Large Generators and High Power Drives

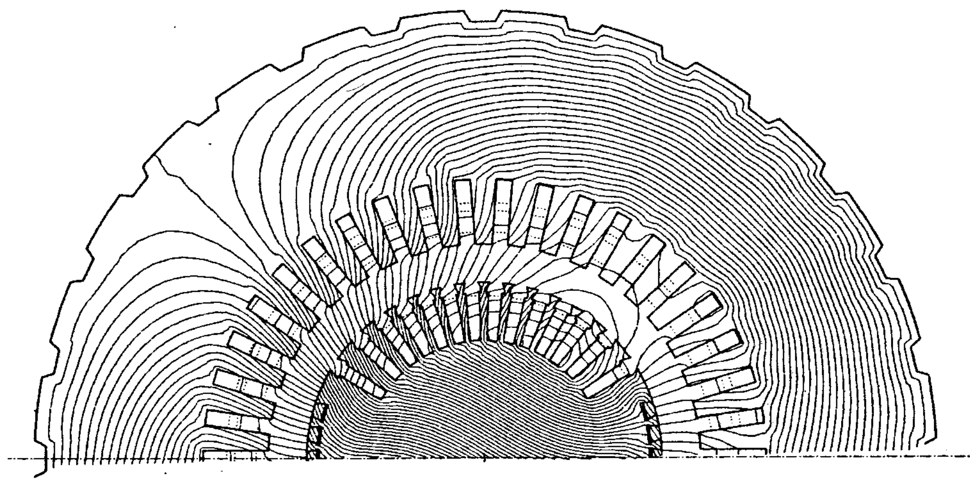
Contents of lectures

1. Manufacturing of Large Electrical Machines
2. Heating and cooling of electrical machines
3. Eddy current losses in winding systems
4. Excitation of synchronous machines
5. Design of large synchronous machines
6. Wind generators and high power drives
7. Forces in big synchronous machines

Source:

Siemens AG, Germany

4. Excitation of synchronous machines



Source: Neidhöfer, G., BBC, Switzerland

4. Excitation of synchronous machines

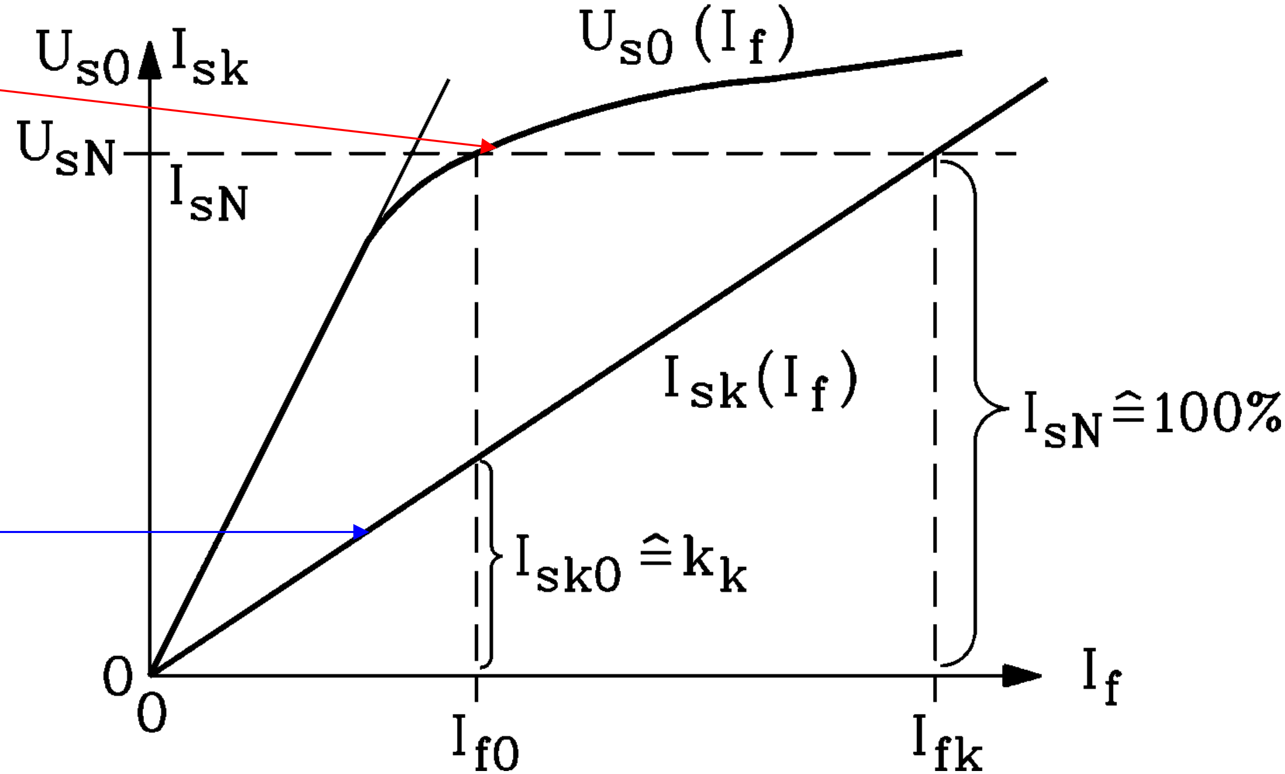
4.1 No-load and short-circuit characteristic

