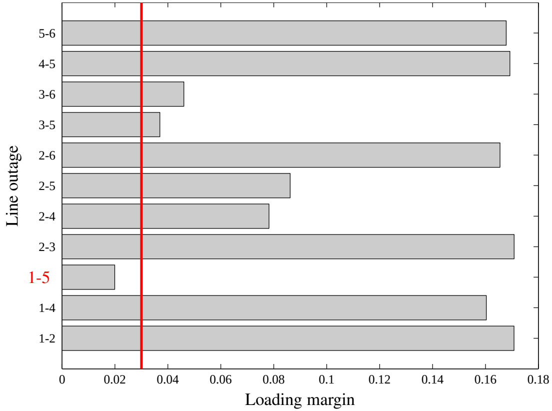
Illustrative example: W&W 6-bus system
Security assessment

- Computation of system loading margins



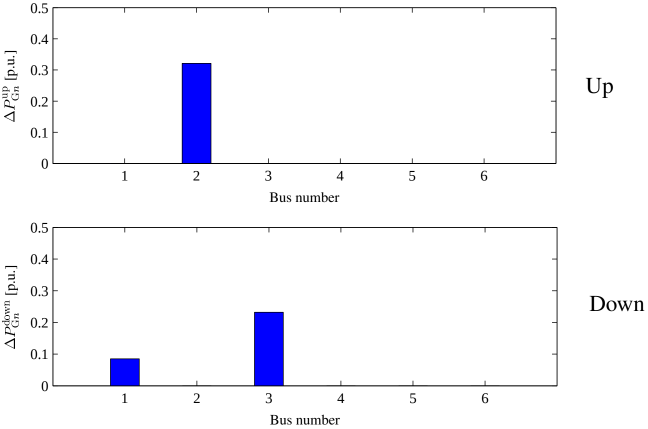
Illustrative example: W&W 6-bus system
Contingency filtering

- Security margin: $\lambda^{\text{SM}} = 0.03$



Illustrative example: W&W 6-bus system
Solution to the VSC-OPF problem

- Generation redispatching for $\lambda^{\mathrm{SM}} = 0.03$



Index

Definition of small-signal stability

Small-signal (rotor-angle) stability

The ability of a power system to maintain synchronism under small disturbances

Undamped rotor angle oscillations

- Local mode oscillations
- Inter-area mode oscillations

Small-signal stability analysis

System model $\rightarrow$ DAE system:

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}) \\ \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}) \end{bmatrix}$$

where

- $\boldsymbol{x}$: state variables (e.g, machine rotor angles)
- $\boldsymbol{y}$: algebraic variables (e.g, voltage magnitude at load buses)
- $\boldsymbol{p}$: control variables (e.g, generator power outputs)
- $\boldsymbol{f}$: equations related to state variables (e.g., synchronous machine equations)
- $\boldsymbol{g}$: algebraic equations (e.g., power flow equations)

Small-signal stability analysis

System equilibrium point:

- The system is at steady-state
- Control variables $\boldsymbol{p}_o$ are known
- Remaining variables $(\boldsymbol{x}_o, \boldsymbol{y}_o)$ are obtained by solving:

$$\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}(\boldsymbol{x}_o, \boldsymbol{y}_o, \boldsymbol{p}_o) \\ \boldsymbol{g}(\boldsymbol{x}_o, \boldsymbol{y}_o, \boldsymbol{p}_o) \end{bmatrix}$$

Small-signal stability analysis

Linearization of DAE system at $(\boldsymbol{x}_o, \boldsymbol{y}_o)$:

$$\begin{bmatrix} \Delta\dot{\boldsymbol{x}} \\ \boldsymbol{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{D_x f} & \boldsymbol{D_y f} \\ \boldsymbol{D_x g} & \boldsymbol{D_y g} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{x} \\ \Delta\boldsymbol{y} \end{bmatrix}$$

System state matrix:

$$\boldsymbol{A}_{\text{sys}} = \boldsymbol{D_x f} - \boldsymbol{D_y f}\left[\boldsymbol{D_y g}\right]^{-1}\boldsymbol{D_x g}$$

Small-signal stability assessment

Eigenvalue analysis of $\boldsymbol{A}_{\text{sys}} \rightarrow$ Lyapunov's first method:

