ELEC0047 - Power system dynamics, control and stability

Transient stability analysis and improvement

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(Rotor) angle stability

- Most of the electrical energy is generated by synchronous machines
- in normal system operation:
  - all synchronous machines rotate at the same *electrical* speed $2\pi f$
  - the mechanical and electromagnetic torques acting on the rotating masses of each generator balance each other
  - the phase angle differences between the internal e.m.f.'s of the various machines are constant = *synchronism*
- following a disturbance, there is an imbalance between the two torques and the rotor speed varies
- rotor angle stability deals with the ability to keep/regain synchronism after being subject to a disturbance

Small-disturbance angle stability

- Small-signal (or small-disturbance) angle stability deals with the ability of the system to keep synchronism after being subject to a "small disturbance"
- "small disturbances" are those for which the system equations can be linearized (around an equilibrium point)
- tools from linear system theory can be used, in particular eigenvalue and eigenvector analysis

Transient (angle) stability

- Transient (angle) stability deals with the ability of the system to keep synchronism after being subject to a large disturbance
- typical "large" disturbances:
  - short-circuit cleared by opening of circuit breakers
  - more complex sequences: backup protections, line autoreclosing, etc.
- the nonlinear variation of the electromagnetic torque with the phase angle of the machine's internal e.m.f. must be taken into account
  - → numerical integration of the differential-algebraic equations is used to assess the system response
- unacceptable consequences of transient instability:
  - generators losing synchronism are tripped by protections (to avoid equipment damages)
  - large angle swings create long-lasting voltage dips that disturb customers.

Remarks

Small-disturbance angle stability:

- depends on operating point and system parameters
- does not depend on the disturbance (assumed infinitesimal and arbitrary)
- is a necessary condition for operating a power system (small disturbances are always present !)

Transient stability:

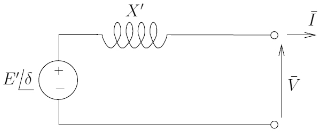
- depends on operating point and system parameters
- depends on the disturbance also
  - the system may be stable wrt disturbance D1 but not disturbance D2
  - if so, the system is *insecure* wrt D2, but as long as D2 does not happen, it can operate. . .

Objectives of this lecture

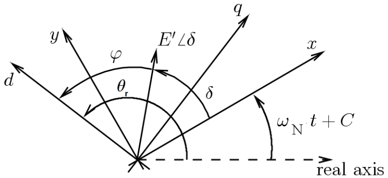
- We focus on a simple system: one machine and one infinite bus
  - allows a complete analytical treatment
  - and, hence, a good understanding of behaviour
  - is a good introduction to more complex systems
- central derivation: *equal-area criterion*
  - analogy with pendulum motion in Mechanics
  - large-disturbance stability analyzed through energy considerations
  - certainly the most classical power system stability development
    (can be found even in the simplest textbooks on power system analysis!).

“Classical model” of synchronous machine

1. damper windings d_1 et q_1 ignored
2. magnetic flux in f and q_2 windings assumed constant
   $\Rightarrow$ model valid over no more than $\simeq$ 1 second
3. same transient reactances in both axes: $X'_d = X'_q = X'$
4. stator resistance neglected.



$$\bar{V} + jX'\bar{I} = \bar{E}' = E'\angle\delta$$



Assumption # 2 $\Rightarrow$ φ constant

Using a synchronous reference (angular speed ω_N):

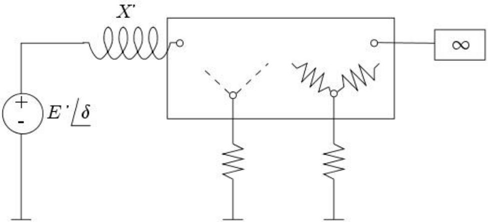
$$\frac{d}{dt}\theta_r = \frac{d}{dt}(\varphi + \delta) + \omega_N \quad \Rightarrow \quad \frac{1}{\omega_N}\frac{d}{dt}\delta = \omega_{pu} - 1$$

$$2H\frac{d}{dt}\omega_{pu} = P_{mpu} - P_{pu}$$

One-machine infinite-bus system under classical model

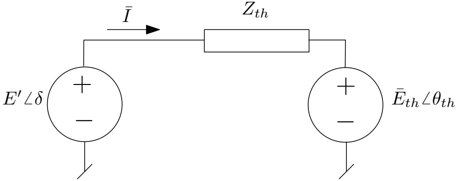
System with:

- one synchronous machine represented by classical model with constant mechanical power P_m
- one infinite bus with constant voltage
- some loads, represented as constant impedances.



