Simple transmission stability

Interconnected systems are operated in a synchronous operation (the same frequency) if active power is less than a limit value. Otherwise, the system gets out of synchronism (parallel operation stability disturbance).

Steady-state stability – is the ability of the system to remain in the synchronous operation during small changes.

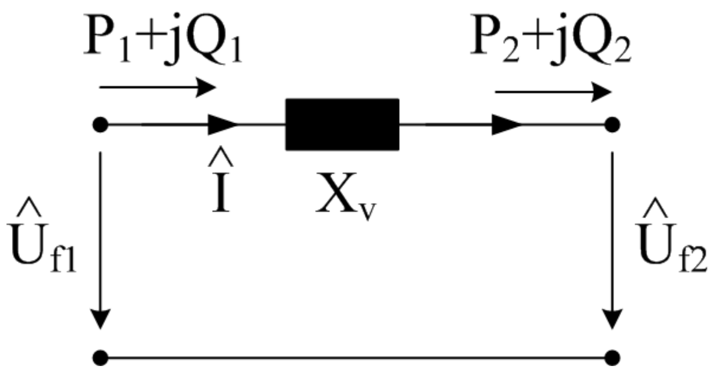
Transient stability – is the ability of the system to remain in the synchronous operation also during sudden large changes (loading, ES parameters).

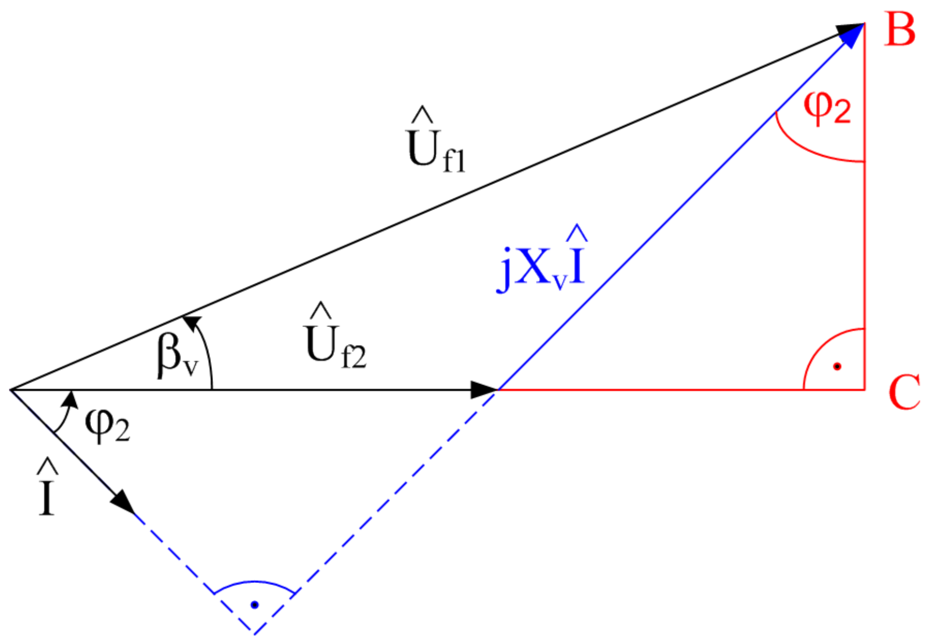
Electromechanical transient events → a need to have a sufficient power reserve during the steady-state operation.

Importance: sources and systems collaboration keeping, AC power lines length limiting

Basic relations

Assumption: only longitudinal reactance is considered
Transmission angle (power angle) β_v – between voltages at both transmission ends





Consumed active and reactive power (single phase)

$$P_f = U_{f2} I \cos\varphi_2 \qquad\qquad Q_f = U_{f2} I \sin\varphi_2$$

$$\overline{BC} \sim X_v I \cos\varphi_2 = U_{f1} \sin\beta_v \qquad X_v I \sin\varphi_2 + U_{f2} = U_{f1} \cos\beta_v$$

$$I \cos\varphi_2 = \frac{U_{f1}}{X_v} \sin\beta_v \qquad I \sin\varphi_2 = \frac{U_{f1}\cos\beta_v}{X_v} - \frac{U_{f2}}{X_v}$$

Transmission power equation

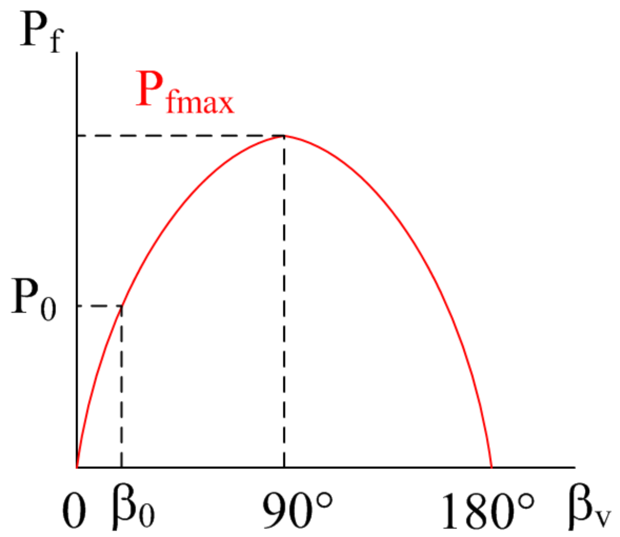
$$P_f = \frac{U_{f1} U_{f2}}{X_v} \sin\beta_v \qquad Q_f = \frac{U_{f1} U_{f2} \cos\beta_v}{X_v} - \frac{U_{f2}^2}{X_v}$$