- If all eigenvalues of matrix $\boldsymbol{A}_{\text{sys}}$ have negative real parts, the system equilibrium point is asymptotically stable
- If at least one of the eigenvalues of matrix $\boldsymbol{A}_{\text{sys}}$ has a positive real part, the system equilibrium point is unstable

Small-signal stability assessment
Bifurcation theory

System model:

$$\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}) \to \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}, \lambda)$$
$$\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}) \to \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}, \lambda)$$

- Parameter λ changes “slowly”
- Small-signal rotor angle instability conditions:
  - Hopf bifurcations (HB)

Small-signal stability assessment
Bifurcation theory

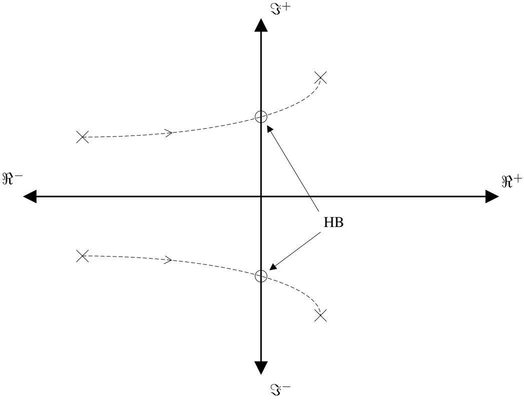


Figure : Hopf bifurcation in the complex plane

Security assessment related to small-signal stability

- Security assessment $\rightarrow$ computation of the loading margin λ^* for post-contingency system configurations + eigenvalue analysis of the state matrix for the maximum loading conditions
- System operator specifies:
  - Initial set of contingencies $\rightarrow N-1$ criterion
  - Time period Δt
- Loading margin λ^* is computed for each contingency of the initial set
- Eigenvalue analysis is performed for the maximum loading conditions
- Critical eigenvalues $\alpha \pm j\beta$ are calculated

Contingency filtering related to small-signal stability

- System operator specifies:
  - Security margin λ^{SM}
- Contingency filtering criterion:
  - If $\lambda^* \leq \lambda^{\mathrm{SM}}$, the contingency is selected as critical. At the loading condition defined by λ^{SM} the system exhibits potential voltage instability
  - If $\alpha > 0$, the contingency is selected as critical. At the loading condition defined by λ^{SM}, the system may suffer from small-signal instability
  - If $\lambda^* > \lambda^{\mathrm{SM}}$ and $\alpha < 0$, the contingency is filtered out

SSSC-OPF problem

Minimize

- Cost of adjustments with respect to the base case solution

subject to

- Power flow equations for the adjusted operating condition
- Power flow equations under stressed operating conditions
- Technical limits
- Ramping constraints
- Small-signal stability constraints

SSC-OPF problem
Small-signal stability constraints

- First order Taylor series expansion of $\alpha^s(P_{\mathrm{G}}^s)$
- Resulting constraint:

$$\alpha^s + F^s \sum_{j \in \mathcal{G}} \left.\frac{\partial \alpha^s}{\partial P_{\mathrm{G}j}^s}\right|_{\mathrm{u}} (P_{\mathrm{G}j}^s - P_{\mathrm{G}j}^{s,\mathrm{u}}) \leq \alpha^{\max}, \quad \forall s \in \mathcal{S}_{\mathrm{u}}$$

where:

- α^s: actual value of the real part of the critical eigenvalue
- $\left.\frac{\partial \alpha^s}{\partial P_{\mathrm{G}j}^s}\right|_{\mathrm{u}}$: sensitivity of α^s with respect to $P_{\mathrm{G}j}^s$
- F^s: scaling factor introduced to limit the size of $(P_{\mathrm{G}j}^s - P_{\mathrm{G}j}^{s,\mathrm{u}})$
- $\alpha^{\max}$: upper limit for the real part of the critical eigenvalue