System reduction:

- replace network, loads and infinite bus by their Thévenin equivalent
- merge the machine and the Thévenin impedances into Z_{th}

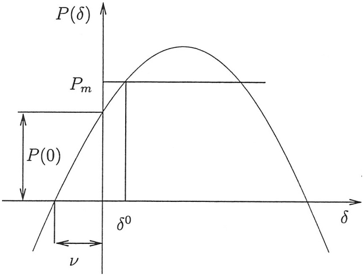


$$Y_{th} = \frac{1}{Z_{th}} = G_{th} + j\, B_{th} = |Y_{th}|\, e^{j\eta}$$

in practice: $-\pi/2 \le \eta \le 0$

Active power produced by the machine :

$$\begin{aligned} P &= real(\bar{E}'\bar{I}^*) = real[E' e^{j\delta} Y_{th}^* (E' e^{-j\delta} - E_{th} e^{-j\theta_{th}})] \\ &= G_{th} E'^2 - E' E_{th} |Y_{th}| \cos(\delta - \theta_{th} - \eta) \end{aligned}$$



$$P(0) = G_{th} E'^2 - E' E_{th} |Y_{th}| \cos(\theta_{th} + \eta)$$

$$\nu = \arccos \frac{G_{th} E'}{|Y_{th}| E_{th}} + \theta_{th} + \eta$$

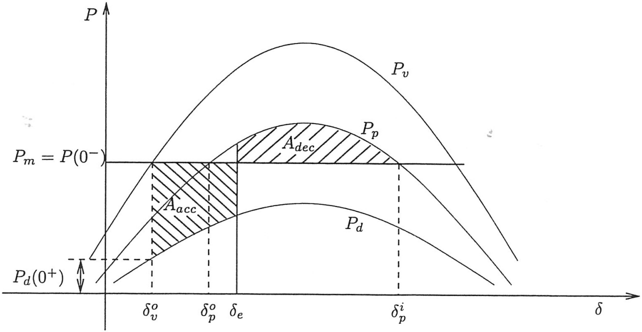
Network configurations and equilibria

Typical large disturbance:
short-circuit at $t = 0$, cleared by protections opening the faulted line at $t = t_e$

configuration	symbol	time interval	stable equilibrium
pre-fault	v	$t < 0$	$(\delta_v^o, \omega_v^o = 1)$
fault-on	d	$t \in [0\ t_e]$	-
post-fault	p	$t > t_e$	$(\delta_p^o, \omega_p^o = 1)$

- a simpler sequence of events: "self-cleared" fault (no line opening). Fictitious scenario, used in quick stability tests
- a more complex sequence of events: line reclosing
  - the fault has been cleared $\longrightarrow$ final configuration = pre-fault
  - the fault is permanent $\longrightarrow$ new line tripping (usually stays open for quite some time)
- what follows applies to any sequence
- in some cases, there may be no post-fault equilibrium (e.g. if many lines are tripped to clear the fault). In this case, the system is unstable.

One Thévenin equivalent per configuration → one $P(\delta)$ function per configuration



The relative positions of the curves is realistic:

- during fault: capability of evacuating power in the network much decreased due to low voltage
- post-fault: system weaker owing to the line tripping.

P_m and E' are supposed to remain constant throughout all configurations.

The equal-area criterion

Swing equation:

$$M\,\ddot{\delta} = P_m - P(\delta)$$

where $M = \dfrac{2H}{\omega_N}$ and $P(\delta)$ changes from one configuration to another.

