Transient Stability

POWER SYSTEM STABILITY ANALYSIS (EEEN40340)

Prof. Federico Milano

Email: federico.milano@ucd.ie

Tel.: 01 716 1844

Room 157a – Engineering & Materials Science Centre

School of Electrical & Electronic Engineering

University College Dublin

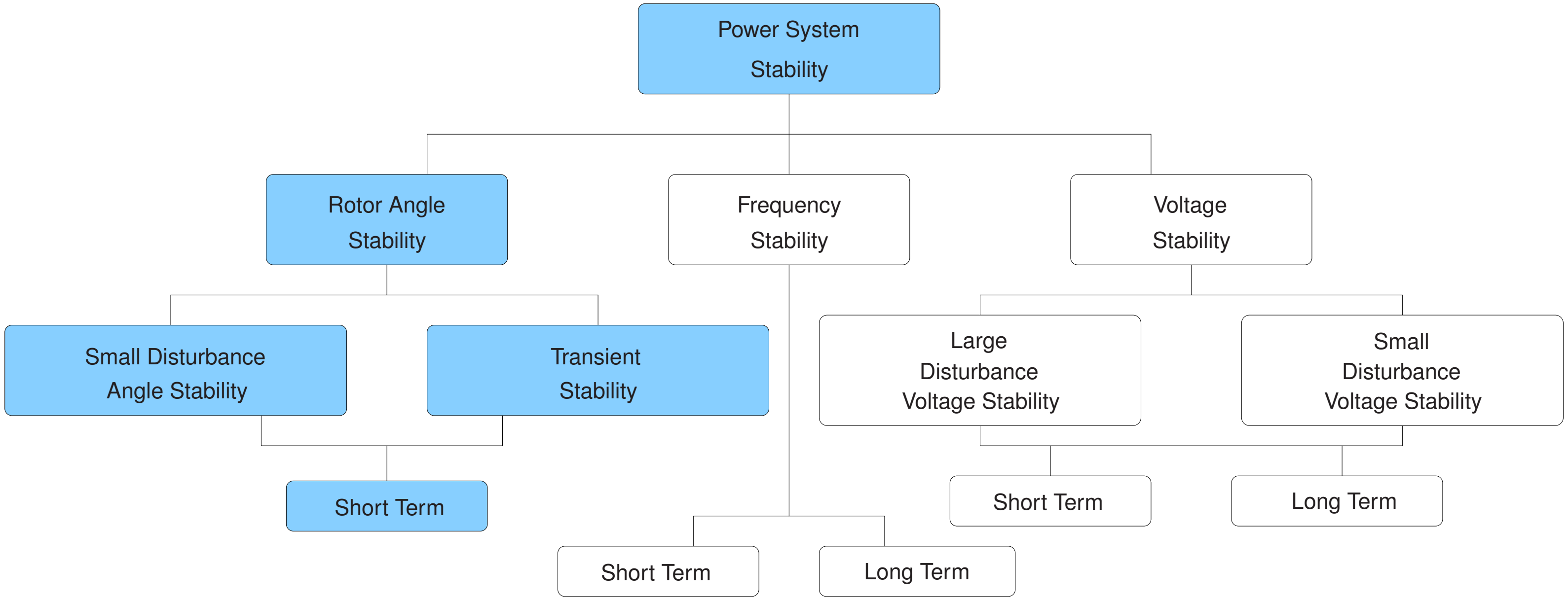
Dublin, Ireland

Angle Stability Outlines

- Definitions.
- Small-signal Stability:
  - Hopf Bifurcations.
  - Control and mitigation.
  - Practical example.
- Transient Stability
  - Time Domain.
  - Direct Methods.
    - Lyapounov function.
    - Equal Area Criterion.
    - Energy functions.
  - Practical applications.

Angle Stability Definitions

- IEEE-CIGRE classification (IEEE/CIGRE Joint Task Force on Stability) Terms and Definitions, “Definitions and Classification of Power System Stability”, *IEEE Trans. Power Systems and CIGRE Technical Brochure 231*, 2003:



Angle Stability Definitions

- "*Rotor angle stability* refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system."
- In this case, the problem becomes apparent through angular/frequency swings in some generators which may lead to their loss of synchronism with other generators.

Transient Stability

- "*Large disturbance rotor angle stability or transient stability*, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship".
- The system nonlinearities determine the system response; hence, linearization does not work in this case.

Transient Stability

- For small disturbances, the problem is to determine if the resulting steady state condition is stable or unstable (eigenvalue analysis) or a bifurcation point (e.g. Hopf bifurcation).
- For large disturbances, the steady state condition after the disturbance can exist and be stable, but it is possible that the system cannot reach that steady state condition.

Transient Stability

- The basic idea and analysis procedures are:
  - *Pre-contingency (initial conditions)*: the system is operating in “normal” conditions associated with a s.e.p.
  - *Contingency (fault trajectory)*: a large disturbance, such as a short circuit or a line trip forces the system to move away from its initial operating point.
  - *Post contingency (fault clearance)*: the contingency usually forces system protections to try to “clear” the fault; the issue is then to determine whether the resulting system is stable, i.e. whether the system remains relatively intact and the associated time trajectories converge to a “reasonable” operating point.

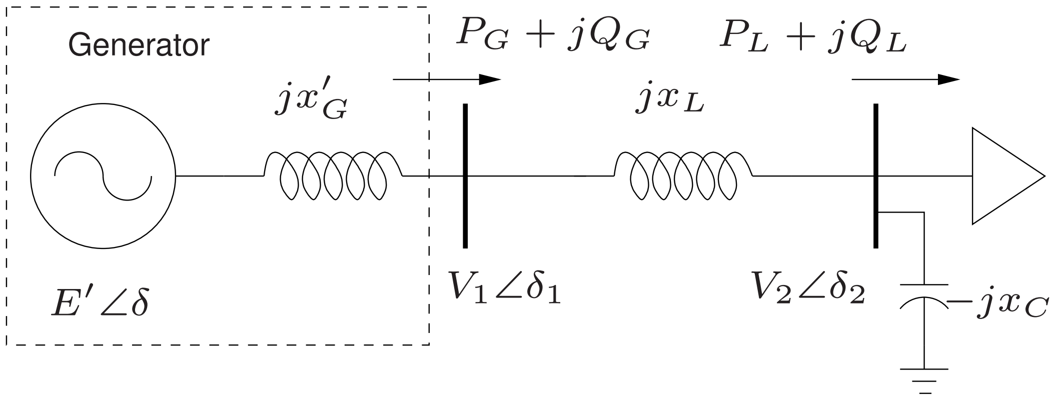
Transient Stability

- Based on non linear theory, this analysis can be basically viewed as determining:
  - Whether the fault trajectory at the "clearance" point is outside or inside of the stability region of the post-contingency s.e.p.; and
  - If the clearance point is inside the stability region, whether the system does not have sufficient "kinetic" energy to get outside the stability region of the s.e.p.

- The second point makes the problem intrinsically "dynamic", i.e., the transient stability analysis cannot be solved considering only the set of e.p. of the system.
- Hence, we needs something more sophisticated than the first Lyapunov's method.

Time domain analysis

- Given the complexity of power system models, the most reliable analysis tool for these types of studies is full time domain simulations.
- For example, for the generator-load example:



Time domain analysis

- The ODE for the simplest generator d-axis transient model and neglecting AVR and generator limits is:

$$\begin{aligned}\dot{\omega} &= \frac{1}{M}(P_d - E'V_2B\sin\delta - D_G\omega)\\ \dot{\delta} &= \omega - \frac{1}{D_L}(E'V_2B\sin\delta - P_d)\\ \dot{V}_2 &= \frac{1}{\tau}[-V_2^2(B - B_C) + E'V_2B\cos\delta - kP_d]\end{aligned}$$

where

$$B = \frac{1}{X} = \frac{1}{X'_G + X_L}$$

Time domain analysis

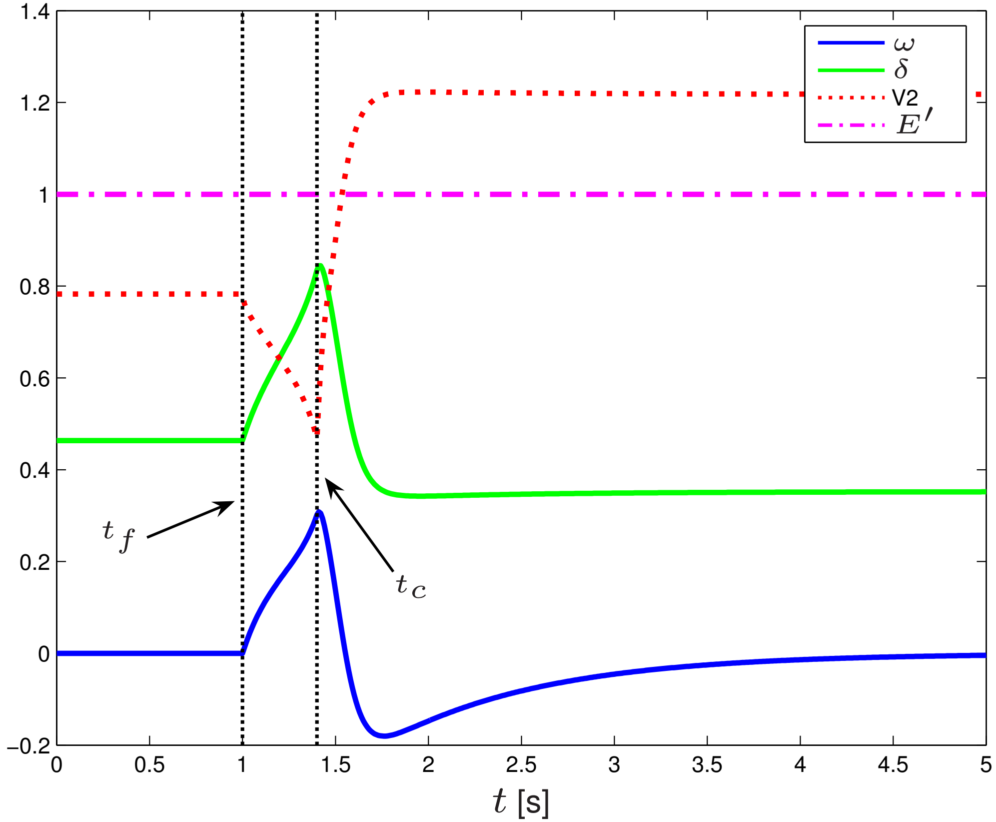
- The objective is to determine how much time an operator would have to connect the capacitor bank B_C after a severe contingency, simulated here as a sudden increase in the value of the reactance X, so that the system recovers.

- In this case, and as previously discussed in the voltage stability section, the contingency is severe, as the s.e.p. disappears if the capacitor bank is not connected to the load.

- Full time domain simulations are carried out to study this problem for the parameter values $M = 0.1$, $D_G = 0.01$, $D_L = 0.1$, $\tau = 0.01$, $E' = 1$, $P_d = 0.7$, $k = 0.25$, $B_C = 0.5$.