$0^\circ \div 90^\circ$ stable area

$90^\circ \div 180^\circ$ unstable area

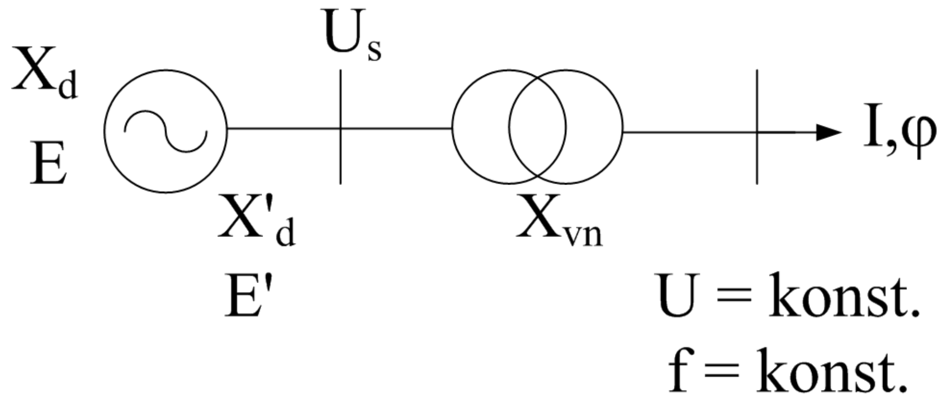
$\beta_v = 90^\circ$ steady-state stability limit

$$P_{f\,max} = \frac{U_{f1} U_{f2}}{X_v}$$



In addition to power lines also reactance of generators, transformers … are added → higher power angle. Generators have the biggest influence (X).