SSSC-OPF problem
Small-signal stability constraints

- The variations in generator powers must be always consistent with the signs of the sensitivities:

$$P_{\mathrm{G}j}^{s} - P_{\mathrm{G}j}^{s,\mathrm{u}} \geq 0 \quad \text{if} \quad \frac{\partial \alpha^{s}}{\partial P_{\mathrm{G}j}^{s}} < 0, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}_{\mathrm{u}}$$

$$P_{\mathrm{G}j}^{s} - P_{\mathrm{G}j}^{s,\mathrm{u}} \leq 0 \quad \text{if} \quad \frac{\partial \alpha^{s}}{\partial P_{\mathrm{G}j}^{s}} > 0, \quad \forall j \in \mathcal{G}, \quad \forall s \in \mathcal{S}_{\mathrm{u}}$$

Proposed redispatching procedure

1 - Base case operating condition:
- Market dispatch solution adjusted by losses

2 - Security assessment:
- Initial set of contingencies: $N - 1$ contingency criterion
- Computation of loading margins λ^*
- Eigenvalue analysis at the maximum loading condition

3 - Contingency filtering:
- Comparison of loading margins λ^* with the require security margin λ^{SM}
- Inspection of critical eigenvalues

4 - Stressed operating conditions for the SSSC-OPF problem:
- One stressed condition per critical contingency
- The system load is increased by λ^{SM} for all stressed systems

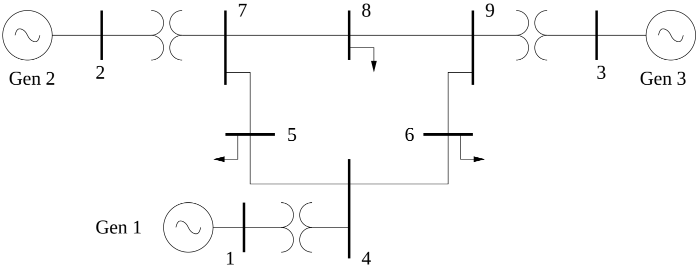
Proposed redispatching procedure

5 - Solve the SSSC-OPF problem

6 - Checking the solution:

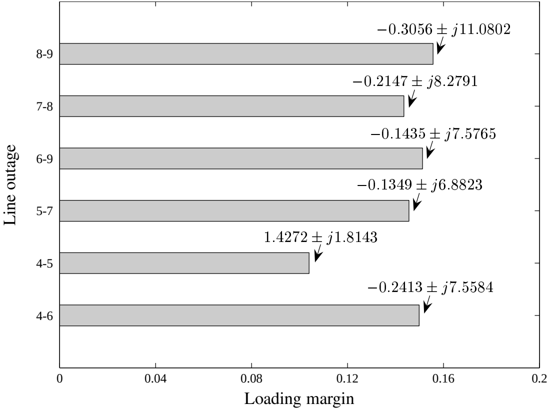
- Eigenvalue analysis of the stressed operating conditions
- If one or more stressed conditions show small-signal instability:
  - Sensitivity computation
  - Small-signal stability constraints are incorporated to the SSSC-OPF problem
  - The procedure continues in step 5
- If all stressed conditions are stable the procedure stops

Illustrative example: WECC 9-bus, 3-machine system



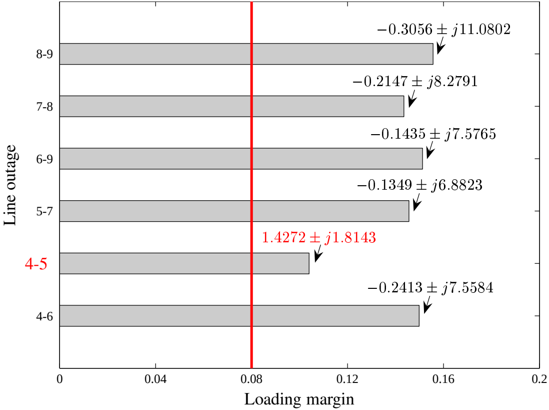
Illustrative example: WECC 9-bus, 3-machine system
Security assessment