Multiplying by $\dot{\delta}$:

$$M\,\ddot{\delta}\,\dot{\delta} = [P_m - P(\delta)]\,\dot{\delta}$$

Integrating from 0 to t:

$$\frac{1}{2}M\dot{\delta}^2 - \int_0^t [P_m - P(\delta)]\,\dot{\delta}\,dt = C$$

Changing variable in the integral:

$$\frac{1}{2}M\dot{\delta}^2 + \int_{\delta_v^0}^{\delta} [P(u) - P_m]du = C$$

"kinetic" energy + "potential" energy = constant

Fault-on period $(t \in [0\ t_e])$: $P(\delta) = P_d(\delta)$

At $t = 0$: $\dot{\delta} = 0$ and $\delta = \delta_v^0$. Hence, $C = 0$ and

$$\frac{1}{2} M \dot{\delta}^2 + \int_{\delta_v^0}^{\delta} [P_d(u) - P_m] du = 0$$

At $t = t_e$: $\delta = \delta_e$ and $\dot{\delta} = \dot{\delta}_e$. Hence

$$\frac{1}{2} M \dot{\delta}_e^2 = - \int_{\delta_v^0}^{\delta_e} [P_d(u) - P_m] du \tag{1}$$

Post-fault period ($t \in [t_e \; \infty[$): $P(\delta) = P_p(\delta)$

$$\frac{1}{2} M \dot{\delta}^2 + \int_{\delta_v^0}^{\delta_e} [P_d(u) - P_m] du + \int_{\delta_e}^{\delta} [P_p(u) - P_m] du = 0$$

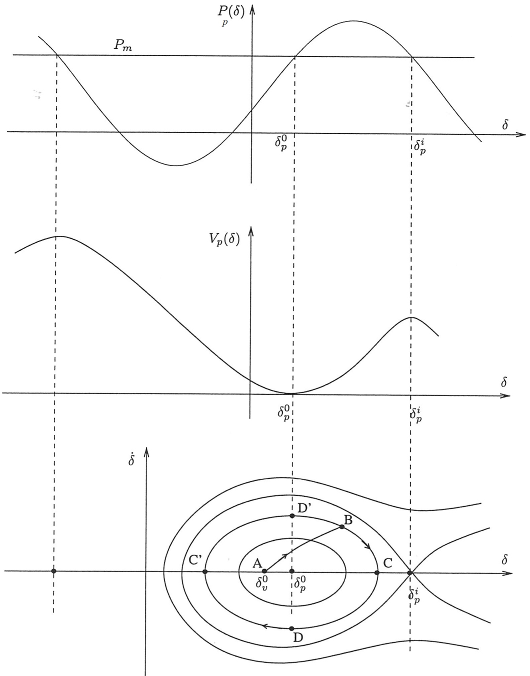
$$\frac{1}{2} M \dot{\delta}^2 + \int_{\delta_v^0}^{\delta_e} [P_d(u) - P_m] du + \int_{\delta_p^0}^{\delta} [P_p(u) - P_m] du + \int_{\delta_e}^{\delta_p^0} [P_p(u) - P_m] du = 0$$

The 2nd and 4th terms being constant:

$$\underbrace{\frac{1}{2} M \dot{\delta}^2}_{V_k} + \underbrace{\int_{\delta_p^0}^{\delta} [P_p(u) - P_m] du}_{V_p} = K$$

V_k: kinetic energy

V_p: potential energy in final configuration with reference in δ_p^0


$P(\delta)$
P_m
δ
δ_p^0
δ_p^i
$V_p(\delta)$
δ
δ_p^0
δ_p^i
$\dot{\delta}$
D'
B
C'
A
C
δ
δ_v^0
δ_p^0
δ_p^i
D

- for small enough t_e values, the system trajectory in the $(\delta, \dot{\delta})$ state space, is a closed curve along which:

$$\forall t \geq t_e \ : \quad V_k(t) + V_p(t) = K = V_k(t_e) + V_p(t_e)$$

- at points C and C': potential energy is maximum, kinetic energy is zero
- at points D and D': potential energy is zero, kinetic energy is maximum
- there is a t_e value for which the trajectory passes through the unstable equilibrium point $(\delta_p^i, 0)$. For this and for larger t_e values, stability is lost
- the domain of attraction of the post-fault stable equilibrium $(\delta_p^0, 0)$ is the part of the $(\delta, \dot{\delta})$ state space bounded by that trajectory; instability results from a lack of attraction towards this equilibrium
- if the system model was dissipative (as the real system is, e.g. to due damping) the stable trajectories would spiral up to $(\delta_p^0, 0)$ and $V_k(t) + V_p(t)$ would decrease with time