No-load characteristic:

- Stator open circuit
- Rotor driven by auxiliary motor
- Variable rotor excitation I_f
- Stator: No-load voltage U_{s0} is back EMF U_p

Short-circuit characteristic:

- Stator short circuited
- Rotor driven by auxiliary motor
- Variable rotor excitation I_f
- Stator: Steady-state short-circuit current I_{sk}



Synchronous reactance x_d (per unit):

$x_d = X_d / Z_N = 1/k_k$

k_k: No-load/short-circuit ratio

4. Excitation of synchronous machines

No-load characteristic

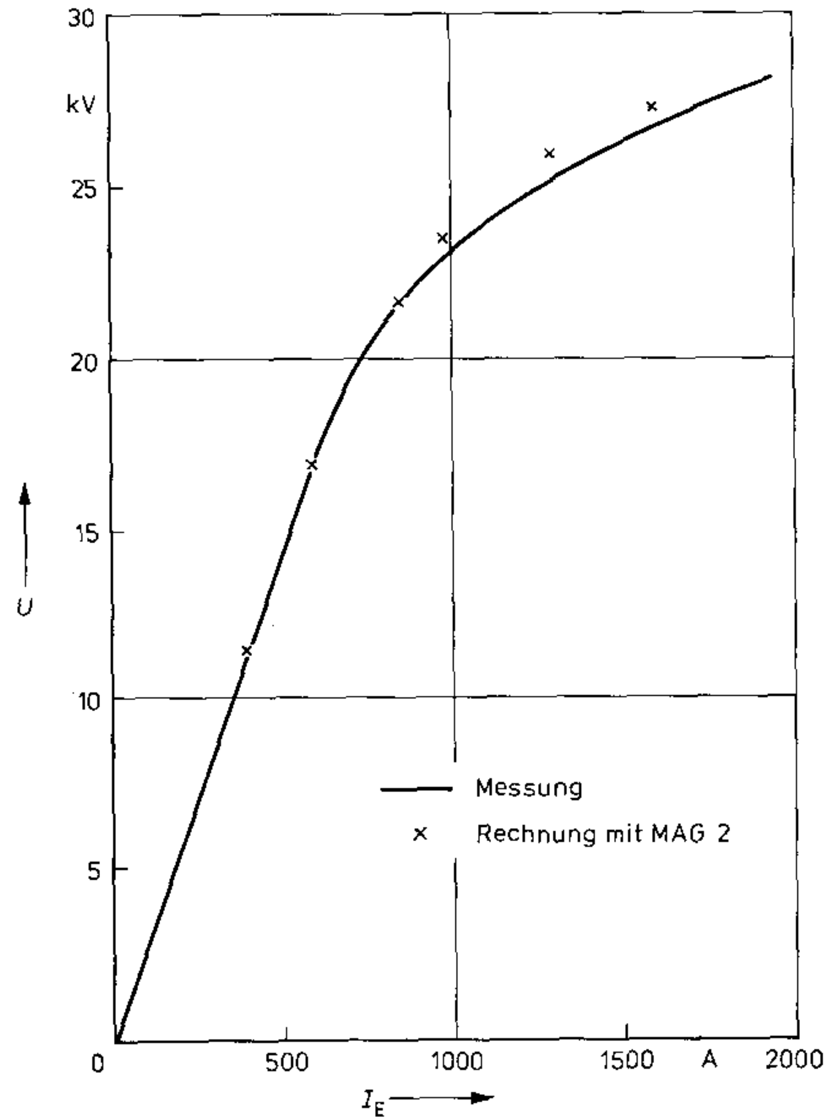
Measured and calculated no-load characteristic:

Line-to-line voltage versus field current at 3000/min, 50 Hz, 2-pole turbine generator, 400 MVA, cos φ_N = 0,75 cap.

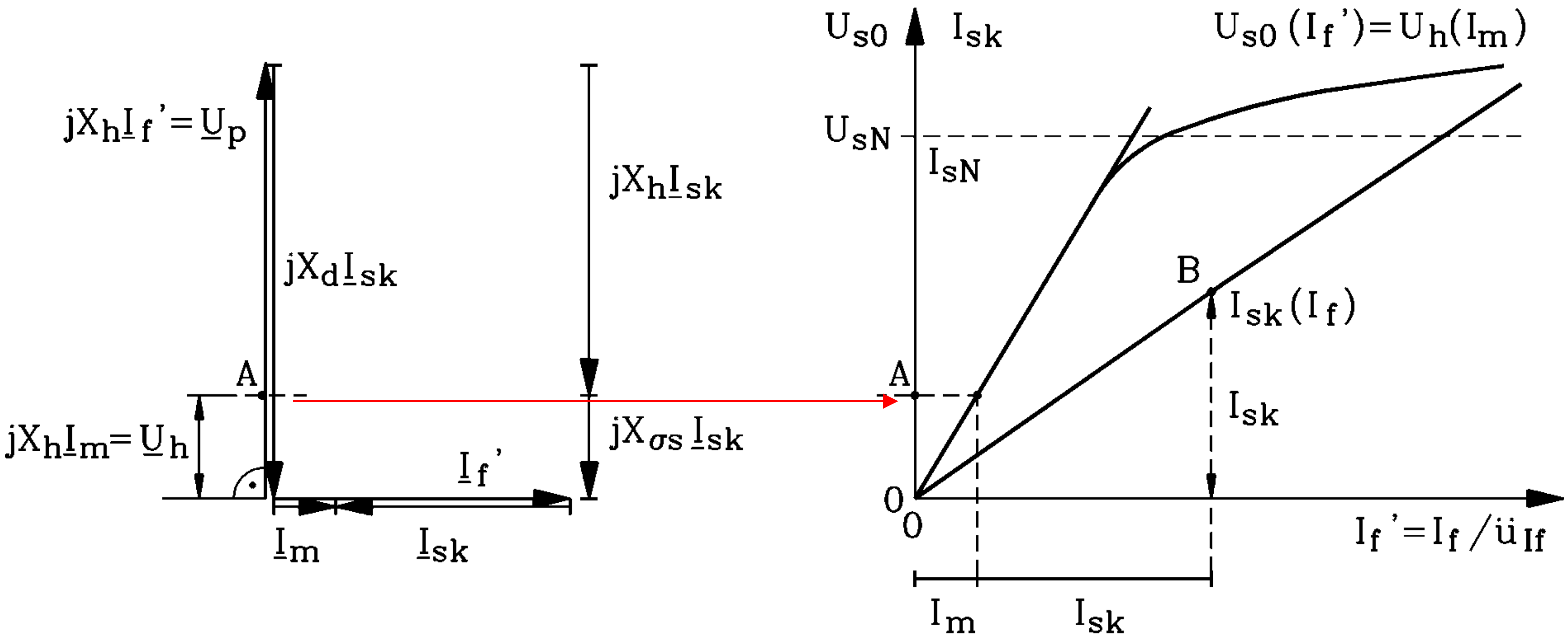
__________ measured

X calculated

Source: AEG, Germany



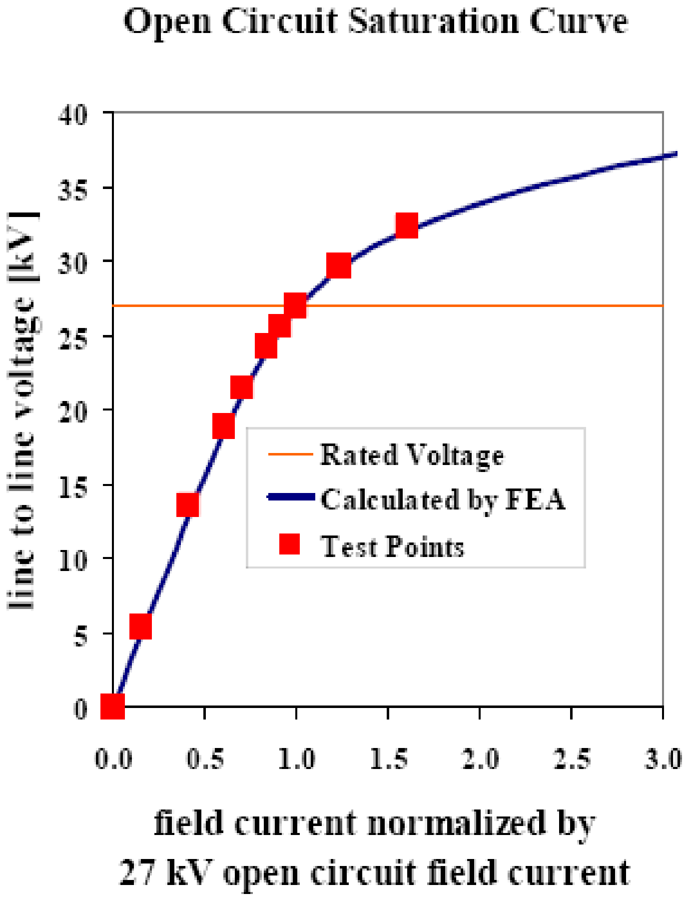
Saturation at no-load, no saturation at short-circuit

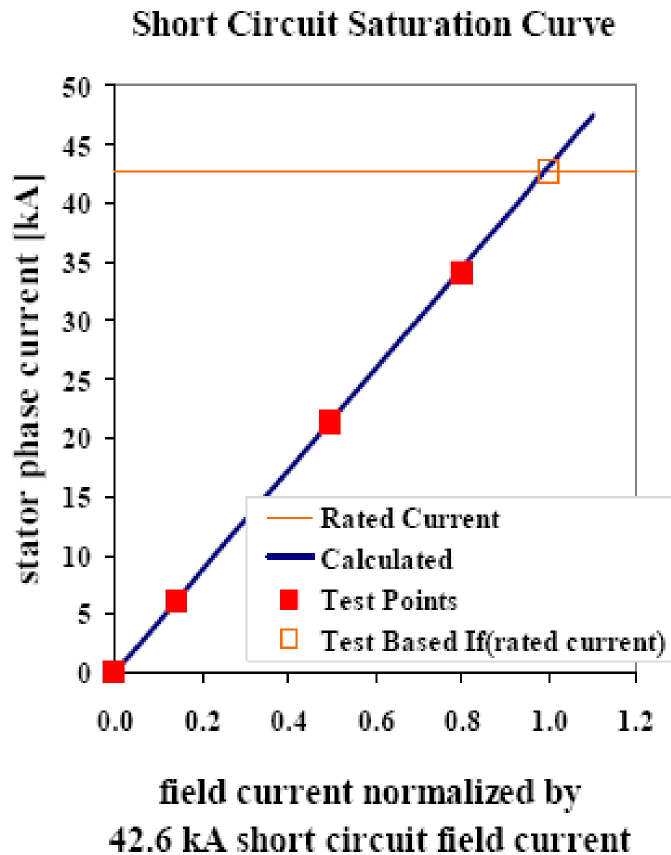


At stator short circuit stator air gap flux linkage $\Psi_{sk} = L_d I_{sk}$ is opposite to rotor air gap flux linkage $\Psi_p = L_d I'_f$. It nearly cancels rotor air gap field, so resulting air gap flux linkage $\Psi_h = L_d I_m$ is small ("magnetic operation point A"). As stator voltage is zero, induced stator internal voltage $\omega\Psi_h = \omega L_d I_m$ must balance voltage, which is induced by stator leakage flux: $\omega\Psi_h = \omega L_d I_m = \omega L_{s\sigma} I_{sk}$. So Ψ_h is small, iron is unsaturated.