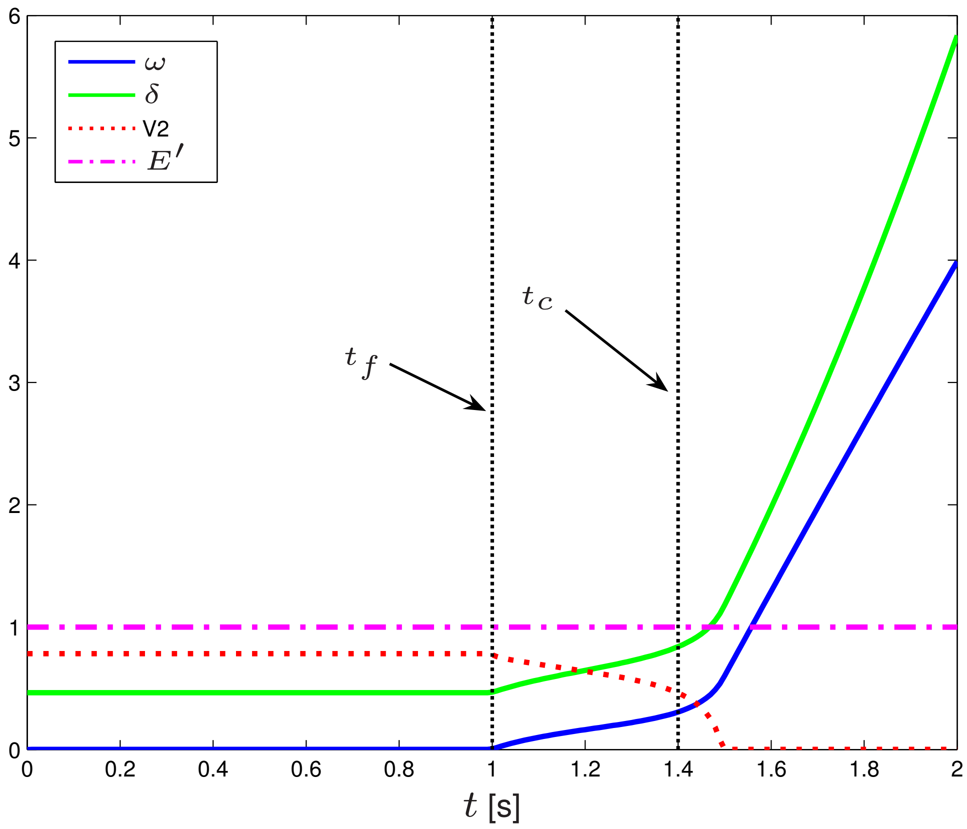
Time domain analysis

- A contingency $X = 0.5 \to 0.6$ at $t_f = 1$ s, with B_C connection at $t_c = 1.4$ s yields a stable system:



Time domain analysis

- If B_C is connected at $t_c = 1.5$ s, the system is unstable:

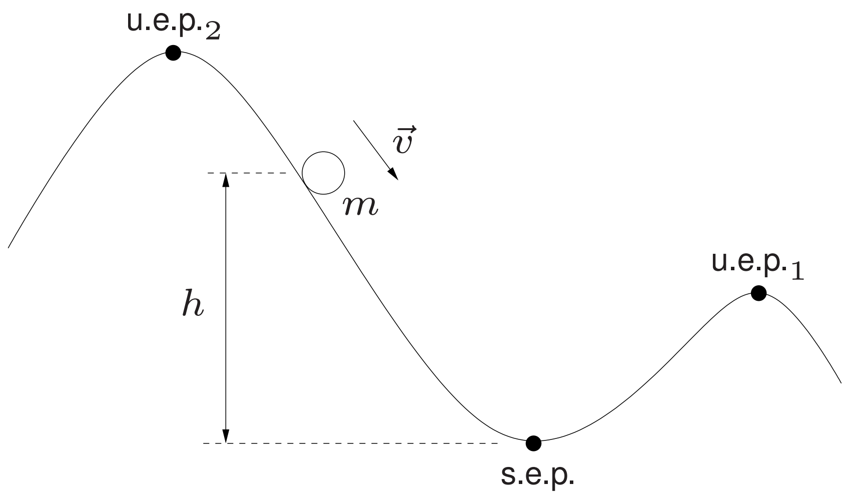


Direct Methods

- Time domain analysis is expensive, so direct stability analysis technique have been proposed based on Lyapounov's stability theory.
- The idea is to define an "energy" or Lyapounov function $\vartheta(x, x_s)$ with certain characteristics to obtain a direct "measure" of the stability region $A(x_s)$ associated with the post-contingency s.e.p. x_s.
- A system's energy is usually a good Lyapounov function, as it yields a stability "measure".

Direct Methods

- The rolling ball example can used to explain the basic behind these techniques:



- There are 3 equilibrium points: one stable (“valley” bottom), two unstable (“hill” tops).

Direct Methods

- The energy of the ball is a good Lyapounov or Transient Energy Function (TEF):

$$\begin{aligned} W &= W_{\text{kinetic}} + W_{\text{potential}} \\ &= W_K + W_P \\ &= \frac{1}{2} m v^2 + m g h \\ &= \vartheta([v, h]^T, 0) \end{aligned}$$

- The potential energy at the s.e.p. is zero, and presents local maxima at the u.e.p.s (W_{P1} and W_{P2}).

- The “closest” u.e.p. is u.e.p.$_1$ since $W_{P1} < W_{P2}$.

Direct Methods

- The stability of this system can then be evaluated using this energy:
  - if $W < W_{P1}$, the ball remains in the "valley", i.e. the system is stable, and will converge to the s.e.p. as $t \to \infty$.
  - If $W > W_{P1}$, the ball *might* or *might not* converge to the s.e.p., depending on friction (inconclusive test).
  - When the ball's potential energy $W_P(t)$ reaches a maximum with respect to time t, the system leaves the "valley", i.e. unstable condition.

Direct Methods

- The “valley” would correspond to the stability region when friction is “large”.
- In this case, the stability boundary $\partial A(x_s)$ corresponds to the “ridge” where the u.e.p.s are located and W_P has a local max. value.
- The smaller the friction in the system, the larger the difference between the ridge and $\partial A(x_s)$.
- For zero friction, $\partial A(x_s)$ is defined by W_{P1}.

Direct Methods

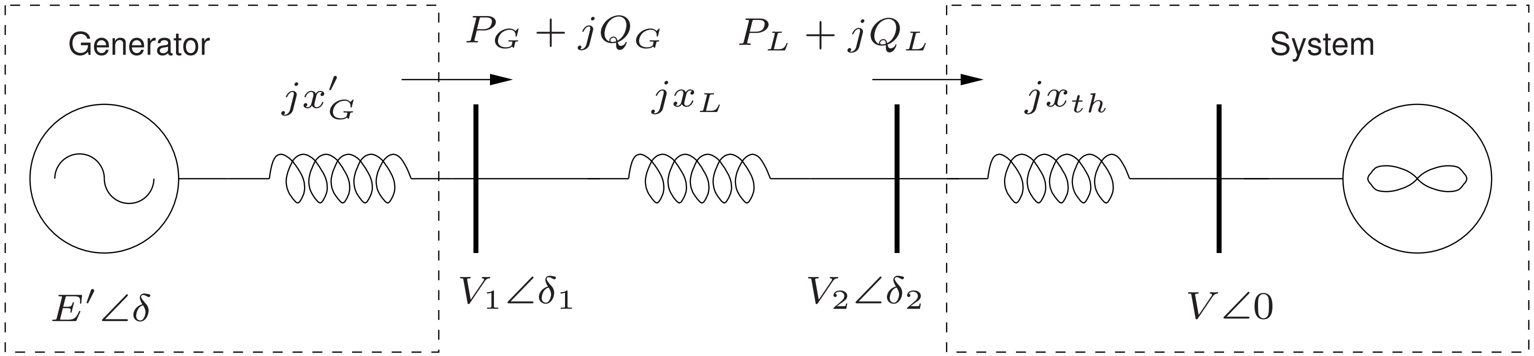
- The direct stability test is only a necessary but not sufficient condition:

$$\vartheta(x, x_s) < c \quad \Rightarrow \quad x \in A(x_s)$$
$$\vartheta(x, x_s) > c \quad \Rightarrow \quad \text{Inconclusive!}$$

where the value of c is usually associated with a local maximum of a "potential energy" function.

Direct Methods

- For the simple generator-infinite bus example, neglecting limits and AVR:



$$
\begin{aligned}
\dot{\delta} &= \omega = \omega_r - \omega_0 \\
\dot{\omega} &= \frac{1}{M}\left(P_L - \frac{E'V}{X}\sin\delta - D\omega\right) \\
X &= X'_G + X_L + X_{th}
\end{aligned}
$$

Direct Methods

- The kinetic energy in this system is defined as:

$$W_K = \frac{1}{2} M \omega^2$$

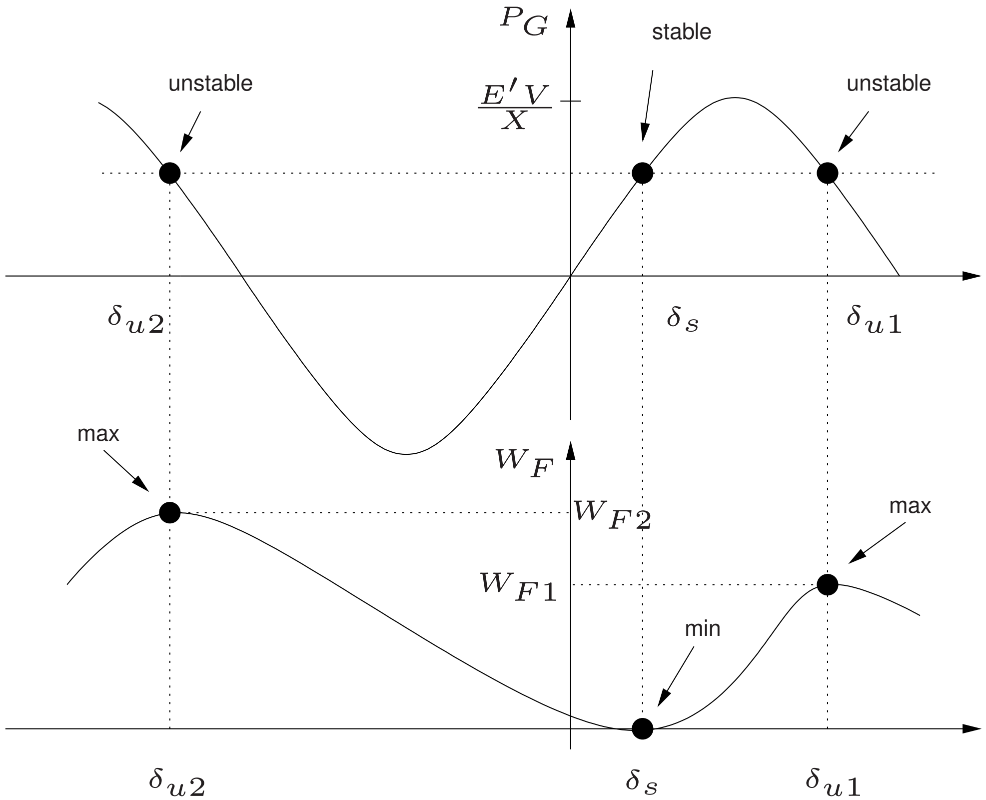
- And the potential energy is:

$$\begin{aligned} W_P &= \int (T_c - T_m) d\delta \\ &\approx \int (P_c - P_m) d\delta \rightarrow \text{in p.u. for } \omega_r \approx \omega_0 \\ &\approx \int_{\delta_s}^{\delta} (P_G - P_L) d\delta \approx \int_{\delta_s}^{\delta} (\frac{E'V}{X} - P_L) d\delta \\ &\approx -E'VB(\cos\delta - \cos\delta_s) - P_L(\delta - \delta_s) \end{aligned}$$

where δ_s is the s.e.p. for this system.