Stability condition

System stable if $(\delta_e, \dot{\delta}_e)$ belongs to the domain of attraction of $(\delta_p^0, 0)$, i.e. if

$$\frac{1}{2} M \dot{\delta}_e^2 + \int_{\delta_p^0}^{\delta_e} [P_p(u) - P_m] du < \int_{\delta_p^0}^{\delta_p^i} [P_p(u) - P_m] du$$

or, using (1):

$$-\int_{\delta_v^0}^{\delta_e} [P_d(u) - P_m] + \int_{\delta_p^0}^{\delta_e} [P_p(u) - P_m] du < \int_{\delta_p^0}^{\delta_p^i} [P_p(u) - P_m] du$$

$$\Leftrightarrow \quad \int_{\delta_v^0}^{\delta_e} [P_m - P_d(u)] du + \int_{\delta_e}^{\delta_p^i} [P_m - P_p(u)] du < 0$$

$$\Leftrightarrow \quad A_{acc} - A_{dec} < 0$$

A_{acc} = "accelerating area", corresponding to $P(\delta) < P_m$

A_{dec} = "decelerating area", corresponding to $P(\delta) > P_m$.

Critical clearing time

Maximum duration t_c of the fault-on period after which the system still returns to (or remains in the neighbourhood of) its post-fault equilibrium

Let us denote by δ_c the rotor angle at $t = t_c$, i.e. $\delta_c = \delta(t_c)$.

The system is at the stability limit when $\delta_e = \delta_c$ and $A_{acc} - A_{dec} = 0$, or

$$\int_{\delta_v^0}^{\delta_c} [P_m - P_d(u)]du + \int_{\delta_c}^{\delta_p^i} [P_m - P_p(u)]du = 0$$

- solve the above equation with respect to δ_c
- integrate the system trajectory in the fault-on configuration, to find the time t_c such that $\delta_c = \delta(t_c)$.
  - except in some simple configurations (e.g. $P_d = 0$), this integration has to be performed numerically.

Extensions of the equal-area criterion

Accounting for damping

- stability becomes asymptotic
- equal-area criterion pessimistic in terms of δ_c and t_c
- the first angle deviation is little decreased by damping. Damping is effective in subsequent oscillations, for which a more detailed model is required.

Two-machine system

$$M_1\ddot{\delta}_1 = P_{m1} - P_1(\delta_1 - \delta_2) \qquad M_2\ddot{\delta}_2 = P_{m2} - P_2(\delta_1 - \delta_2)$$

can be combined into:

$$\ddot{\delta}_1 - \ddot{\delta}_2 = \frac{P_{m1}}{M_1} - \frac{P_{m2}}{M_2} - \left(\frac{P_1(\delta_1 - \delta_2)}{M_1} - \frac{P_2(\delta_1 - \delta_2)}{M_2}\right) \tag{2}$$

Defining:

$$M_{12} = \frac{M_1 M_2}{M_1 + M_2} \qquad \delta_{12} = \delta_1 - \delta_2$$

$$P_{m12} = \frac{P_{m1} M_2 - P_{m2} M_1}{M_1 + M_2} \qquad P_{12} = \frac{P_1(\delta_{12})\, M_2 - P_2(\delta_{12})\, M_1}{M_1 + M_2}$$

(2) can be rewritten as:

$$M_{12}\, \ddot{\delta}_{12} = P_{m12} - P_{12}(\delta_{12})$$

which is the swing equation of an equivalent one-machine infinite-bus system.

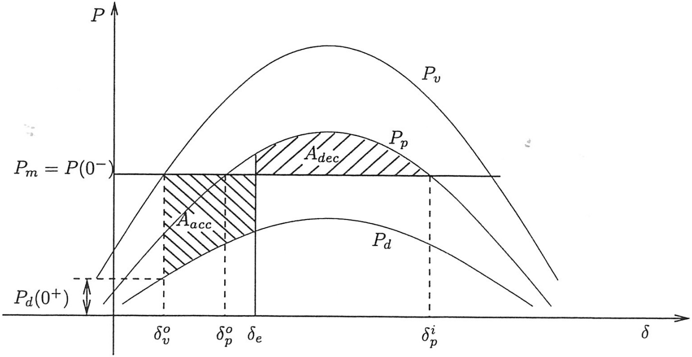
Remark. If $M_1 = M_2 = M$, then $M_{12} = M/2$: two machines of inertia M oscillate against each other as one machine of inertia $M/2$ against an infinite bus.

Extensions to multi-machine systems ?