Measured no-load and short-circuit curve: 2000 MW generator

S_N = 2222 MVA, $\cos\varphi_N$ = 0.9 over-excited, 27 kV, Y, 50 Hz, 1500/min, I_{sN} = 47.5 kA

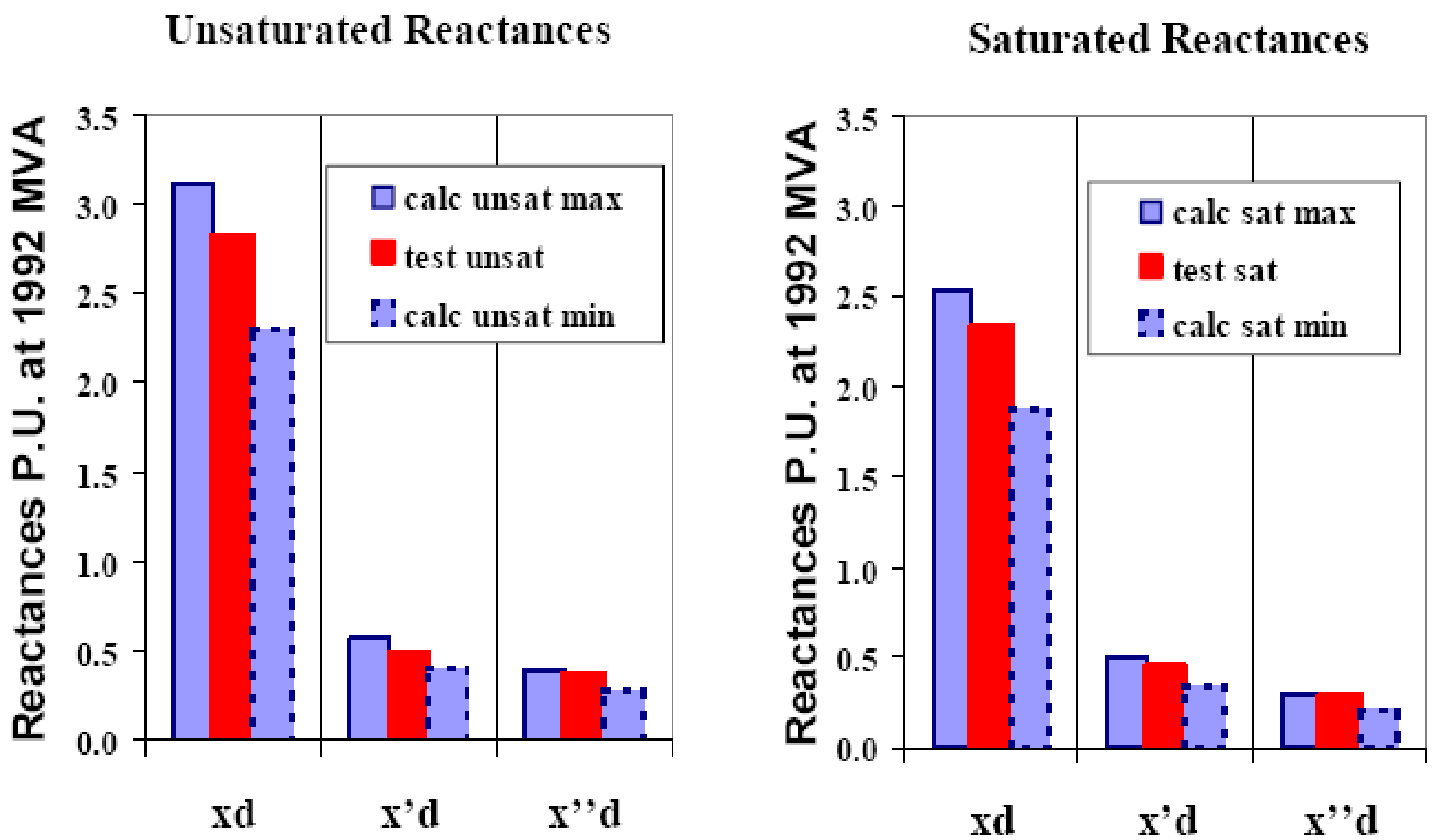




Olkiluoto 3: 2 GW turbo generator

Source: Siemens, Germany

Measured reactances: Turbine generator 2000 MW



Olkiluoto 3: 2 GW turbo generator

Source: Siemens, Germany

4. Excitation of synchronous machines

Transfer ratio for rotor field current

- **Amplitude and phase shift of $\underline{U}_p$**: may be described in equivalent circuit by **fictive AC stator current $\underline{I}'_f$:** $\underline{U}_p = jX_h \underline{I}'_f$