Direct Methods

- With W_P presenting a very similar profile as the rolling ball example:



Direct Methods

- The potential energy W_P allows defining the stability of the equilibrium points.
- one has to compute the second derivative with respect to the position δ of the potential energy at the equilibrium points. Then the equilibrium point is:
  - stable if $\partial^2 W_P / \partial\delta^2 > 0$;
  - unstable if $\partial^2 W_P / \partial\delta^2 < 0$.
- Note that, for the OMIB example, $\partial^2 W_P / \partial\delta^2$ is positive for δ_s and negative for δ_{u1} and δ_{u2}, as expected.

Direct Methods

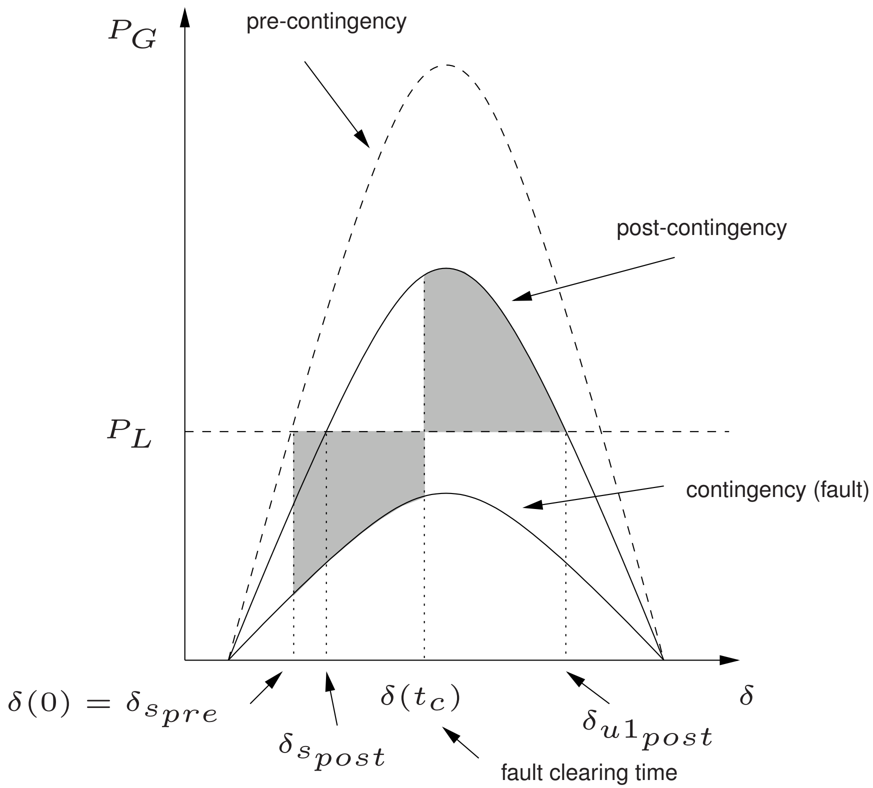
- Hence, the system Lyapounov function of TEF is:

$$
\begin{aligned}
TEF &= \vartheta(x, x_s) \\
&= \vartheta([\delta, \omega]^T, [\delta_s, 0]^T) \\
&= \frac{1}{2}M\omega^2 - E'VB(\cos\delta - \cos\delta_s) \\
&\quad -P_L(\delta - \delta_s)
\end{aligned}
$$

- Thus, using similar criteria as in the case of the rolling ball:
  - If $TEF < W_{P1} \Rightarrow$ system is stable.
  - If $TEF > W_{P1} \Rightarrow$ inconclusive for $D > 0$ ("friction").
  - If $TEF > W_{P1} \Rightarrow$ unstable for $D = 0$ (unrealistic).

Direct Methods

- This is equivalent to compare “areas” in the P_G vs. δ graph (Equal Area Criterion or EAC):



Direct Methods

- Thus, comparing the "acceleration" area:

$$\begin{aligned} A_a &= \int_{\delta_{spre}}^{\delta(t_c)} (P_L - P_{G_{fault}}) d\delta \\ &= \int_{\delta_{spre}}^{\delta(t_c)} \left(P_L - \frac{E'V}{X_{fault}} \right) d\delta \end{aligned}$$

- versus the "deceleration" area:

$$\begin{aligned} A_d &= \int_{\delta(t_c)}^{\delta_{spost}} (P_{G_{post}} - P_L) d\delta \\ &= \int_{\delta(t_c)}^{\delta_{spost}} \left(\frac{E'V}{X_{post}} - P_L \right) d\delta \end{aligned}$$

Direct Methods

- In conclusion:
  - If $A_a < A_d \Rightarrow$ system is stable at t_c.
  - If $A_a > A_d \Rightarrow$ inconclusive for $D > 0$.
  - If $A_a > A_d \Rightarrow$ unstable for $D = 0$ (unrealistic).

Direct Methods: Example 1

- A 60 Hz generator with a 15% transient reactance is connected to an infinite bus of 1 p.u. voltage through two identical parallel transmission lines of 20% reactance and negligible resistance. The generator is delivering 300 MW at a 0.9 leading power factor when a 3-phase solid fault occurs in the middle of one of the lines; the fault is then cleared by opening the breakers of the faulted line.
- Assuming a 100 MVA base, determine the critical clearing time for this generator if the damping is neglected and its inertia is assumed to be $H = 5$ s.
- Assuming $D = 0.1$ s, determine the actual critical clearing time.

Direct Methods: Example 1

- Pre-contingency or initial conditions:

$$
\begin{aligned}
P_{G_{pre}} &= P_L = \frac{E'V}{X_{pre}} \sin \delta_{s_{pre}} \\
Q_L &= -\frac{V^2}{X_{pre}} + \frac{E'V}{X_{pre}} \cos \delta_{s_{pre}}
\end{aligned}
$$

Direct Methods: Example 1

- Where:

$$
\begin{aligned}
X_{pre} &= 0.15 + \frac{0.2}{2} = 0.25 \\
P_L &= \frac{300 \text{ MW}}{100 \text{ MVA}} \\
3 &= \frac{E'}{0.25} \sin \delta_{s_{pre}} \\
Q_L &= 3 \tan(\cos^{-1} 0.9) \\
1.4530 &= -\frac{1}{0.25} + \frac{E'}{0.25} \cos \delta_{s_{pre}}
\end{aligned}
$$

Direct Methods: Example 1

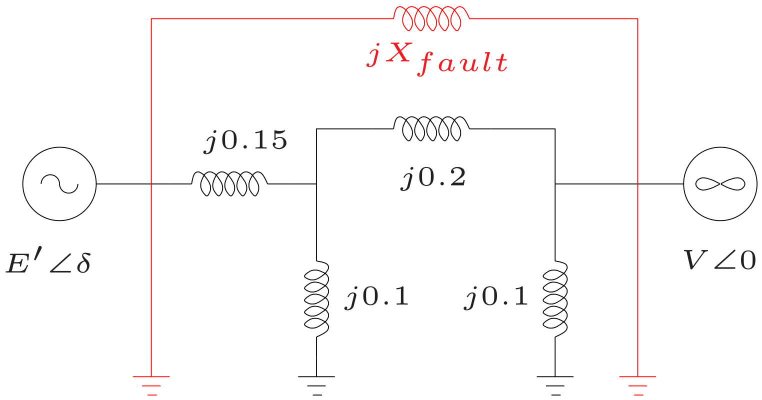
$$
\begin{aligned}
\Rightarrow \quad E'_{i_{pre}} &= E' \sin \delta_{s_{pre}} \\
&= 0.75 \\
E'_{r_{pre}} &= E' \cos \delta_{s_{pre}} \\
&= 1.3633 \\
E' &= \sqrt{E'^2_{r_{pre}} + E'^2_{i_{pre}}} \\
&= 1.5559 \\
\delta_{s_{pre}} &= \tan^{-1}\left(\frac{E'_{i_{pre}}}{E'_{r_{pre}}}\right) \\
&= 28.82^\circ = 0.5030 \text{ rad}
\end{aligned}
$$

Direct Methods: Example 1

- Fault conditions:

$$
\begin{aligned}
P_{G_{fault}} &= \frac{E'V}{X_{fault}} \sin\delta \\
&= \frac{1.5559}{X_{fault}} \sin\delta
\end{aligned}
$$

where, using a Y-Δ circuit transformation due to the fault being in the middle of one of the parallel lines:



Direct Methods: Example 1

$$
\begin{aligned}
X_{fault} &= \frac{0.15 \times 0.2 + 0.1 \times 0.2 + 0.15 \times 0.1}{0.1} \\
\Rightarrow \quad P_{G_{fault}} &= 2.394 \sin \delta \\
A_a &= \int_{\delta_{s_{pre}}}^{\delta(t_{cc})} (P_L - P_{G_{fault}}) d\delta \\
&= \int_{0.503}^{\delta(t_{cc})} (3 - 2.394 \sin \delta) d\delta \\
&= 3(\delta(t_{cc}) - 0.503) + 2.394(\cos \delta(t_{cc}) - \cos(0.503)) \\
&= 3\delta(t_{cc}) + 2.394 \cos \delta(t_{cc}) - 3.6065
\end{aligned}
$$

Direct Methods: Example 1

- Post contingency conditions:

$$
\begin{aligned}
X_{post} &= 0.15 + 0.2 = 0.35 \\
\Rightarrow \quad P_{G_{post}} &= \frac{E'V}{X_{post}} \sin\delta \\
&= 4.446 \sin\delta \\
\Rightarrow \quad 3 &= 4.446 \sin\delta_{s_{post}} \\
\delta_{s_{post}} &= 42.44^\circ \\
&= 0.7407 \text{ rad}
\end{aligned}
$$