Turbo-alternator operating to an infinite power system



$$X_{dc} = X_d + X_{vn}$$

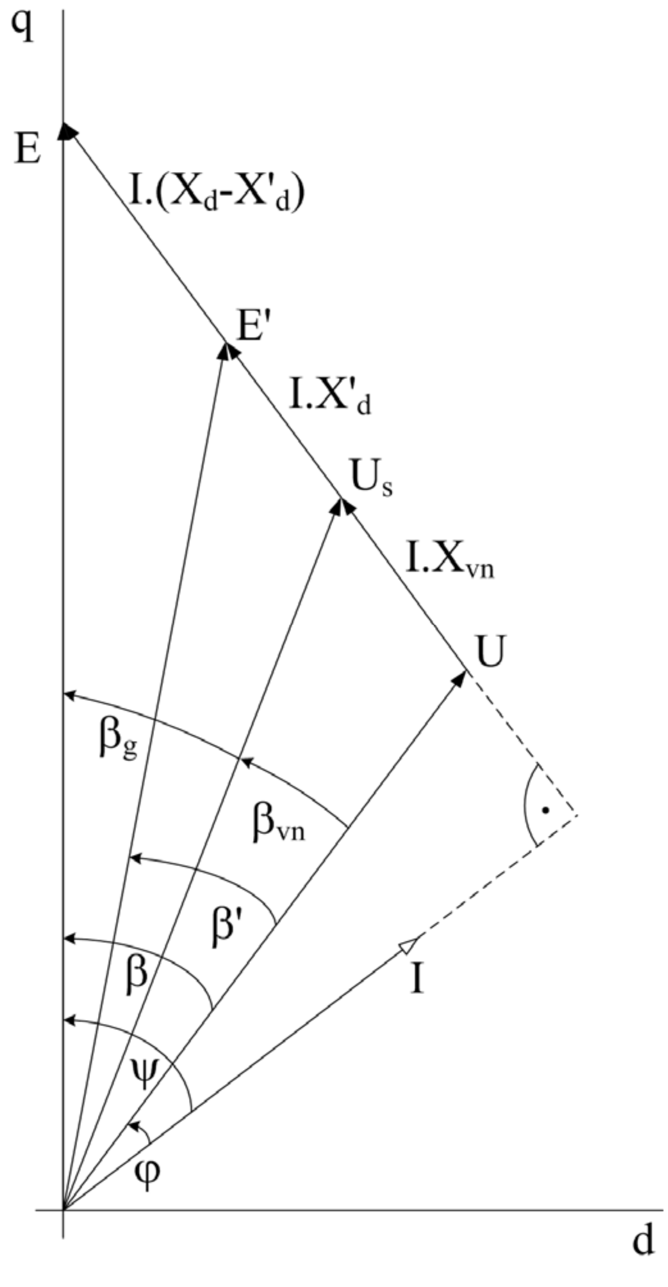
Alternator internal power

$$P = \frac{E \cdot U}{X_{dc}} \sin\beta$$

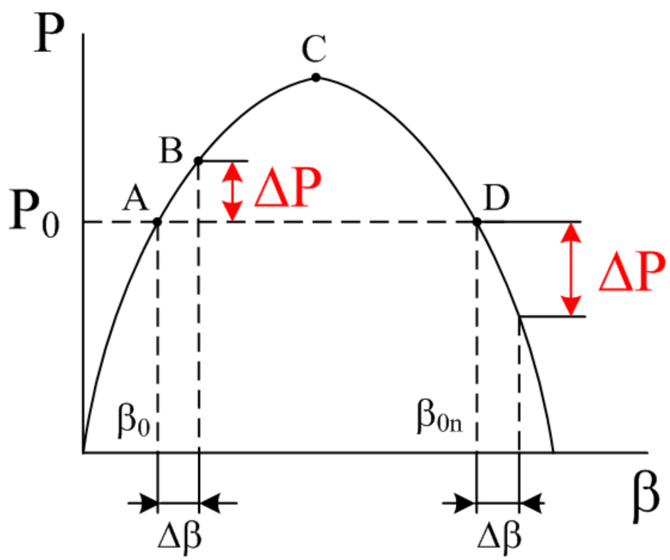
$$Q_i = \frac{E^2}{X_{dc}} - \frac{E \cdot U}{X_{dc}} \cos\beta$$

Valid for the infinite power system (f, U = const., X = 0), constant source voltage (E), smooth-core rotor (turbo-alternator).

Stability is influenced by transmitted power (P), source voltage (E) and transmission configuration (X) → longitudinal compensation (C), higher excitation



System steady-state stability



Stable state

$$P_0 = P_m$$

(electrical (generator) = mechanical (turbine), no losses)

$\omega_0 = \text{konst.}$ (system and machine)

Turbine mechanical power is constant – it doesn't depend on β but depends on ω (P-f control).

Point A: rotor acceleration $\rightarrow \Delta\beta \rightarrow (P_0+\Delta P) \rightarrow P_{el} > P_{mech} \rightarrow$ rotor deceleration $\rightarrow$ stabilization $\rightarrow$ point A is stable

Point D: rotor acceleration $\rightarrow \Delta\beta \rightarrow (P_0-\Delta P) \rightarrow P_{el} < P_{mech} \rightarrow$ rotor acceleration $\rightarrow$ loss of synchronism $\rightarrow$ point D is unstable

Synchronization power

$$P_c = \frac{dP}{d\beta} = \frac{E \cdot U}{X_{dc}} \cos\beta$$

Stable area

$$P_c > 0$$

Steady-state stability limit

$$P_c = 0$$

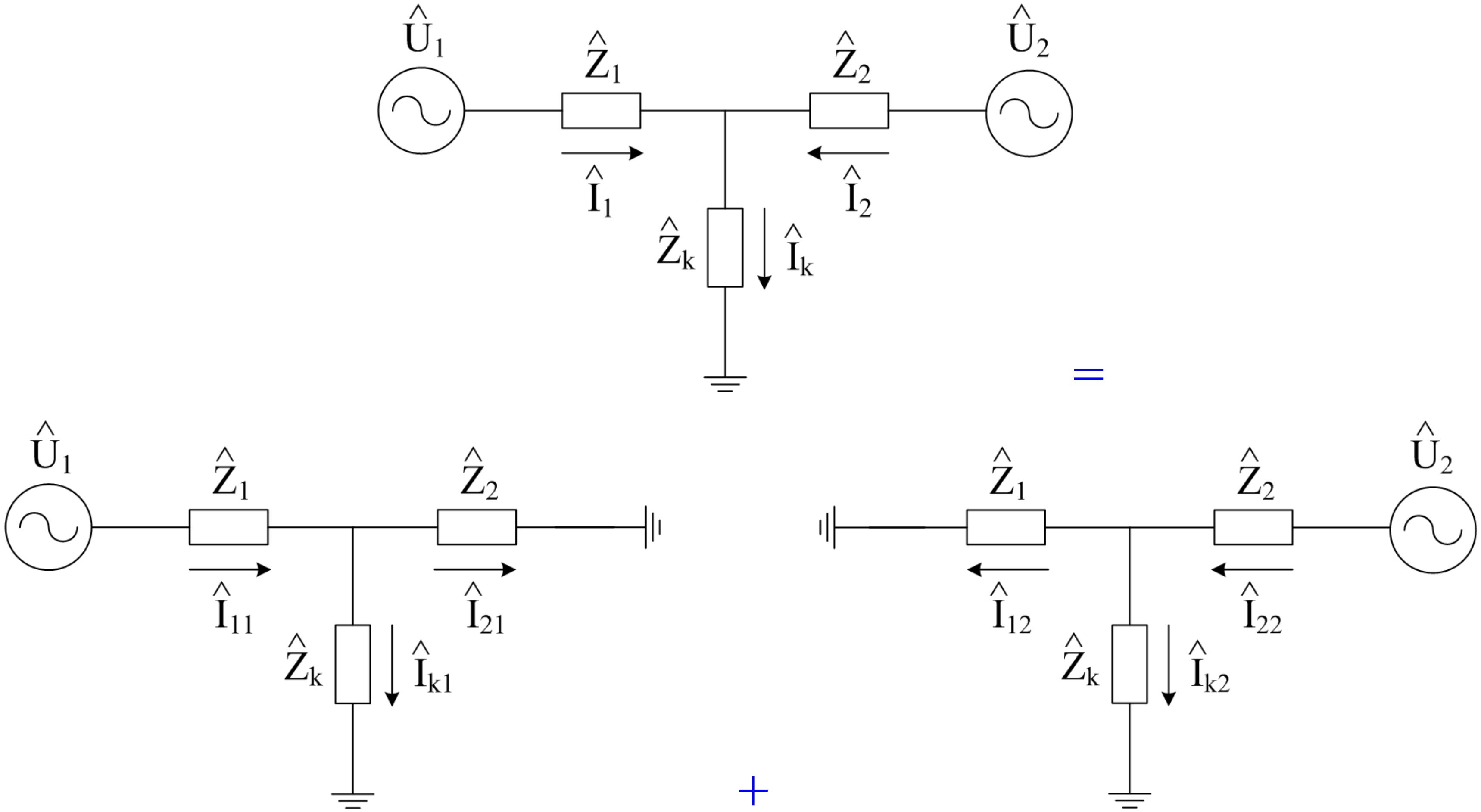
Coefficient of reserved power (usually above 20%)