- Computation of system loading margins + eigenvalue analysis



Illustrative example: WECC 9-bus, 3-machine system
Contingency filtering

- Security margin: $\lambda^{\text{SM}} = 0.08$



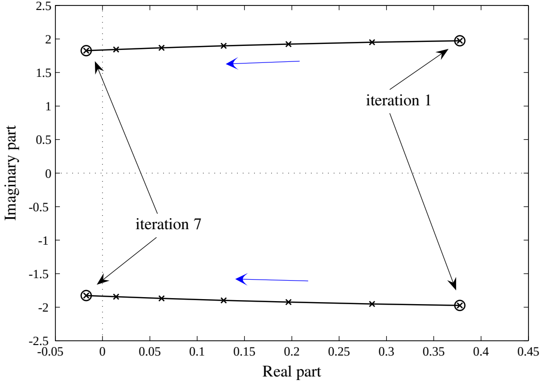
Illustrative example: WECC 9-bus, 3-machine system

First iteration of the procedure

- The stressed condition exhibits small-signal instability:
  - Critical eigenvalue $= 0.3775 \pm j1.9729$
- Sensitivities are computed
- Small-signal stability constraints are incorporated into the OPF problem
- SSSC-OPF problem is solved again

Illustrative example: WECC 9-bus, 3-machine system
Procedure iterations

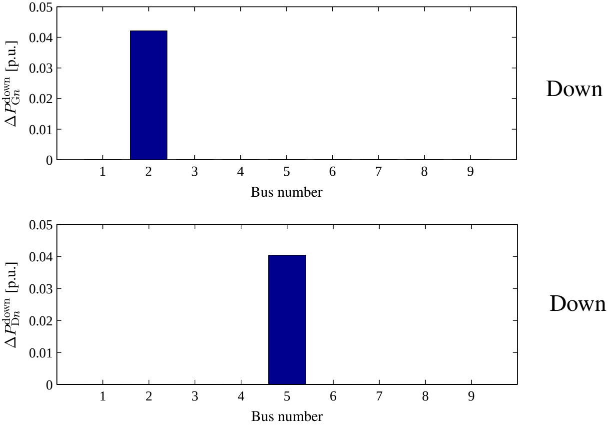
- Evolution of the critical eigenvalue in the complex plain



Illustrative example: WECC 9-bus, 3-machine system

Procedure solution

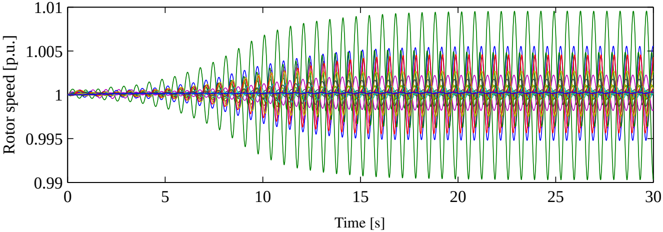
- Redispatching actions

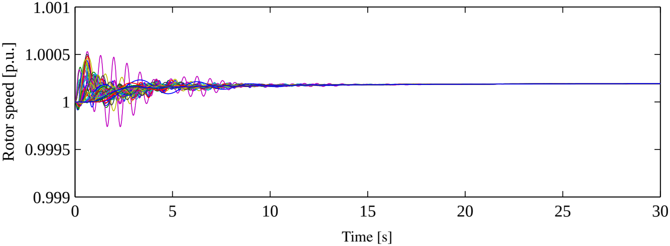


Case study: IEEE 145-bus, 50-machine system

- Security assessment: 434 contingencies analyzed
- Contingency filtering for $\lambda^{\mathrm{SM}} = 0.05$:
  - Two contingencies selected due to voltage stability issues
  - Three contingencies selected due to small-signal stability issues
- SSSC-OPF problem includes five stressed operating conditions
- First iteration:
  - Only one stressed operating condition shows small-signal instability for $\lambda^{\mathrm{SM}} = 0.05$
- Solution attained after nine iterations:
  - Generator redispatching + load curtailment

Case study: IEEE 145-bus, 50-machine system





Index

Definition of transient stability

Transient stability

The ability of a power system to maintain synchronism after large disturbances

Loss of synchronism

- Aperiodic angular separation of the system machines
  - First-swing instability
  - Multi-swing instability

Transient stability analysis
System model

DAE system:

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}) \\ \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{p}) \end{bmatrix}$$

where

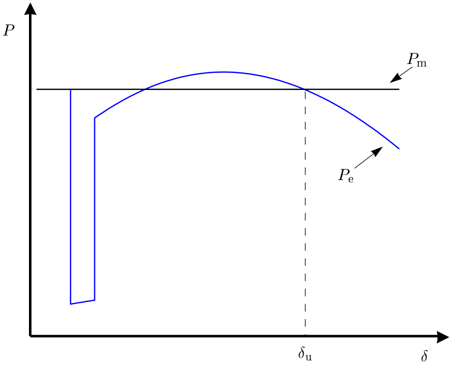
- $\boldsymbol{x}$: state variables (e.g, machine rotor angles)
- $\boldsymbol{y}$: algebraic variables (e.g, voltage magnitudes at load buses)
- $\boldsymbol{p}$: control variables (e.g, generator power outputs)
- $\boldsymbol{f}$: equations related to state variables (e.g., synchronous machine equations)
- $\boldsymbol{g}$: algebraic equations (e.g., power flow equations)

Transient stability assessment
SIME method

- Combines the time-domain simulation and the Equal-Area Criterion (EAC)
- Identifies the separation pattern of the system machines:
  - Group of critical machines
  - Group of non-critical machines
- One-Machine Infinite Bus (OMIB) equivalent system
- Stability of the OMIB equivalent system is checked by using the EAC

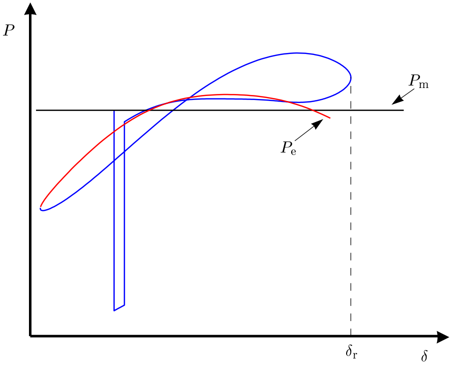
Transient stability assessment
SIME method

- First-swing unstable case



Transient stability assessment
SIME method

- Multi-swing unstable case



Security assessment related to transient stability

- Initial set of contingencies $\rightarrow N - 1$ criterion
- Contingencies analyzed:
  - Three-phase-to-ground symmetrical fault and the subsequent fault clearing by tripping the corresponding line
- Time-domain simulation complemented by the SIME method

Contingency filtering related to transient stability

- Contingency filtering criterion:
  - Either the system exhibits first-swing or multi-swing instability the contingency is selected

- If the system presents first-swing instability:
  - The SIME method provides the OMIB equivalent and the unstable angle δ_{u}

- If the system presents multi-swing instability:
  - The SIME method provides the OMIB equivalent and the return angle δ_{r} in the first-swing

TSC-OPF problem

Minimize

- Cost of adjustments with respect to the base case solution

subject to

- Power flow equations for the adjusted operating condition
- Technical limits
- Transient stability constraints

Transient stability constraints

- Discrete-time equations of the multi-machine system:

$$\delta_j^{t+1} - \delta_j^t - \frac{t_{\rm step}}{2}\omega_{\rm b}(\omega_j^{t+1} - 1 + \omega_j^t - 1) = 0, \quad \forall t \in \mathcal{T}$$

$$\omega_j^{t+1} - \omega_j^t - \frac{t_{\rm step}}{2}\frac{1}{M_j}(P_{{\rm m}j}^{t+1} - P_{{\rm e}j}^{t+1} + P_{{\rm m}j}^t - P_{{\rm e}j}^t) = 0, \quad \forall t \in \mathcal{T}$$

Transient stability constraints

- OMIB rotor angle:

$$\delta^t_{\mathrm{OMIB}} = \frac{1}{M_{\mathrm{C}}} \sum_{j \in \mathcal{G}_{\mathrm{C}}} M_j \delta^t_j - \frac{1}{M_{\mathrm{NC}}} \sum_{j \in \mathcal{G}_{\mathrm{NC}}} M_j \delta^t_j, \quad \forall t \in \mathcal{T}$$

- Limit on the OMIB rotor angle:

$$\delta^t_{\mathrm{OMIB}} \leq \delta^{\max}_{\mathrm{OMIB}}, \quad \forall t \in \mathcal{T}$$