Direct Methods: Example 1

$$
\begin{aligned}
\Rightarrow A_d &= \int_{\delta(t_{cc})}^{\pi-\delta_{s_{post}}} (P_{G_{post}} - P_L)d\delta \\
&= \int_{\delta(t_{cc})}^{2.4} (4.446\sin\delta - 3)d\delta \\
&= -4.446(\cos 2.4 - \cos\delta(t_{cc})) - 3(2.4 - \delta(t_{cc})) \\
&= 3\delta(t_{cc}) + 4.446\cos\delta(t_{cc}) - 3.9215
\end{aligned}
$$

Direct Methods: Example 1

$$\begin{aligned} A_a &= A_d \\ &= 3\delta(t_{cc}) + 2.394\cos\delta(t_{cc}) - 3.6065 \\ &= 3\delta(t_{cc}) + 4.446\cos\delta(t_{cc}) - 3.9215 \end{aligned}$$

$$\begin{aligned} \Rightarrow \quad \delta(t_{cc}) &= 81.17^\circ \\ &= 1.4167 \text{ rad} \end{aligned}$$

Direct Methods: Example 1

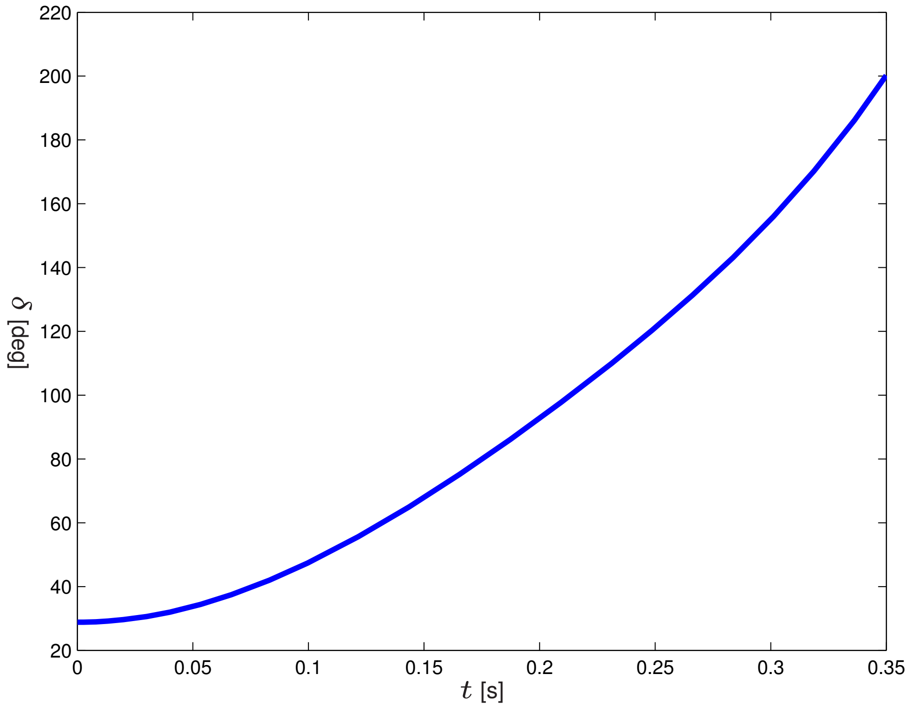
- During the fault:

$$
\begin{aligned}
\dot{\delta} &= \omega \\
\dot{\omega} &= \frac{1}{M}\left(P_L - \frac{E'V}{X_{fault}}\sin\delta\right) \\
M &= \frac{H}{\pi f} \\
&= \frac{5\ \mathrm{s}}{\pi 60\ \mathrm{Hz}} \\
&= 0.0265\ \mathrm{s}^2
\end{aligned}
$$

$$
\begin{aligned}
\Rightarrow \quad \dot{\delta} &= \omega \\
\dot{\omega} &= 37.70(3 - 2.394\sin\delta)
\end{aligned}
$$

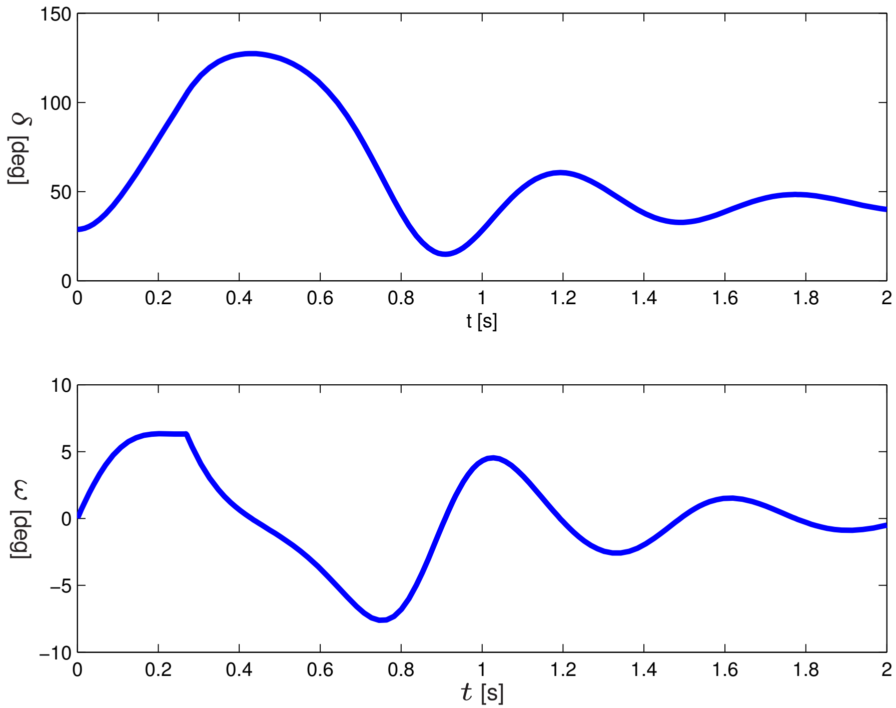
Direct Methods: Example 1

- Integrating these equations numerically for $\delta(0) = \delta_{s_{pre}} = 28.82°$:



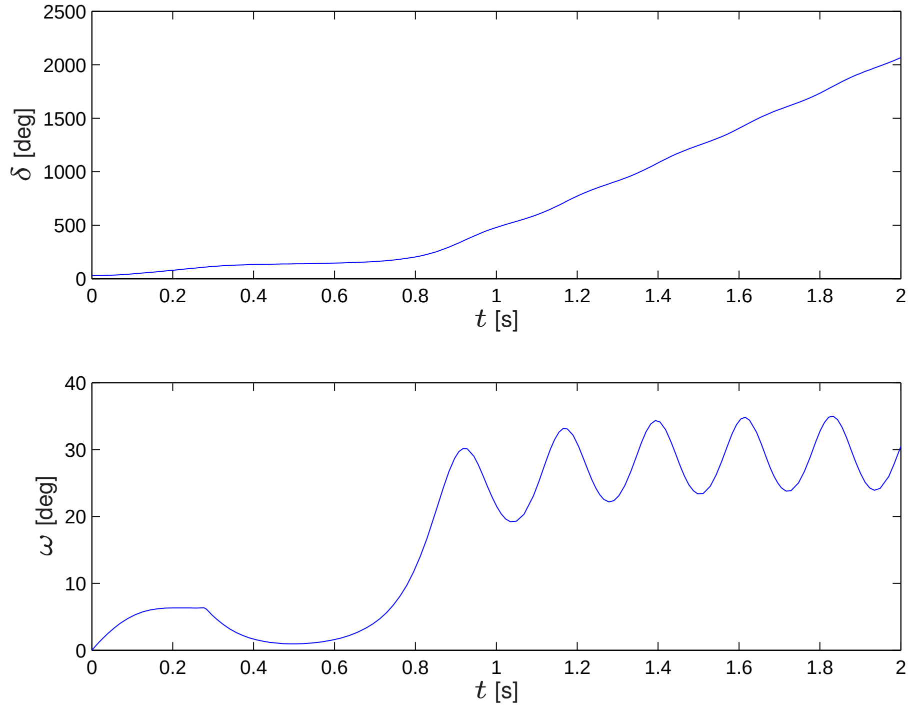
Direct Methods: Example 1

- For $D = 0.1$ and a clearing time of $t_c = 0.27$ s, the system is stable:



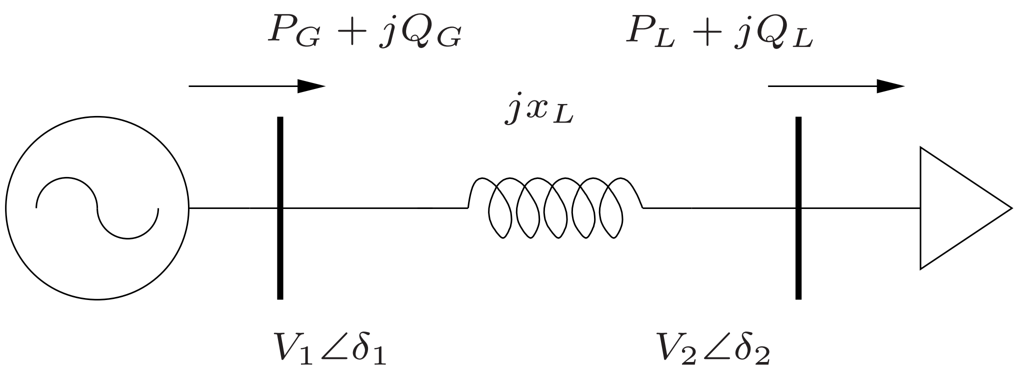
Direct Methods: Example 1

- For a clearing time of $t_c = 0.28$ s, the system is unstable; hence $t_{cc} \approx 0.275$ s:



Direct Methods: Example 2

- Generator-motor, i.e. system-system, cases may also be studied using the EAC method based on an equivalent inertia $M = M_1 M_2/(M_1 M_2)$, and damping $D = MD_1/M_1 = MD_2/M_2$.
- For the generator-load example neglecting the internal generator impedance and assuming an “instantaneous” AVR:



Direct Methods: Example 2

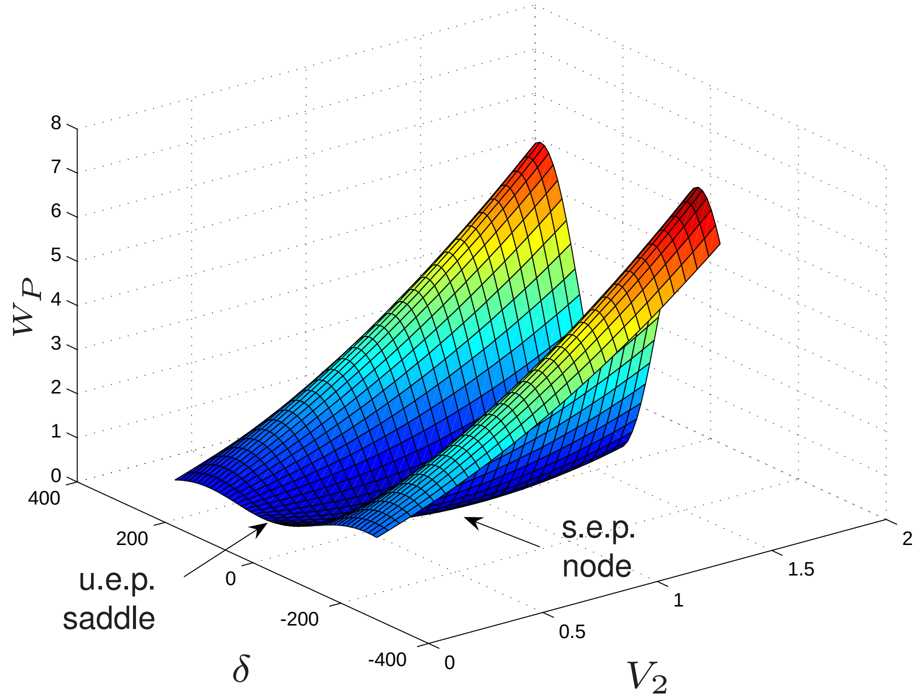
- The "energy" functions, with or without generator limits, can be shown to be:

$$\begin{aligned} W_K &= \frac{1}{2}M\omega^2 \\ W_P &= -B(V_1V_2\cos\delta - V_{10}V_{20}\cos\delta_0) \\ &\quad +\frac{1}{2}B(V_2^2 - V_{20}^2) + \frac{1}{2}B(V_1^2 - V_{10}^2) \\ &\quad -P_d(\delta-\delta_0) + Q_d\ln\left(\frac{V_2}{V_{20}}\right) - Q_G\ln\left(\frac{V_1}{V_{10}}\right) \end{aligned}$$

- The stability of this system can then be studied using the same "energy" evaluation previously explained for $TEF = \vartheta(x, x_0) = W_K + W_P$.

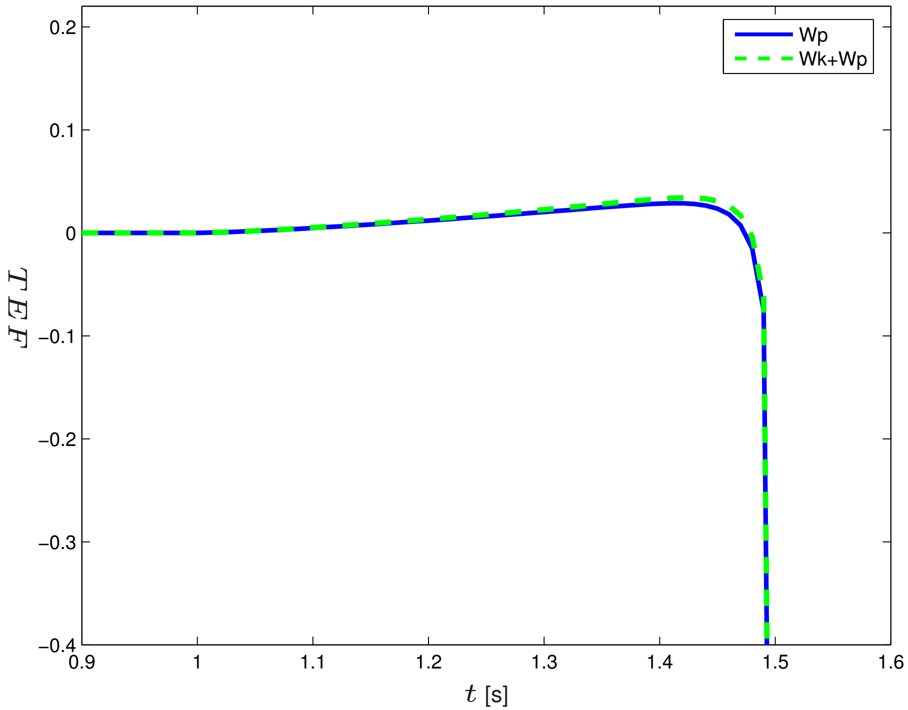
Direct Methods: Example 2

- Thus for $V_1 = 1$, $X_L = 0.5$, $P_d = 0.1$, and $Q_d = 0.25P_d$, the potential energy $W_P(\delta, V_2)$ that defines the stability region withr espect to the s.e.p. is:



Direct Methods: Example 2

- Simulating the critical contingency $X_L = 0.5 \rightarrow 0.6$ for $P_d = 0.7$ and neglecting limits, the "energy" profiles are:



Direct Methods: Example 2

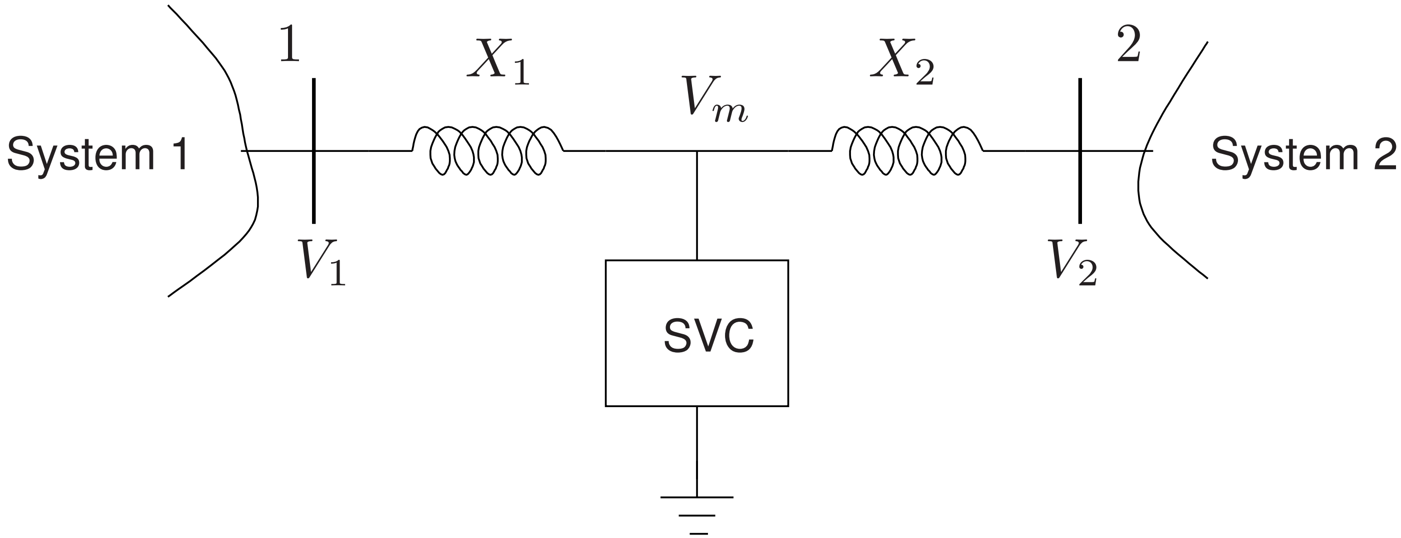
- The "exit" point on $\partial A(x_s)$ is approximately at the maximum potential energy point.
- Thus, the critical clearing time is:

$$t_{cc} \approx 1.42 \text{ s}$$

- A similar value can be obtained through trial-and-error.

Direct Methods: Example 3

- Consider the following system:



Direct Methods: Example 3

- Without the SVC, the active power tha flows from bus 1 to bus 2 is as follows:

$$P_{12} = \frac{V_1 V_2}{X_1 + X_2} \sin \delta_{12} = \frac{V^2}{X} \sin \delta$$

where we assume $V_1 = V_2 = V$ and define $X_1 = X_2 = X/2$ and $\delta_{12} = \delta$.

- With the SVC device, one has:

$$P_{12} = P_{1m} = \frac{V_1 V_m}{X/2} \sin \delta_{1m} = \frac{2V^2}{X} \sin \frac{\delta}{2}$$

where we assume that the SVC regulates the voltage V_m so that $V_m = V$.

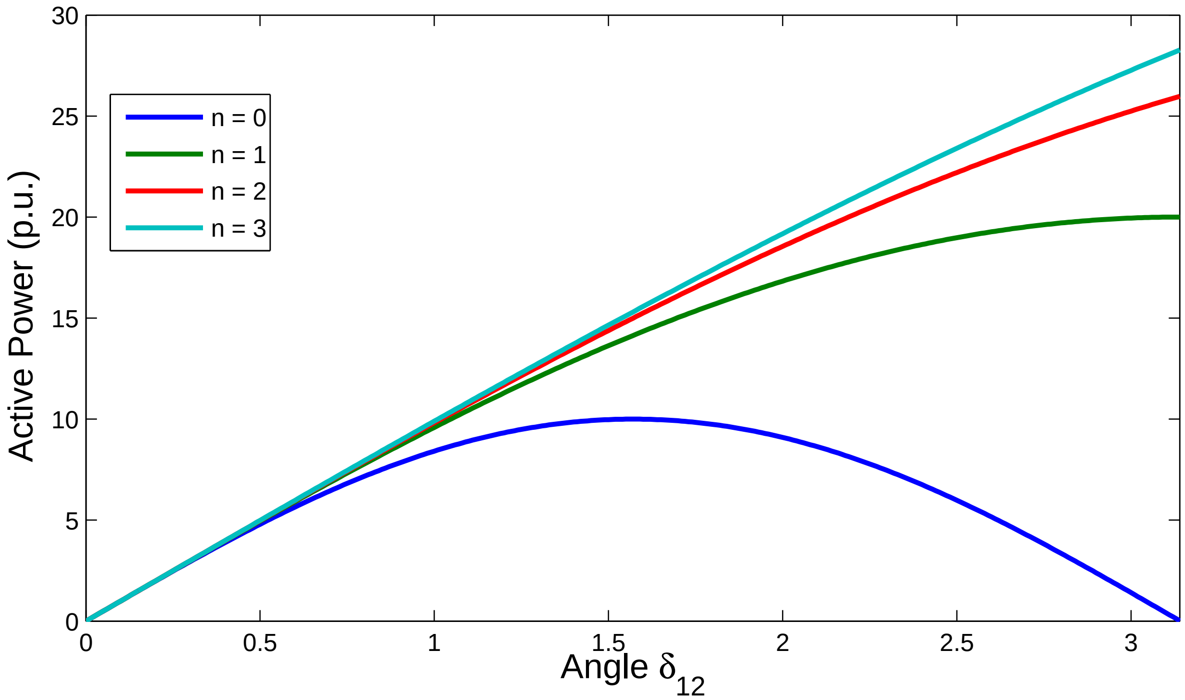
Direct Methods: Example 3

- We can generalize the active power that can be transmitted from bus 1 to bus 2 using n SVC devices, as follows:

$$P_{12} = \frac{(n+1)V^2}{X} \sin \frac{\delta}{(n+1)}$$

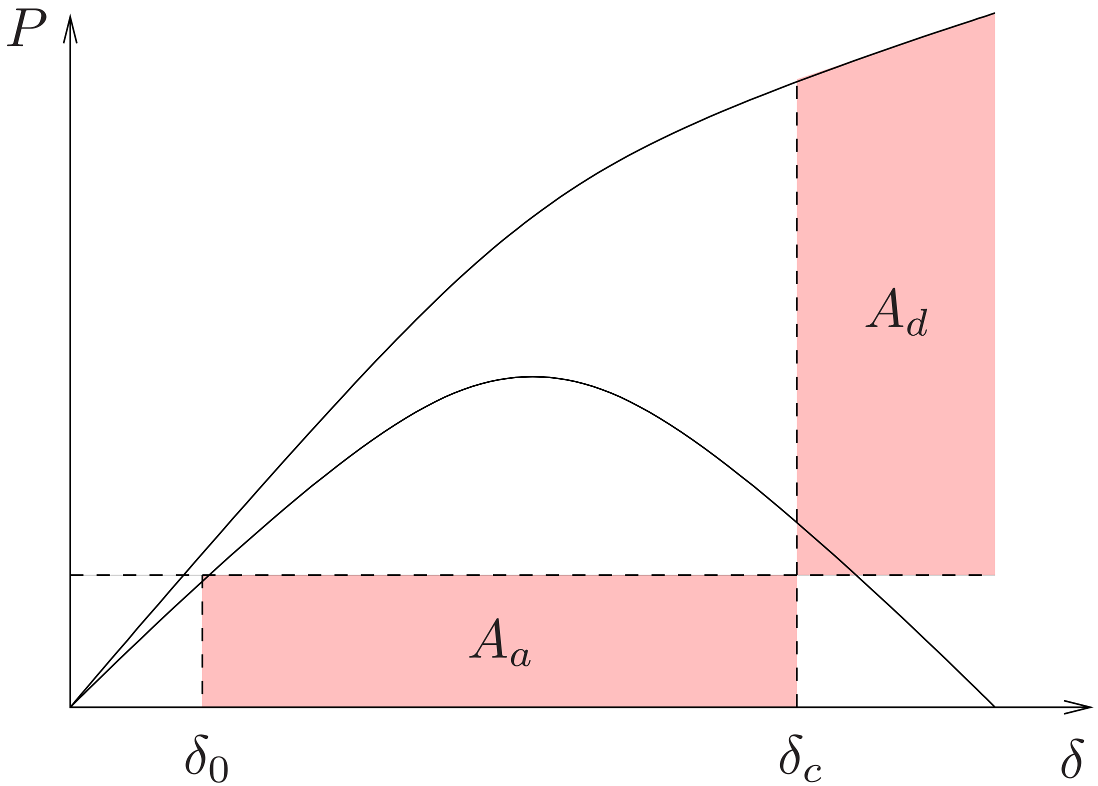
Direct Methods: Example 3

- Active power as a function of $\delta_{12} = \delta$ and n:



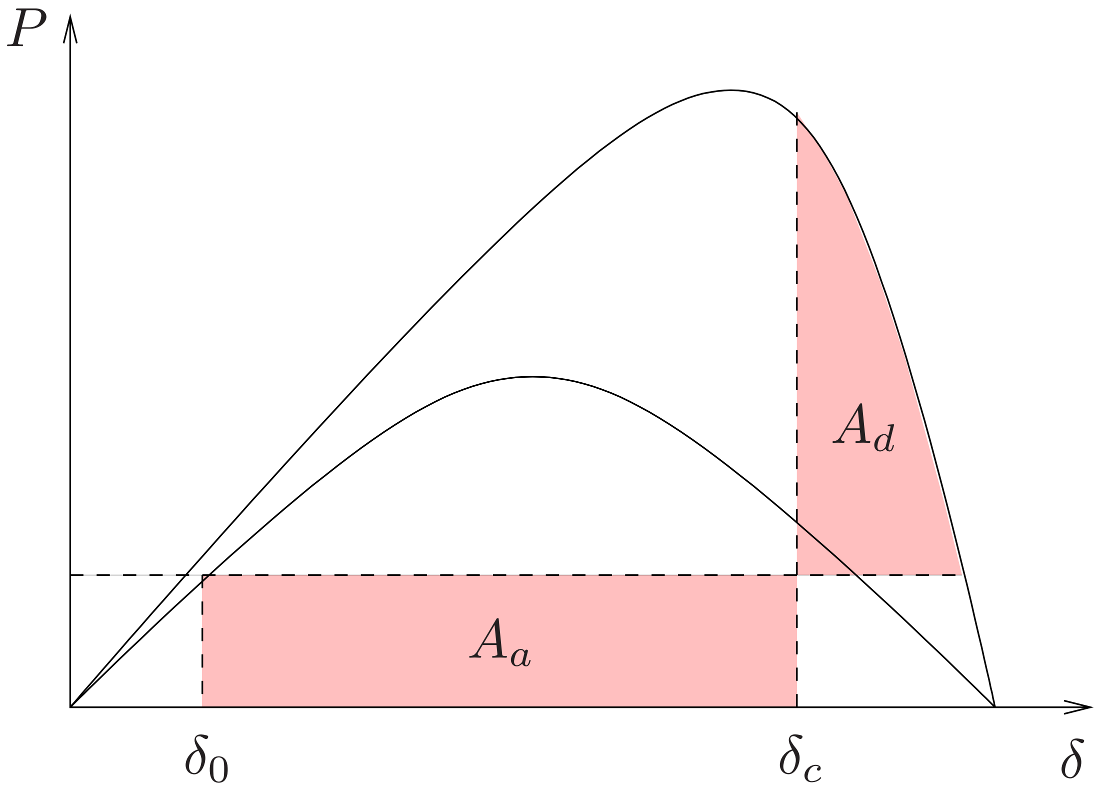
Direct Methods: Example 3

- The increased power transfer capability obtined by means of the SVC can be used to improve the transient stability of the system, as follows:



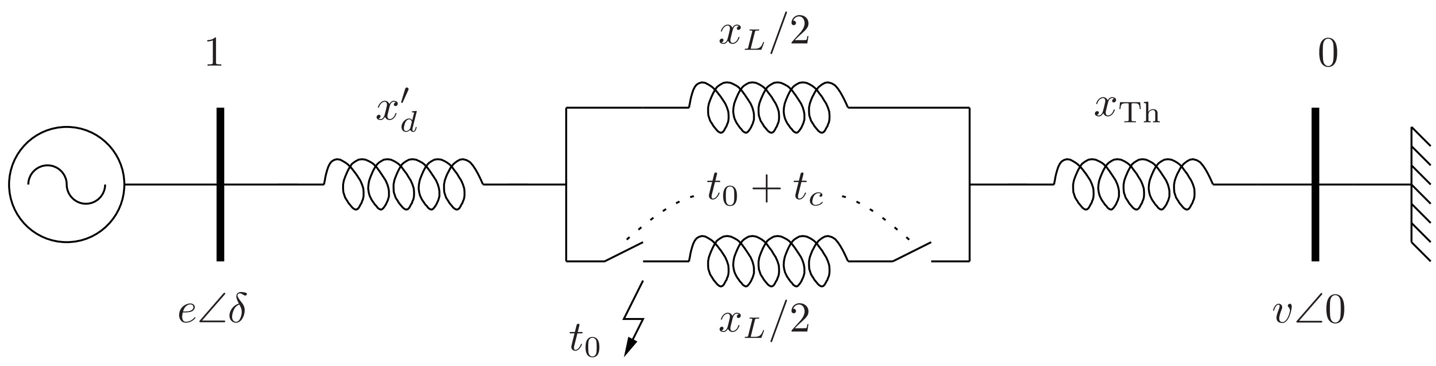
Direct Methods: Example 3

- Typically, it is more economic a partial compensation:



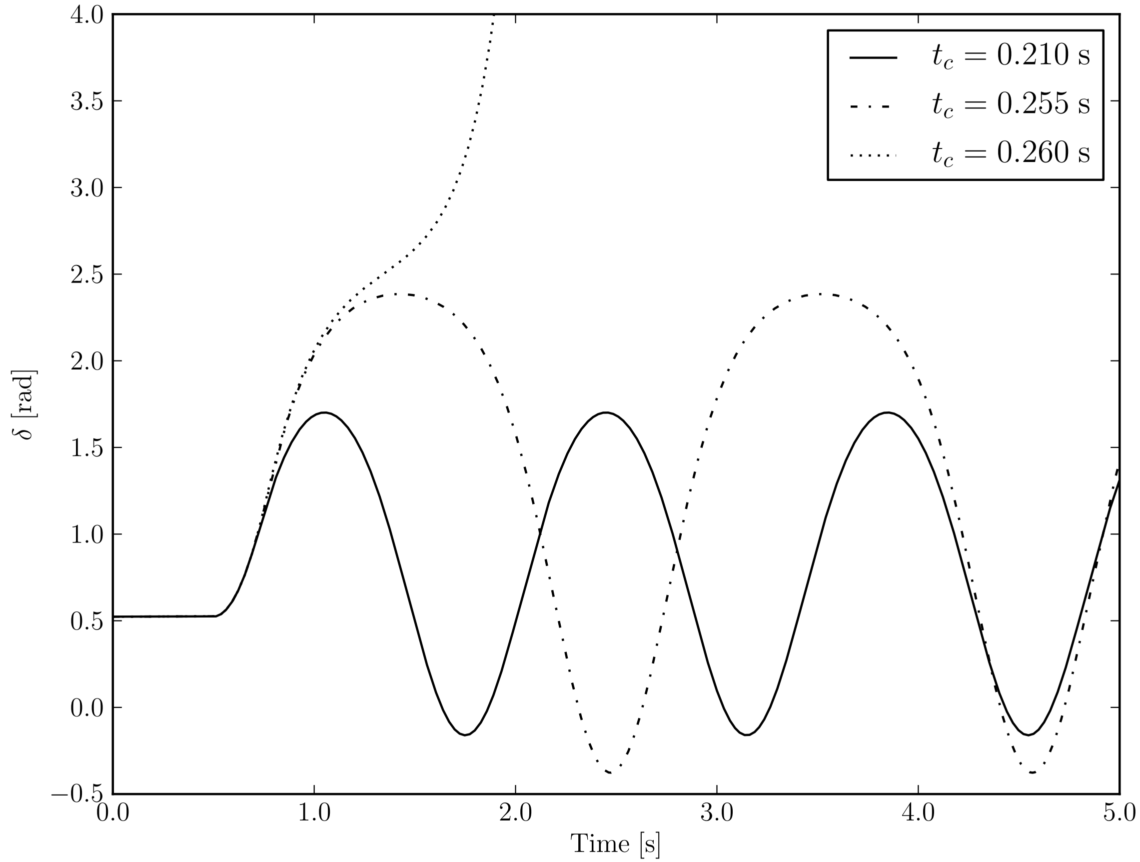
Direct Methods: Example 4

- Let study the effect of the machine damping on the CCT.
- OMIB system with three-phase fault and line outage.