$$k_P = \frac{P_m - P_0}{P_0}$$

Note: More machines → need to monitor P curve of each machine

Two-machine task with a load (fault)

Superposition



$$\hat{I}_1 = \hat{I}_{11} - \hat{I}_{12} \qquad \hat{I}_2 = \hat{I}_{22} - \hat{I}_{21} \qquad \hat{I}_k = \hat{I}_{k1} + \hat{I}_{k2}$$

$$\hat{I}_{11} = \frac{\hat{U}_1}{\hat{Z}_{11}} \quad \hat{I}_{22} = \frac{\hat{U}_2}{\hat{Z}_{22}} \quad \hat{I}_{12} = \frac{\hat{U}_2}{\hat{Z}_{12}} \quad \hat{I}_{21} = \frac{\hat{U}_1}{\hat{Z}_{21}}$$

$$\hat{Z}_{11} = \hat{Z}_1 + \frac{\hat{Z}_2 \hat{Z}_k}{\hat{Z}_2 + \hat{Z}_k}$$

$$\hat{Z}_{22} = \hat{Z}_2 + \frac{\hat{Z}_1 \hat{Z}_k}{\hat{Z}_1 + \hat{Z}_k}$$

$$\hat{Z}_{12} = \hat{Z}_{21} = \hat{Z}_1 + \hat{Z}_2 + \frac{\hat{Z}_1 \hat{Z}_2}{\hat{Z}_k}$$

$$\hat{S}_1 = \hat{U}_1 \hat{I}_1^* = \frac{U_1^2}{\hat{Z}_{11}^*} - \frac{\hat{U}_1 \hat{U}_2^*}{\hat{Z}_{12}^*}$$

$$\hat{S}_1 = \frac{U_1^2}{\hat{Z}_{11}^*} - \frac{U_1 U_2}{\hat{Z}_{12}^*} e^{j\beta}$$

$$P_1 = \mathrm{Re}\{\hat{S}_1\} \qquad Q_1 = \mathrm{Im}\{\hat{S}_1\}$$

For R=0:

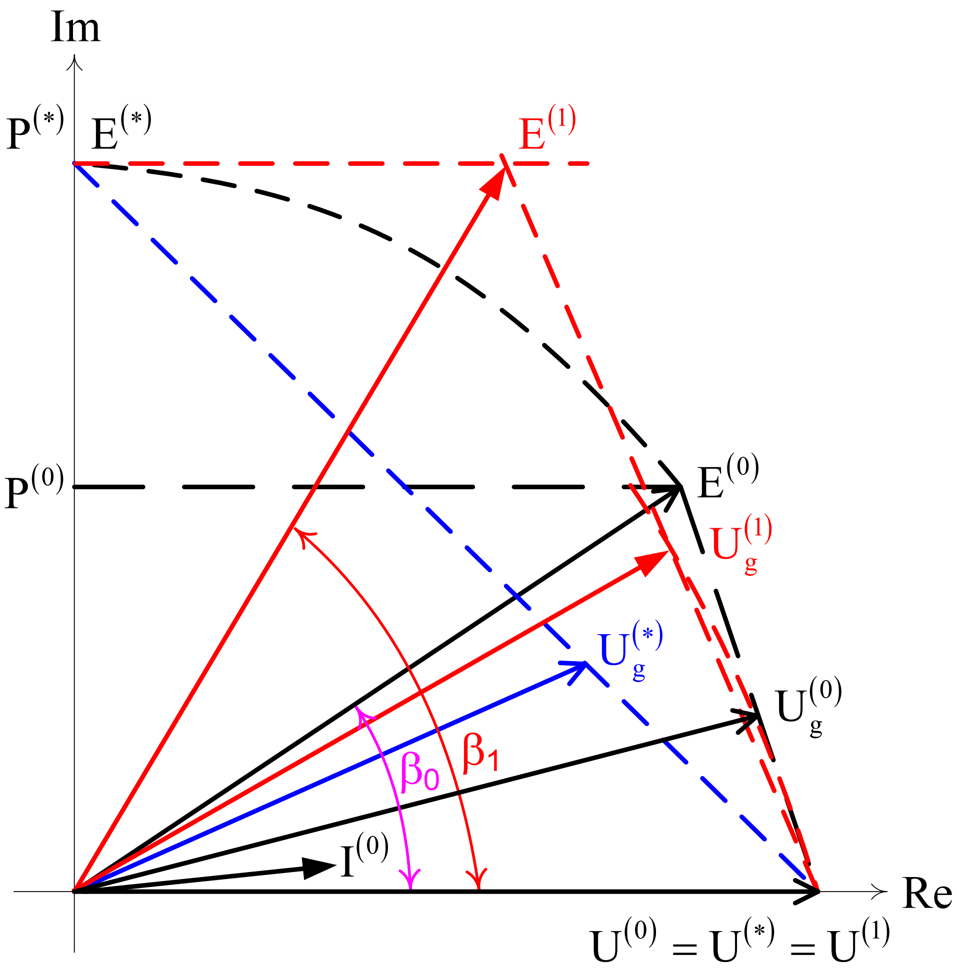
$$\hat{S}_1 = \frac{U_1^2}{-jX_{11}} - \frac{U_1 U_2}{-jX_{12}} \left(\cos\beta + j\sin\beta\right)$$