- **This defines transfer ratio of field current $ü_{If}$:** $$I'_f = \frac{1}{ü_{If}} I_f$$

- **$\underline{I}'_f$ is the "equivalent" stator AC field current, that flows in stator winding and by self-induction causes the same back EMF $\underline{U}_p$ as the real rotor DC field current I'_f does by rotation of rotor.**

$$I'_f = \frac{X_h I'_f}{X_h I_s} I_s = \frac{U_p}{U_{s,s}} I_s = \frac{B_p}{B_{s,\delta}} I_s = \frac{\hat{V}_f}{\hat{V}_s} I_s = \frac{1}{ü_{If}} I_f$$

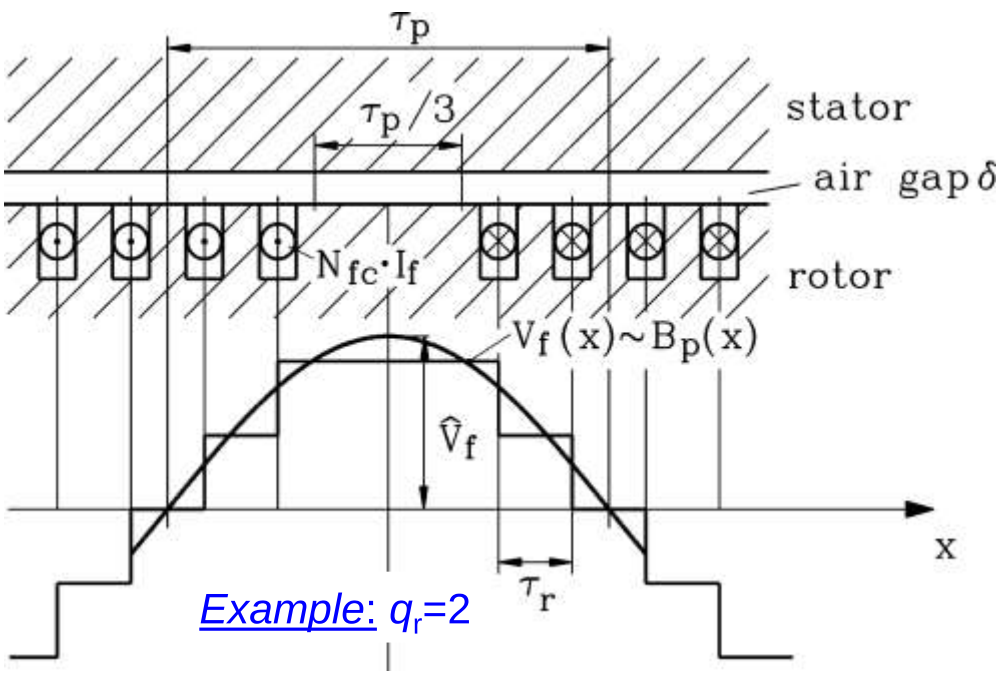
Example: Turbine generator:

Rotor m.m.f. fundamental: $\hat{V}_f = \frac{2}{\pi} \cdot \frac{N_f}{p} \cdot k_{wf} \cdot I_f$

Stator m.m.f. fundamental: $\hat{V}_s = \frac{\sqrt{2}}{\pi} \cdot \frac{m_s N_s}{p} \cdot k_{ws} \cdot I_s$

we get: $$ü_{If} = \frac{m_s N_s k_{ws} \sqrt{2}}{2 N_f k_{wf}}$$

Fundamental of rotor field of turbine generator



Example: $q_r=2$

- **Rotor m.m.f. and air gap field distribution have steps due to slots and contain fundamental**