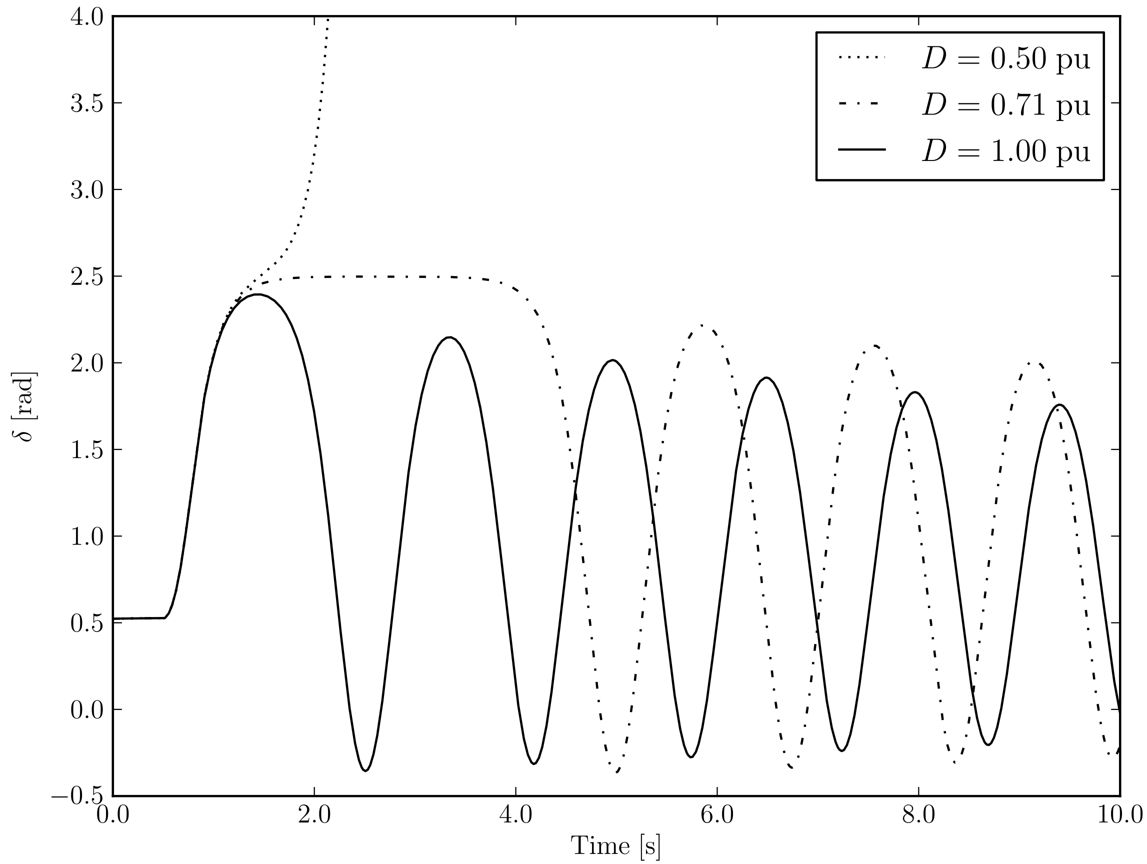
Direct Methods: Example 4

- Without damping the CCT is ≈ 0.26 s.



Direct Methods: Example 4

- With damping, the CCT can increase considerably.



Direct Methods: Conclusions

- The advantages of using Lyapounov functions are:
  - Allows reduced stability analysis.
  - Can be used as an stability index.
- The problems are:
  - Lyapounov functions are model dependent; in practice, only approximate “energy” functions can be found.
  - Inconclusive if test fails.
  - The post-perturbation system state must be known ahead of time, as the energy function is defined with respect to the corresponding s.e.p.
- Can only be used as an “approximate” stability analysis tool.

Hybrid Methods - I

- Considering the methods that we have seen so far, this are relevant conclusions:
  - Time domain simulations are accurate, but can be computationally expensive.
  - Direct methods are fast but have several theoretical limitations.

- Hybrid methods attempt to take the best from the two approaches.

Hybrid Methods - II

- An important issue to solve when dealing with numerical integration is *when* to stop the simulation.
- A simple method for determining if the trajectory is going to be unstable is to monitor the rotor angle of synchronous machines.
- If at a certain time t, the maximum difference between two rotor angles exceeds 2π
- Then some machine is certainly losing the synchronism and the simulation can be stopped.

Hybrid Methods - III

- However, the previous method does not allow saving time if the simulation is stable.
- In fact, if the simulation is stable, one has to wait for the final assigned time t_f before stopping the numerical method.
- A well-known technique that allows defining the stability or instability of a given trajectory is the SIME method (developed at Univ. of Liège, Belgium).

SIME Method - I

- At each step of the numerical integration, the machine rotor angles are sorted and the maximum difference of two consecutive synchronous machine rotor angles is found.
- Assuming that these angles are δ_i and δ_j, with $\delta_i > \delta_j$, all machines whose rotor angles satisfy $\delta_h \geq \delta_i$ are considered *critical* machines, while all machines whose rotor angles satisfy $\delta_h \leq \delta_j$ are considered *non-critical* machines.

SIME Method - II

- Once defined the critical and non-critical machine sets, say $\mathcal{G}_{\rm C}$ and $\mathcal{G}_{\rm NC}$, the equivalent OMIB rotor angle is defined as:

$$\delta^{\rm OMIB} = \frac{1}{H_{\rm C}} \sum_{j=\mathcal{G}_{\rm C}} H_j \delta_j - \frac{1}{H_{\rm NC}} \sum_{j=\mathcal{G}_{\rm NC}} H_j \delta_j \tag{1}$$

where the sub-indexes $\rm C$ and $\rm NC$ stand for critical and non-critical, and the equivalent inertia constants are:

$$\begin{aligned} H_{\rm C} &= \sum_{j=\mathcal{G}_{\rm C}} H_j \\ H_{\rm NC} &= \sum_{j=\mathcal{G}_{\rm NC}} H_j \end{aligned} \tag{2}$$

SIME Method - III

- Similarly, OMIB electrical and mechanical powers are defined as:

$$
\begin{aligned}
p_e^{\rm OMIB} &= H^{\rm OMIB} \left[\frac{1}{H_{\rm C}} \sum_{j=\mathcal{G}_{\rm C}} p_{ej} - \frac{1}{H_{\rm NC}} \sum_{j=\mathcal{G}_{\rm NC}} p_{ej} \right] \\
p_m^{\rm OMIB} &= H^{\rm OMIB} \left[\frac{1}{H_{\rm C}} \sum_{j=\mathcal{G}_{\rm C}} p_{mj} - \frac{1}{H_{\rm NC}} \sum_{j=\mathcal{G}_{\rm NC}} p_{mj} \right]
\end{aligned}
\tag{3}
$$

where $H^{\rm OMIB} = H_{\rm C} H_{\rm NC} / (H_{\rm C} + H_{\rm NC})$.

- According to the EAC, the equivalent OMIB accelerating power $p_a^{\rm OMIB}$ is:

$$
p_a^{\rm OMIB} = p_m^{\rm OMIB} - p_e^{\rm OMIB} \tag{4}
$$

SIME Method - IV

- The following stability conditions hold for the equivalent OMIB:

1. If, at a certain time step t, $p_a^{\rm OMIB} = 0$ and $\dot{p}_a^{\rm OMIB} > 0$ and $\dot{\delta}^{\rm OMIB} > 0$ the system is unstable. In fact, the previous conditions ensure that the system has no further kinetic energy to spend for decelerating the system. Furthermore, $\dot{\delta}^{\rm OMIB} > 0$ implies that the rotor angle is increasing. These are sufficient conditions to define instability.
2. If, at a certain time step t, $p_a^{\rm OMIB} < 0$ and $\dot{\delta}^{\rm OMIB} \leq 0$ the system is first-swing stable. In fact, in this case, the kinetic energy is enough to stop the critical machine rotor angles and make them to "come back". These stability conditions are only necessary. In fact, the system can later on show multi-swing instability. Only the numerical integration can show if the trajectory is multi-swing stable or not.
3. If $p_a^{\rm OMIB} > 0, \forall t > 0$, then the system is certainly unstable. However, some heuristic is needed to determine when to stop the simulation.

SIME Method - V

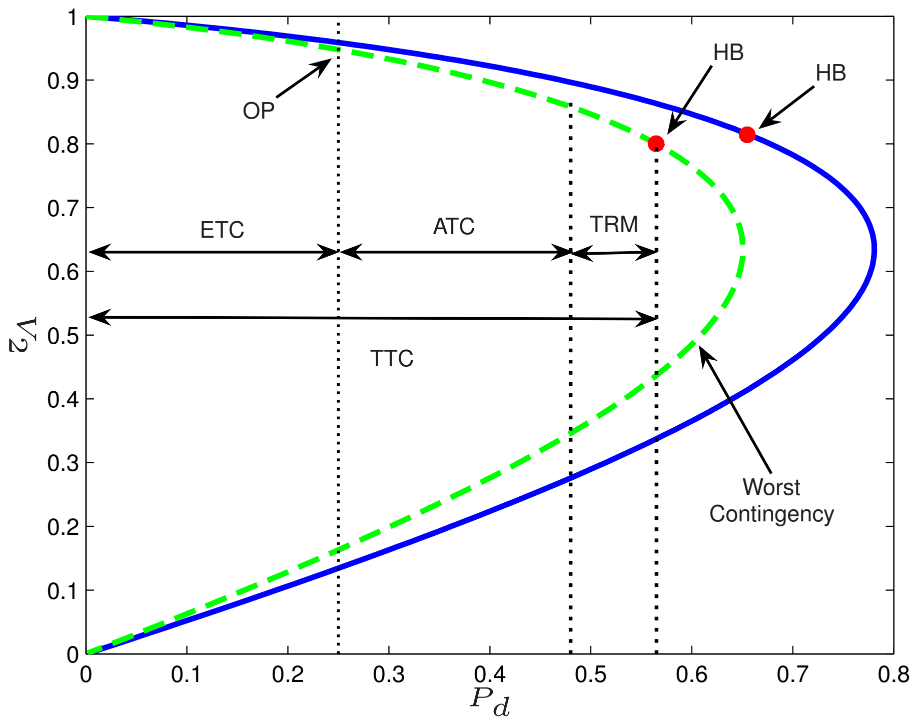
- The main assumption of the SIME method is that the two sets of critical and non-critical machines can be considered as an OMIB system.
- One may argue that there could be a case in which the system separates into three or more groups.
- Actually, there is no experimental result that shows a system separating in more than two groups since it becomes unstable.
- Thus, until a case study will prove the contrary, the main assumption of the SIME method can be considered true.

Transient Stability Applications

- In practice, transient stability studies are carried out using time-domain trial-and-error techniques.
- These types of studies can now be done on-line even for large systems.
- The idea is to determine whether a set of “realistic” contingencies make the system unstable or not (contingency ranking), and thus determine maximum transfer limits or ATC in certain transmission corridors for given operating conditions.

Transient Stability Applications

- Thus, the maximum loadability of the system may be affected by the “size” of the stability region, leading to the definition of a “true” ATC value.