$$P_1 = \frac{U_1 U_2}{X_{12}} \sin\beta$$

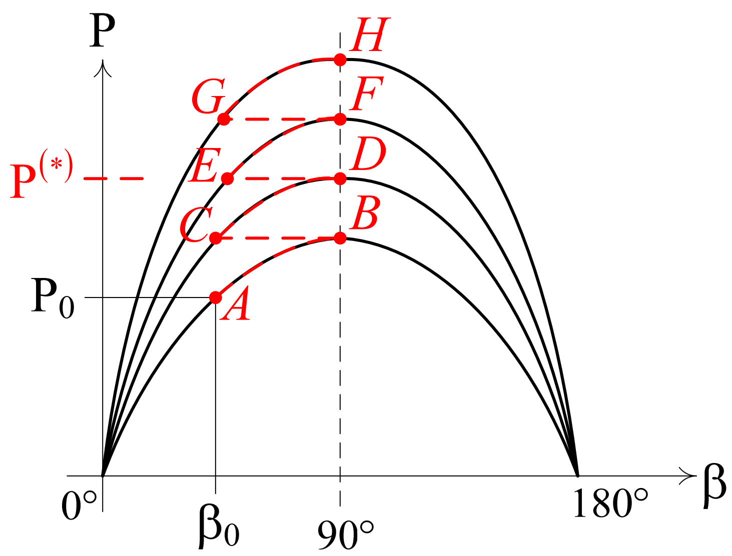
$$Q_1 = \frac{U_1^2}{X_{11}} - \frac{U_1 U_2}{X_{12}} \cos\beta$$

Excitation control

$$P = \frac{E \cdot U}{X_{dc}} \sin\beta = k \cdot E \cdot \sin\beta$$



External char. (U_g = konst.) →



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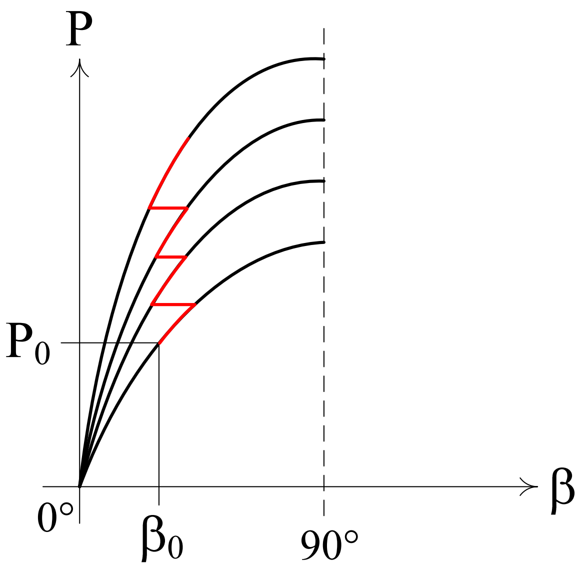

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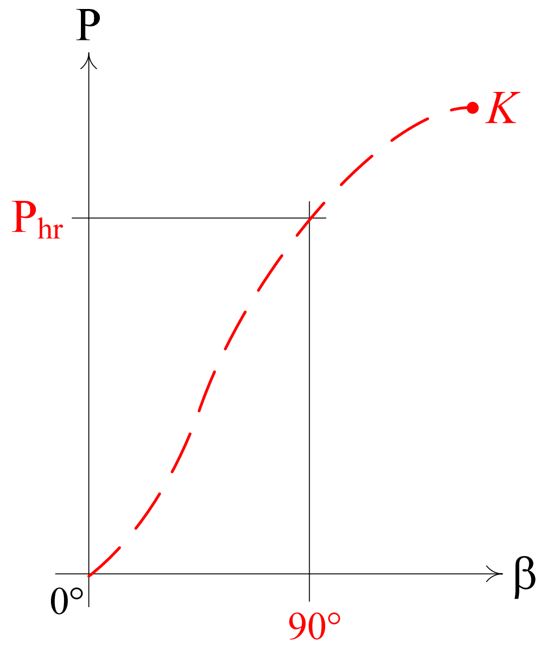