- rigorously speaking, the equal-area criterion does not apply to systems with more than two machines
- but the underlying energy concept inspired much research into "direct methods" for transient stability analysis
- it also inspired "hybrid" methods:
  - detailed time simulation complemented with stability assessment inspired of equal-area criterion
  - relying on a two-machine equivalent: one machine corresponds to the machine(s) loosing synchronism, the other machine to the rest of the system

- the concept of critical clearing time t_c applies, whatever the complexity of the model
- "critical group": the set of machines which loose synchronism with respect to the remaining of the system, for a clearing time a little larger than t_c.

Transient stability improvement



Decrease the accelerating area and/or increase the decelerating area

Modifying the pre-disturbance operating point:

- reducing the active power generation
- operating with higher excitation

Automatic emergency controls:

- actions on network:
  - line auto-reclosing
  - fast series capacitor reinsertion
  - fast fault clearing - single pole breaker operation
- actions in generators:
  - (turbine) fast valving
  - generation shedding
- action on "load": dynamic braking

Other means:

- equip generators with fast excitation system
- control voltage at intermediate points in a long corridor: through synchronous condensers or static var compensators.

Modifying the pre-disturbance operating point

Active power generation

Decreasing P_m:

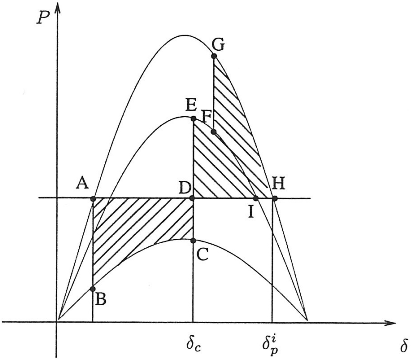
- decreases the accelerating area
- increases the decelerating area
- (side effect: pre- and post-fault equilibria also modified)

Reactive power generation

$$E'(0^+) = E'(0^-) = \sqrt{(V + X'\frac{Q}{V})^2 + (X'\frac{P}{V})^2}$$

- For given values of V and P, increasing the reactive power production Q increases the emf E' which prevails in the post-fault period
- this, in turn, somewhat increases the magnitude of the $P(\delta)$ curve
- and, hence, the decelerating area and the stability margin.

Line auto-reclosing



- coming back to pre-fault configuration increases the decelerating area
- reclosing possible only after air has recovered its insulating properties (delay $\simeq$ 0.5 s).

Fault clearing

Fault clearing delay:

- should be as short as possible
- typical values : 5 cycles (0.1 s at 50 Hz)
- stability must be checked with respect to scenarios where primary protection fails clearing the fault (due to protection or breaker malfunction), which is eliminated by the slower backup protection.

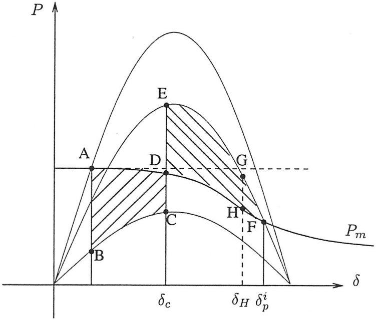
Single-phase tripping-reclosing:

- most of the faults ($\simeq$ 75 %) are of the phase-ground type
- for such faults, it is of interest to open the faulted phase *only* and keep the other two in service $\Rightarrow$ protect each phase separately
- in case of 3-phase fault with malfunction of one breaker, the other two operate and the fault changes into phase-ground (less severe, cleared by backup protection)
- at EHV level, the three poles of the breaker are usually separate (for insulation reasons); it does not cost much to add a separate control on each phase.

Turbine fast valving

Principle

Decrease the mechanical torque as fast as possible



$P_m(\delta)$ curves obtained from the $P_m(t)$ and $\delta(t)$ evolutions (eliminating t)

- fast valving not fast enough to act during fault
- main effect = increase of decelerating area.

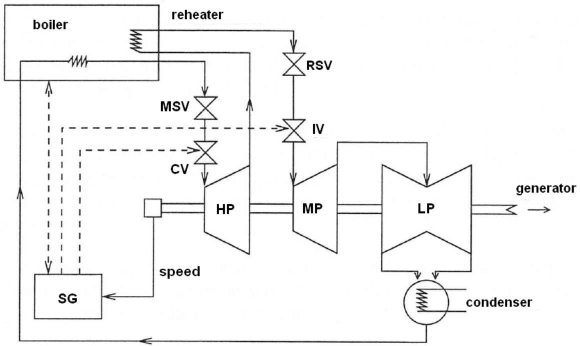
Speed of action

- mechanical torque must be decreased rapidly: typically less than 0.5 s
- gates of hydro turbines cannot be moved so quickly $\Rightarrow$ applies to steam turbines
- delays:
  - to take the decision from measurements (selectivity !)
  - to close the valves. They are closed much faster than in normal operating conditions by emptying the servomotor of its oil.