($\mu = 1$):

$$\hat{V}_f = \frac{2}{\pi}\cdot\frac{N_f}{p}\cdot(k_{p,f}k_{d,f})\cdot I_f$$

$$\hat{B}_p = \mu_0\frac{\hat{V}_f}{\delta}, \quad N_f = 2p\cdot q_r\cdot N_{fc}$$

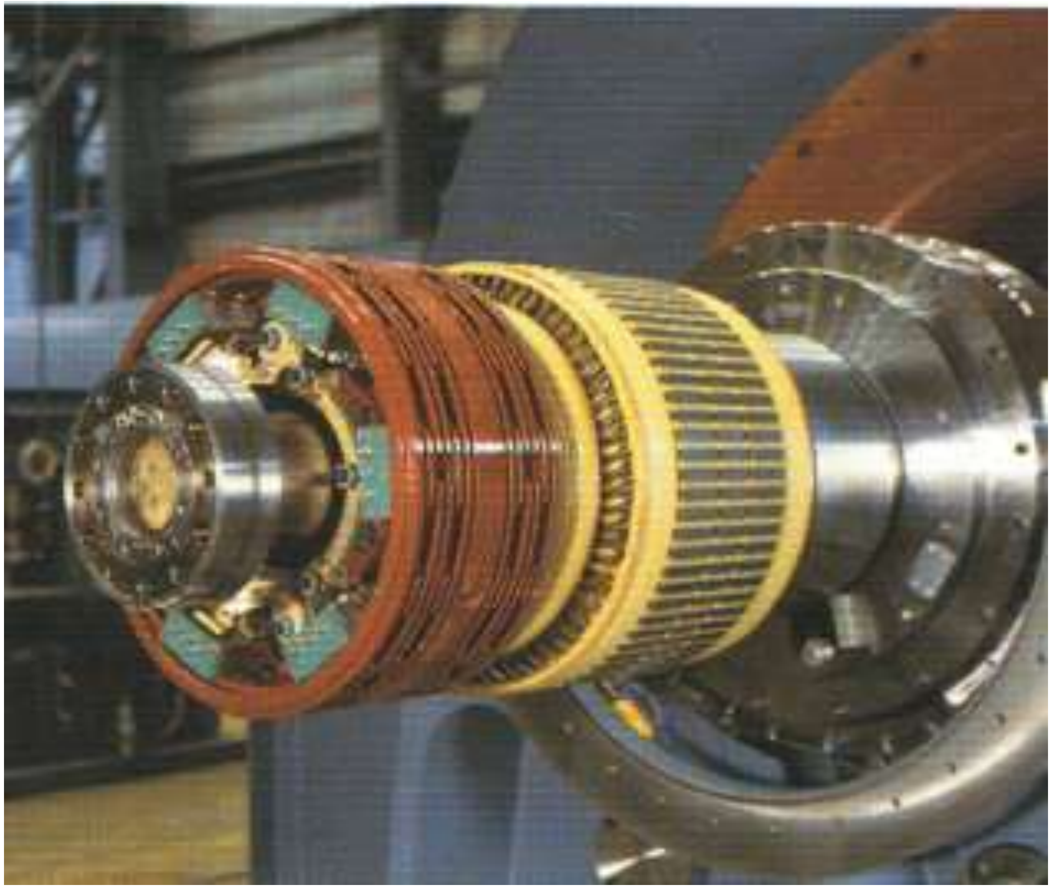
$$k_{p,f} = \sin\left(\frac{W}{\tau_p}\cdot\frac{\pi}{2}\right) = \sin(\pi/3) = \frac{\sqrt{3}}{2}$$