Machine with salient poles

$$I \cdot X_q \cdot \cos\varphi = E_q \cdot \sin\beta$$

$$E_q = E - I_d \cdot (X_d - X_q)$$

$$I_d \cdot X_d = E - U_g \cos\beta$$

Modifications

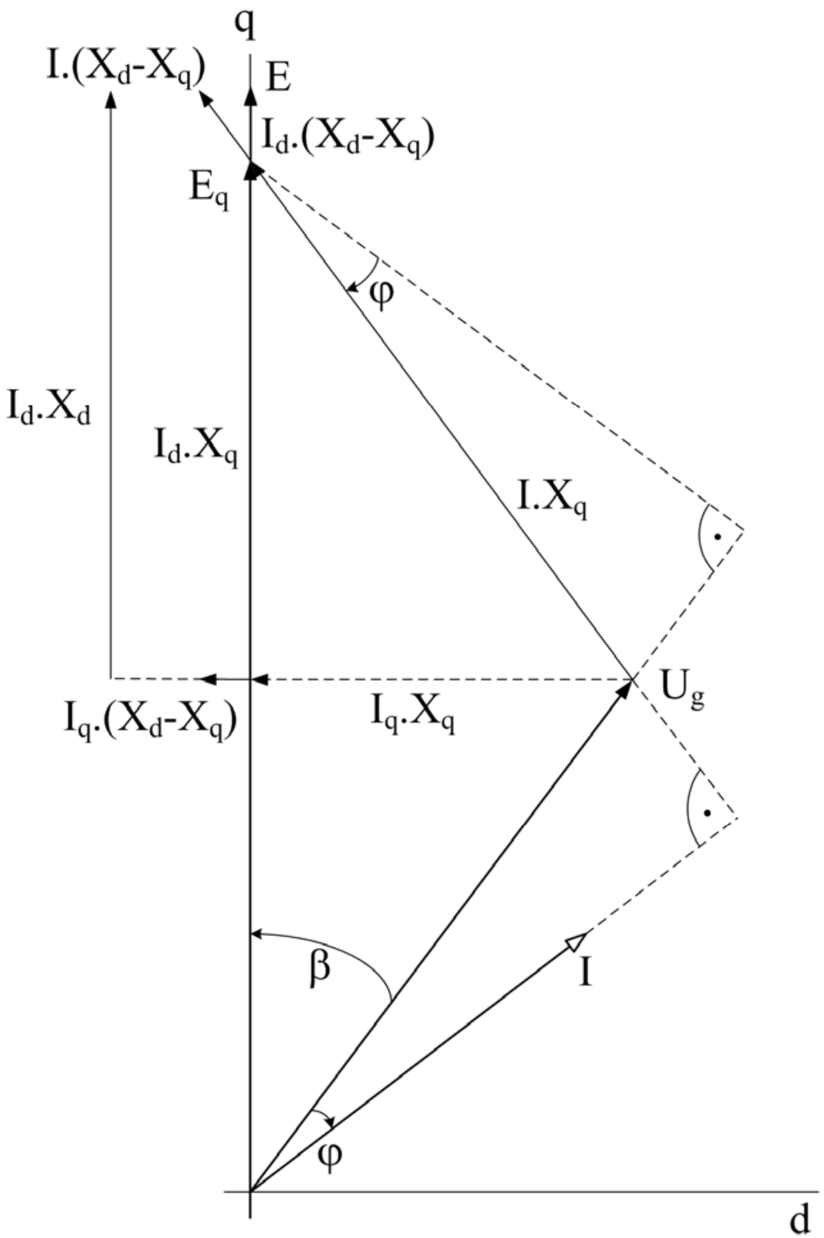
$$I_d = \frac{E}{X_d} - \frac{U_g}{X_d}\cos\beta$$

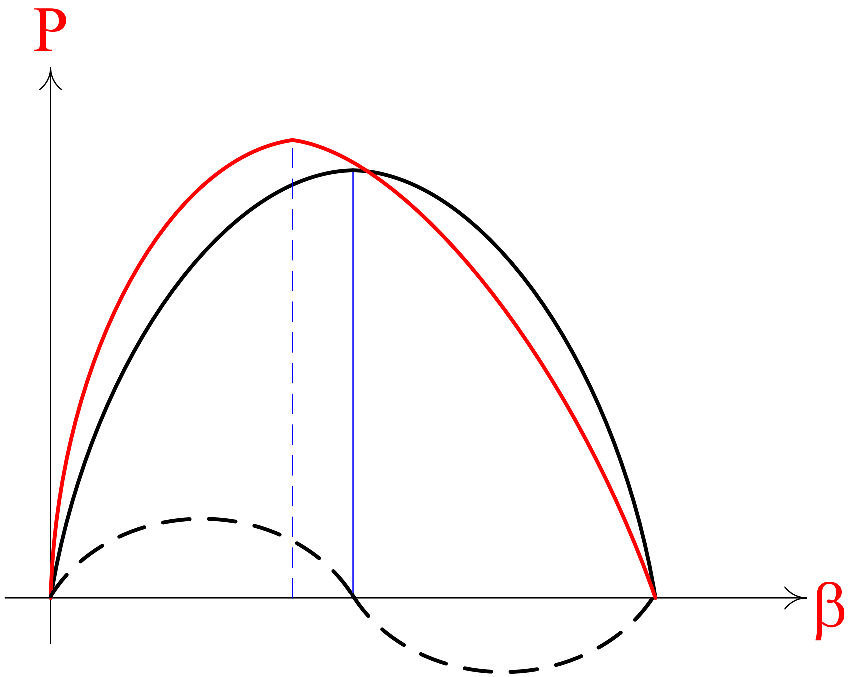
$$E_q = E \cdot \frac{X_q}{X_d} + U_g \cos\beta \cdot \frac{X_d - X_q}{X_d}$$