Transient Stability Applications

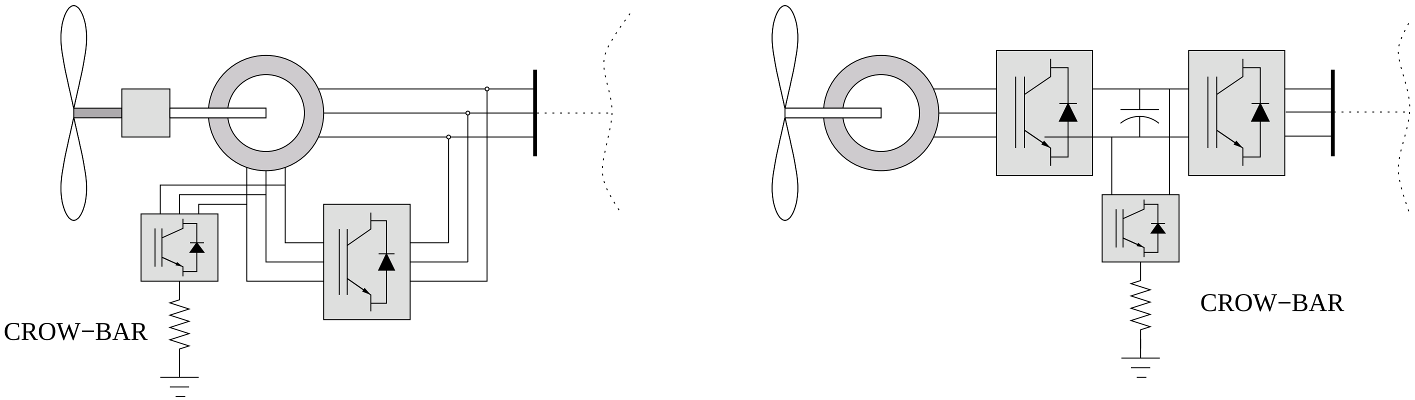
- Critical clearing times are not really an issue with current fast acting protections.
- Simplified direct methods such as the “Extended Equal Area Criterion” (Y. Xue et al., “Extended Equal Area Criterion Revisited”, *IEEE Transaction on Power Systems*, Vol. 7, No. 3, Aug. 1992, pp. 1012-1022) have been proposed and tested for on-line contingency pre-ranking, and are being implemented for practical applications through an E.U. project.

Impact of Wind Generation on Transient Stability

- Wind generators do not show the loss of synchronism as conventional synchronous generators.
- Nevertheless, even wind generators can become unstable following a fault or a line trip.
- For Type A figures, the generator can “stall”, i.e. the mechanical torque is greater than the maximum electrical one. This leads to a dangerous acceleration of the machine (short term-voltage collapse).
- In case of Type C and Type D figures, current limiters avoid unexepcted behaviors of the generators. However the mechanical power has to be properly regulated or dissipated (crow-bar).

Overcurrent Protection through Crow-Bar

- The crow-bar is a reasonable solution to allow existing generators and Type D figures standing faults.



- New generators can be equipped with overdesigned inverters that avoid disconnecting the generator during the faults (only Type C).

Operational Metrics

- Operational metrics reflect operation values showing a strong relationship with relevant system variables.
- Let define the ratio of inertialess power from wind plus import and instantaneous load plus export as follows:

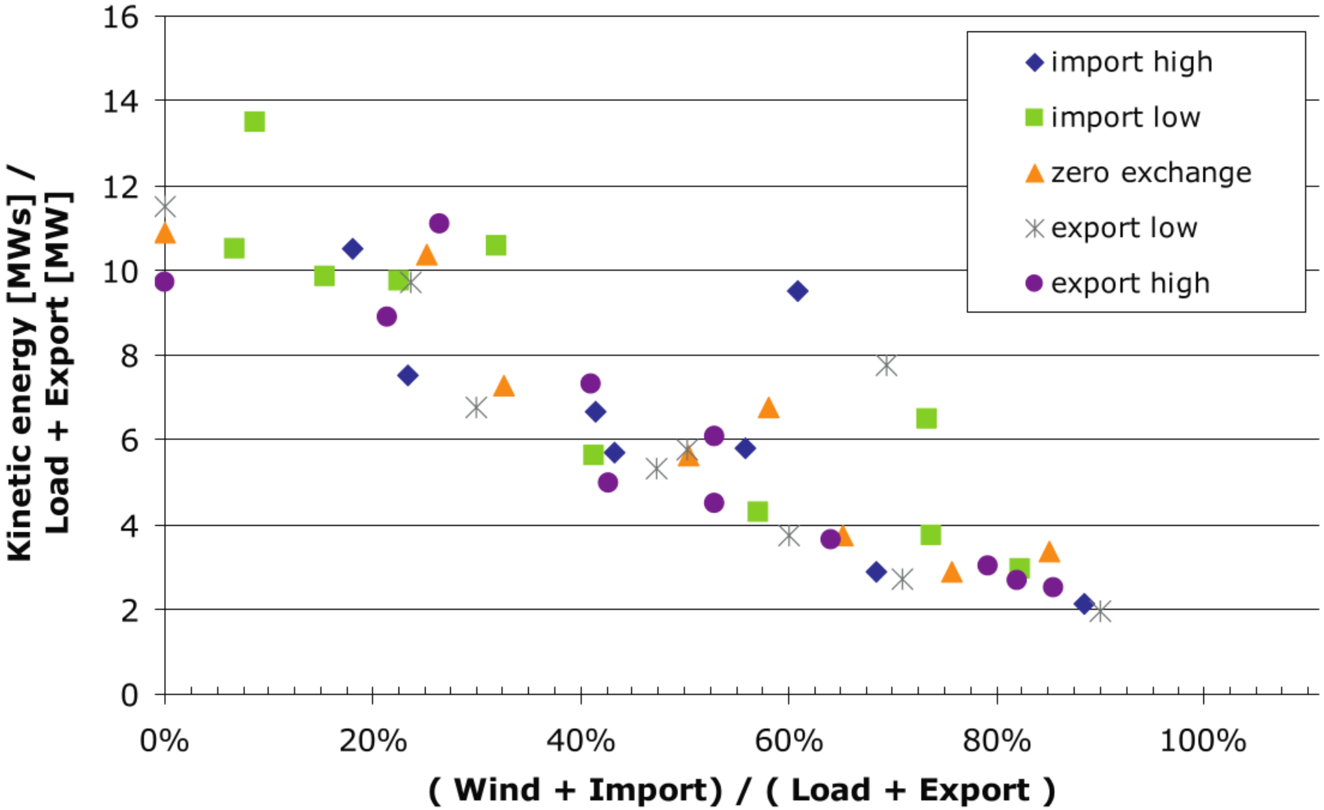
$$\mathrm{OM}_1 = \frac{P_{\text{wind}} + P_{\text{import}}}{P_{\text{load}} + P_{\text{export}}} \tag{5}$$

- Let define the ratio of kinetic energy stored in conventional generators plus load and the dispatched power of the largest infeed as follows:

$$\mathrm{OM}_2 = \frac{KE_{\text{conv gen}} + KE_{\text{load}}}{P_{\text{largest infeed}}} \tag{6}$$

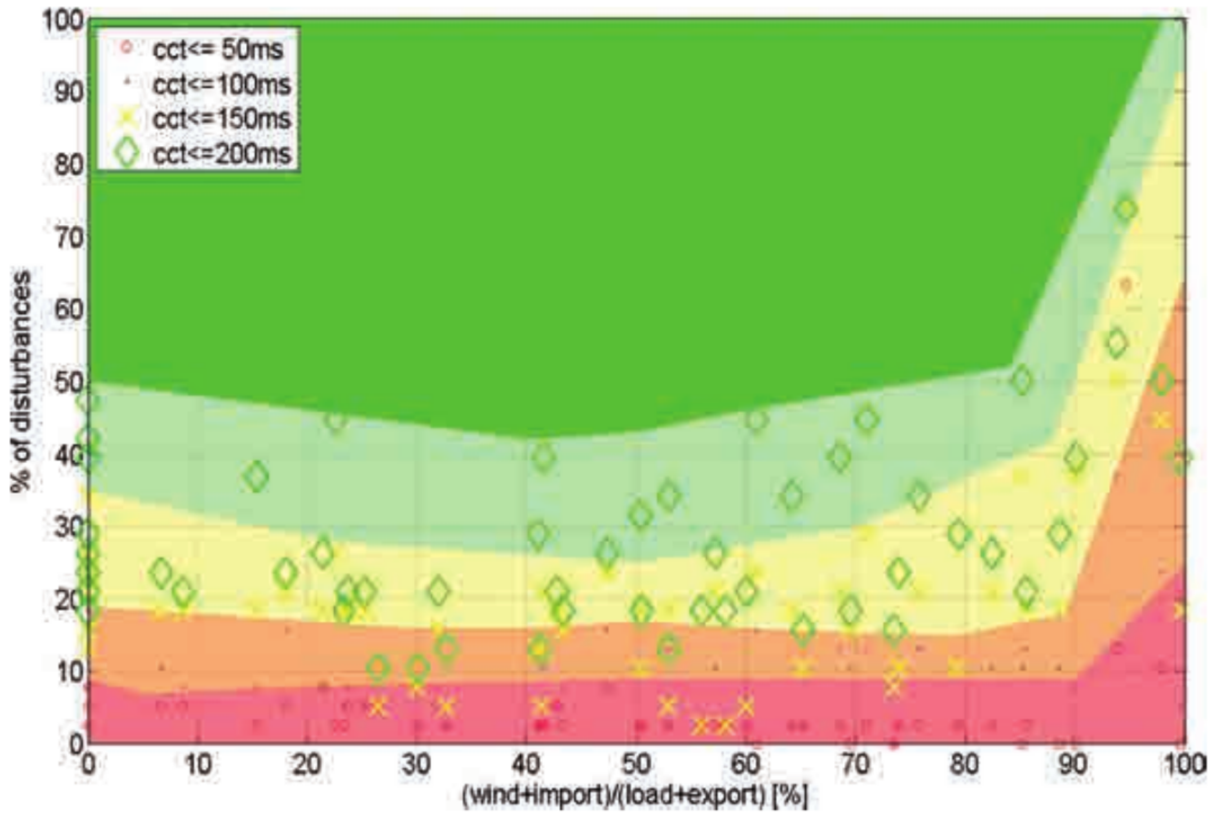
System Inertia Constant as a Function of OM_1

- System inertia vs OM_1 for the Irish system.



Example: Irish System

- Percentage of disturbances with certain CCTs as a function of OM_1 for the Irish system.



Example: Irish System

- In the Irish transmission system break times (including circuit breaker separation) are about 50-80ms.
- Eirgrid defined a share of 30%...40% of disturbances associated with critical clearance times of $\leq$150ms as tolerance range.
- In the previous figure, we observe that as long as value of OM_1 is below 70%...80%,the 30% tolerance is respected for CCTs $\leq$150ms.
- Source: “All Island TSO Facilitation of Renewables Studies”, EirGrid & Soni, 2012.