Proposed redispatching procedure

1 - Base case operating condition

2 - Security assessment:
- Initial set of contingencies: $N-1$ contingency criterion
- Time-domain simulation complemented by the SIME method

3 - Contingency filtering:
- First-swing and multi-swing instability contingencies

4 - Transient stability constraints:
- For first-swing instability $\rightarrow \delta_{\mathrm{OMIB}}^{\max} = \delta_{\mathrm{u}}$
- For multi-swing instability $\rightarrow \delta_{\mathrm{OMIB}}^{\max} = \delta_{\mathrm{r}} - \Delta\delta$

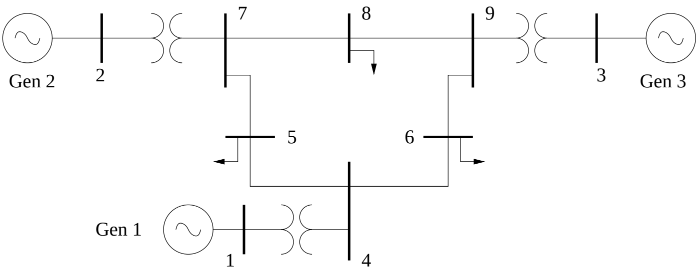
Proposed redispatching procedure

5 - Solve the TSC-OPF problem

6 - Checking the solution:

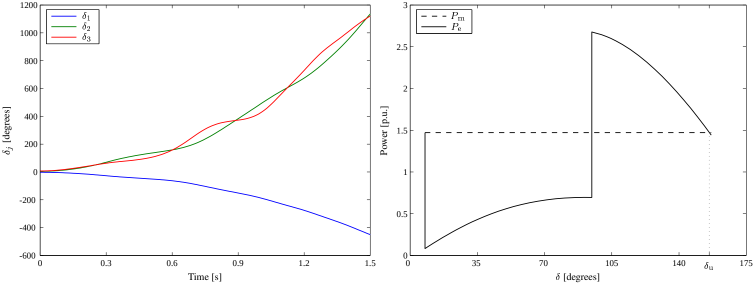
- Time-domain simulation complemented by the SIME method
- If one or more contingencies show transient instability:
  - Updating $\delta_{\mathrm{OMIB}}^{\max}$
  - The procedure continues in step 5
- If all contingencies are stable the procedure stops

Illustrative example: WECC 9-bus, 3-machine system



Illustrative example: WECC 9-bus, 3-machine system
Security assessment

- Fault at bus 7, cleared after 0.3 s by tripping the line 7-5
- First-swing instability → $\delta_u = 155.01$ degrees

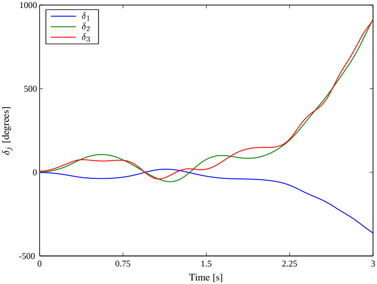


(a) Rotor angle trajectories (b) OMIB plot

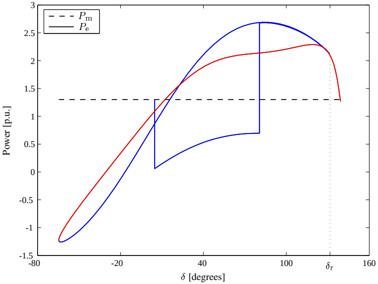
Illustrative example: WECC 9-bus, 3-machine system

Procedure iterations

- First iteration
- Multi-swing instability $\rightarrow \delta_r = 131.11$ degrees