Generator power

$$P = U_g \cdot I \cdot \cos\varphi$$

$$P = \frac{E \cdot U_g}{X_d}\sin\beta + \frac{U_g^2}{2} \cdot \frac{X_d - X_q}{X_d X_q}\sin 2\beta$$



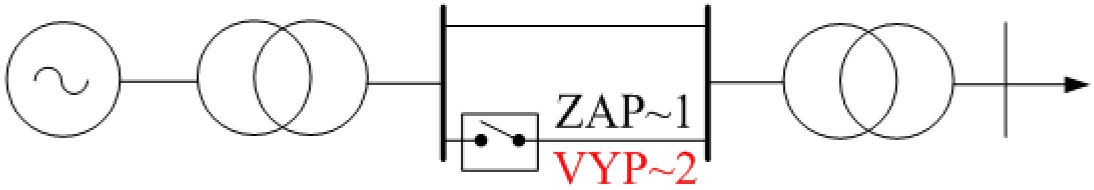


Generator to the system through series impedances

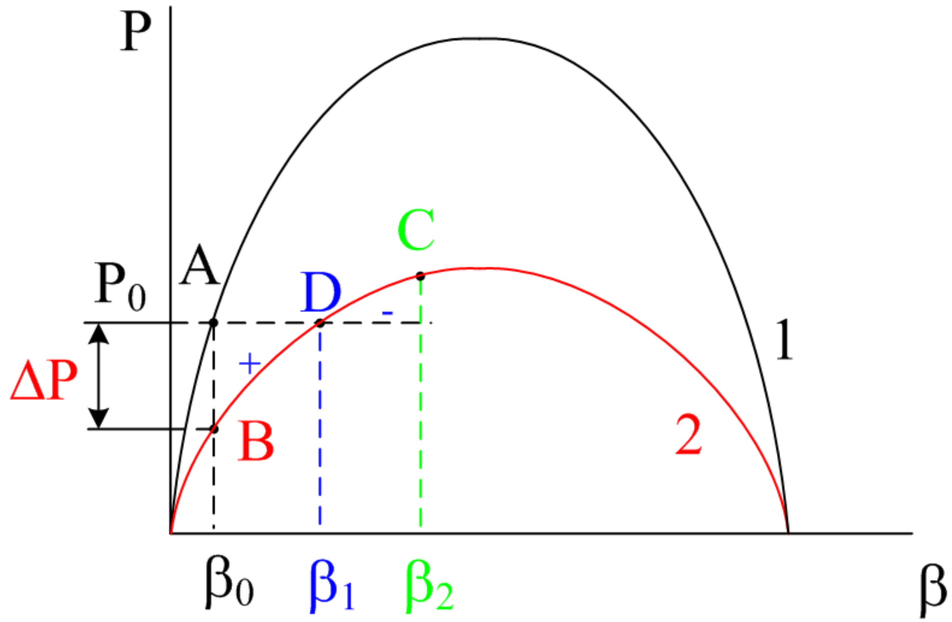
$$P = \frac{E \cdot U_g}{X_d + X_{vn}} \sin\beta + \frac{U_g^2}{2} \cdot \frac{X_d - X_q}{(X_d + X_{vn})(X_q + X_{vn})} \sin 2\beta$$

System transient stability

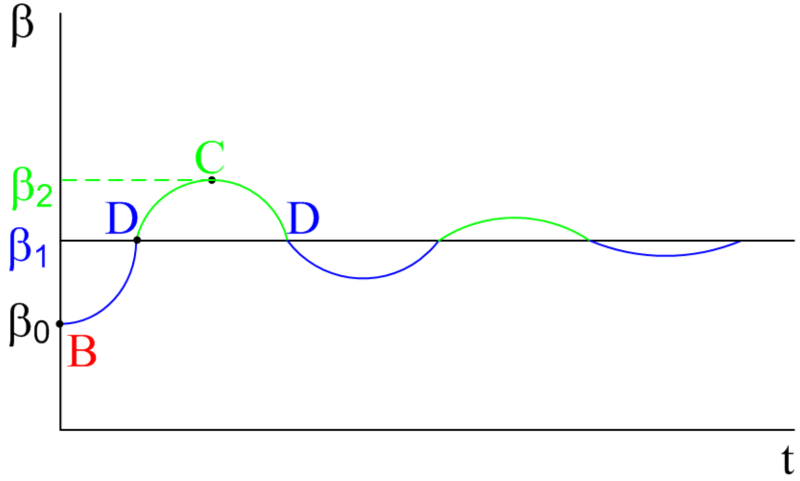
Parameters change in the system → sudden power changes → possible loss of stability.