Decision criterion

- cannot rely on rotor speed *only*: due to inertia it takes time to reach an emergency value
- additional signal: rotor acceleration, drop of electrical power, difference between electrical power and an image of mechanical power.

Implementation



Action:

- on Control Valves (CV), normally controlled by Speed Governor (SG)
- on Intercept Valves (IV): fully open in normal conditions, closed to cancel the torque developed in Medium Pressure (MP) and Low Pressure (LP) bodies

Temporary valving:

- P_m returns to its pre-disturbance value
- typical sequence:
  - intercept valves are closed for a short time, then re-opened
  - control valves are left unchanged

Sustained valving:

- P_m remains at a lower than pre-disturbance value
  - e.g. because post-disturbance network configuration expected to be too weak
  - even if it produces less, the generator remains synchronized with the network
- typical sequence:
  - intercept valves are quickly closed
  - control valves are closed partially and at a lower speed
  - intercept valves are re-opened
  - control valves remain partially closed.

Valve re-opening:

- after some delay due to servomotors
- with a limited speed to avoid wearing the turbine, but this is not an issue if stability has been preserved.

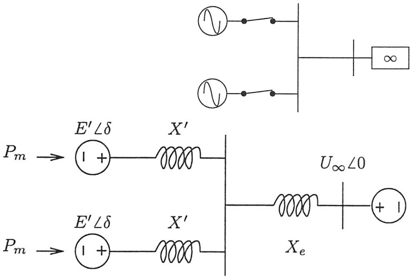
Generation shedding

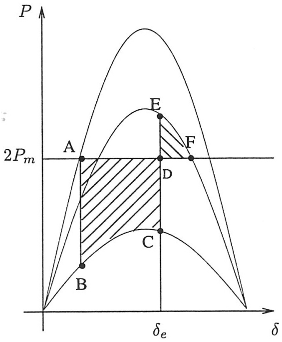
Principle

Trip one or several generators in order to preserve synchronous operation of the remaining generators

- applies mainly to hydro plants
  - those including multiple generators
  - combinations of 1, 2, 3, . . . generators can be dropped
- may be also used with thermal plants:
  - tripped generator not stopped, used to feed its own auxiliaries (called *tripping to houseload*)
  - plant remains in operation and can be re-synchronized with shorter delay
- usually applies to large power plants evacuating power through long corridors.

Simple illustrative example





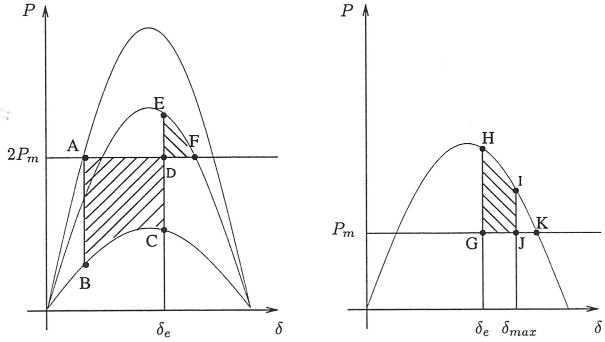
Assumptions:

- two identical machines oscillating in phase ("coherent" machines)
- each machine: inertia M, transient reactance X', mechanical power P_m
- both machines = machine of inertia $2M$, reactance $X'/2$, mech. power $2\,P_m$

Equal-area criterion:

- area ABCD > area DEF $\Rightarrow$ system unstable
- ABCD area = energy acquired by both machines at the time the fault is cleared.

Assume that one machine is tripped intentionally.
Assume for simplicity that this takes place at the time the fault is cleared.



The right figure relates to the remaining generator. Compared to the left figure:

- the $P(\delta)$ curve has lower magnitude, since the reactance between the emf and the infinite bus is $X_e + X'$ instead of $X_e + \frac{X'}{2}$
- the mechanical power is P_m instead of $2P_m$.

The system is stable if area GHK is larger than half of area ABCD .