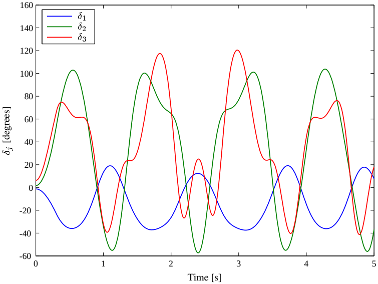
(c) Rotor angle trajectories



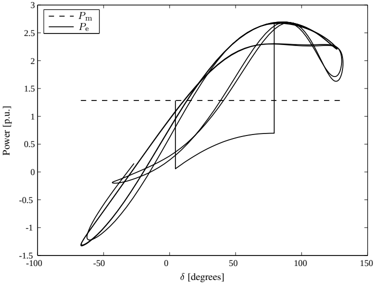
(d) OMIB plot

Illustrative example: WECC 9-bus, 3-machine system
Procedure iterations

- Second and final iteration
- The system is stable



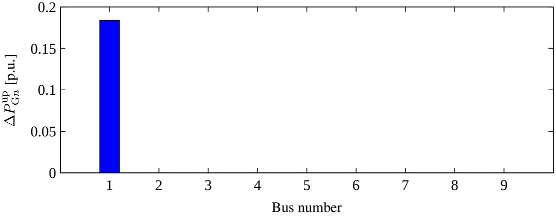
(e) Rotor angle trajectories



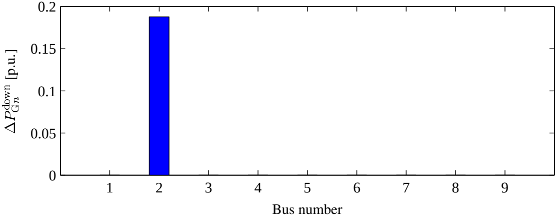
(f) OMIB plot

Illustrative example: WECC 9-bus, 3-machine system
Procedure solution

- Redispatching actions:



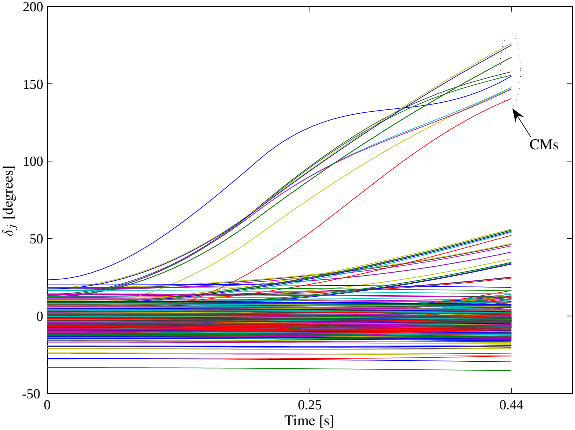
Up



Down

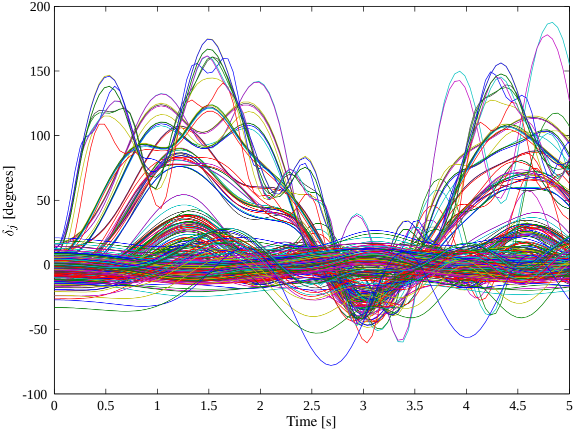
Case study: Real-world 1228-bus, 292-machine system
Security assessment

- Fault at a bus, cleared after 0.2 s
- First-swing instability → $\delta_u = 157.75$ degrees



Case study: Real-world 1228-bus, 292-machine system
First and final iteration

- The system is stable after generation redispatching



Index

Contributions

1 - R. Zárate-Miñano, A. J. Conejo and F. Milano, "OPF-based security redispatching including FACTS devices", *IET Generation Transmission & Distribution*.

2 - R. Zárate-Miñano, T. Van Cutsem, F. Milano and A. J. Conejo, "Securing transient stability using time-domain simulations within and optimal power flow", *IEEE Transactions on Power Systems*.

3 - R. Zárate-Miñano, F. Milano and A. J. Conejo, "An OPF methodology to ensure small-signal stability", *IEEE Transactions on Power Systems*.

Ongoing research

- Impact of renewable generation on power system security
  - Modeling of stochastic perturbations in power sytems
    - Stochastic differential-algebraic equations (SDAE)
  - Stability of power systems with an important penetration of renewable generation
    - Stability of power systems modeled as SDAE