$X_2 > X_1$



- point A before the change
- inertia → β_0 doesn't change in a step → generator power drops by ΔP
- $P_m - P_{el}$ = accelerating power
- in the point D $\omega > \omega_0$ → β grows up to the point C, gradual deceleration
- stabilization after several swings in the point D (a few seconds period)



If the point C is too far (ΔP accelerating) → loss of synchronism.

Behaviour solution $\beta = f(t)$

Motion equation

$$W_k = \frac{1}{2} J\omega^2$$

$$P_a = P_m - P_e = \frac{dW_k}{dt} = \frac{1}{2} J 2\omega \frac{d\omega}{dt}$$

$P_a > 0$ - accelerating power

$P_a < 0$ - decelerating power

Swing equation

$$P_m - \frac{E \cdot U}{X_{dc}} \sin\beta(t) = J\omega(t) \frac{d\omega(t)}{dt}$$

$$\omega(t) = \omega_0 + \frac{d\beta(t)}{dt}$$

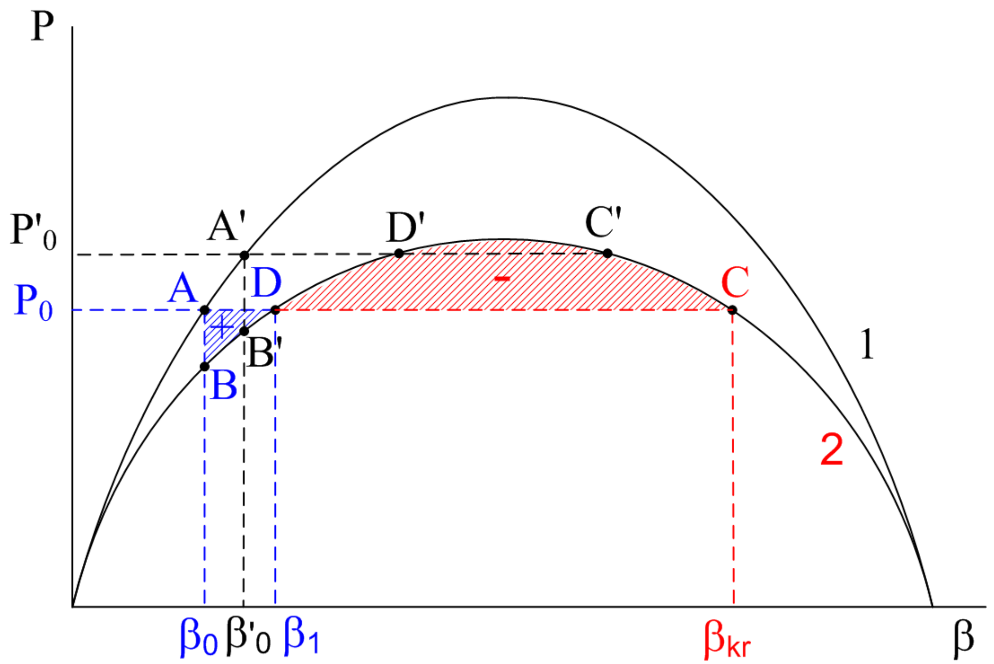
$$\beta(0) = \beta_0 \ ; \ \ \omega(0) = \omega_0$$

Inertia moment from start-up time

$$P = M\omega = J\varepsilon\omega \cong J\frac{\Delta\omega}{\Delta t}\omega = \frac{J\omega^2}{T}$$

$$J = \frac{T_m P_n}{\omega_0^2}$$

Equal areas method



Accelerating energy (area +)

$$A_a = \int_{\beta_0}^{\beta_1} (P_0 - P_{el}) d\beta$$

Deceleration energy (area -)

$$A_r = \int_{\beta_1}^{\beta_{kr}} (P_{el} - P_0) d\beta$$

For keeping in synchronism

$$A_a \le A_r$$

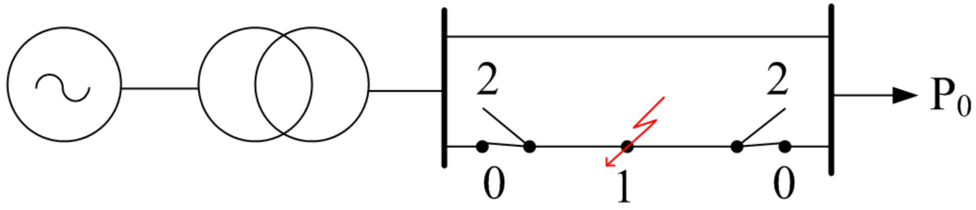
Transient stability

- limit for $A_a = A_r$, there is no strict angle limit
- during swinging the angle can be $\beta > 90^\circ$

Auto-reclosing (AR)

After a fault short-term disconnection and after a while repeated reclosing of the faulted section.

- temporary failure disappeared → operation
- permanent failure → final disconnection



A_0	initial state
A_1 - B_1	short-circuit
B_1	short-circuit disconnecting
B_2 - C_2	disconnected power line
C_2	AR (successful)
C_3 - D_3	swinging on the original characteristic

AR disconnecting time ~ between angles β_1 and β_2 (compromise between stability and arc burning).