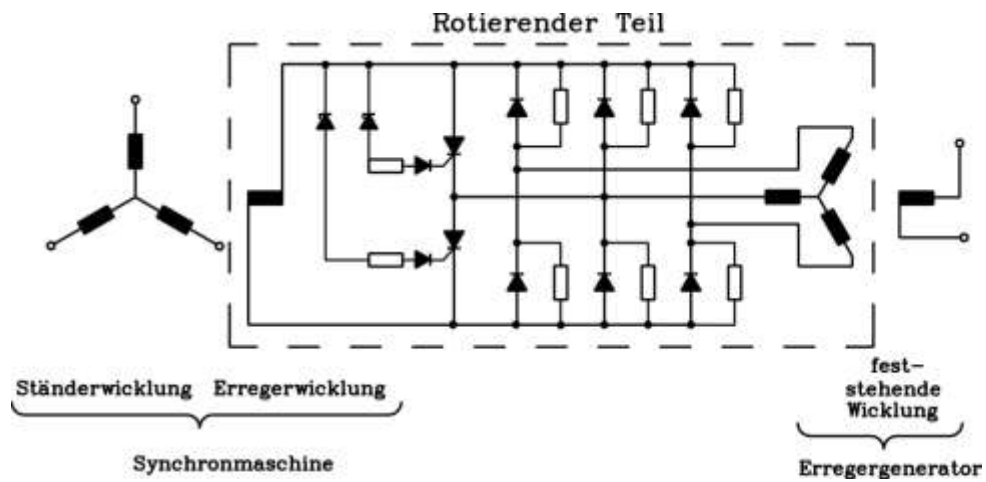
$$k_{d,f} = \frac{\sin(\pi/6)}{q_r\sin(\pi/(6q_r))}, \quad k_{wf} = k_{pf}k_{df}$$

Rotor field winding is "one phase" of a three phase distributed winding, which is pitched by 2/3 and fed by DC current.

4. Excitation of synchronous machines

Brushless excitation armature and diode wheel



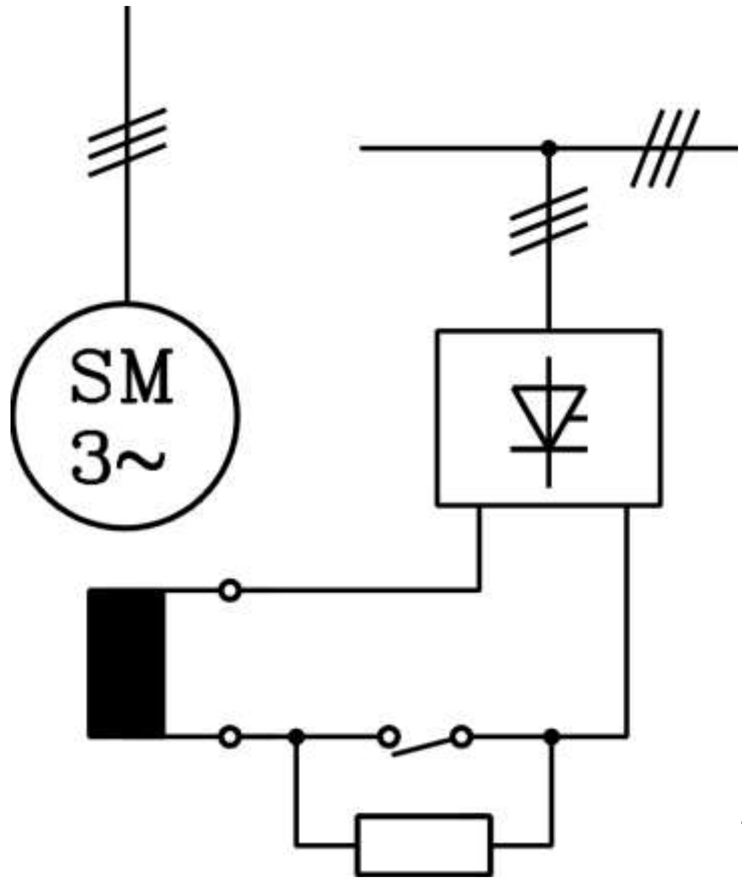


Source:

Siemens AG, Mülheim/Ruhr, Germany

4. Excitation of synchronous machines

Static excitation collector via two slip rings and carbon brushes



Source:

Siemens AG, Mülheim/Ruhr, Germany

Summary:

No-load und short-circuit characteristic

- No-load characteristic: Back EMF over excitation current at open-circuit
- Non-linear voltage curve due to iron saturation

- Short-circuit characteristic: Stator current over excitation current at short-circuit
- Small resulting air gap flux linkage → No saturation

- Back EMF $\underline{U}_p$ may be described by equivalent stator current: $I'_f = \frac{1}{\ddot{u}_{If}} I_f$

- Rotor excitation methods:
    - External with slip rings and brushes
    - Brushless with rotation diode bridge

4. Excitation of synchronous machines

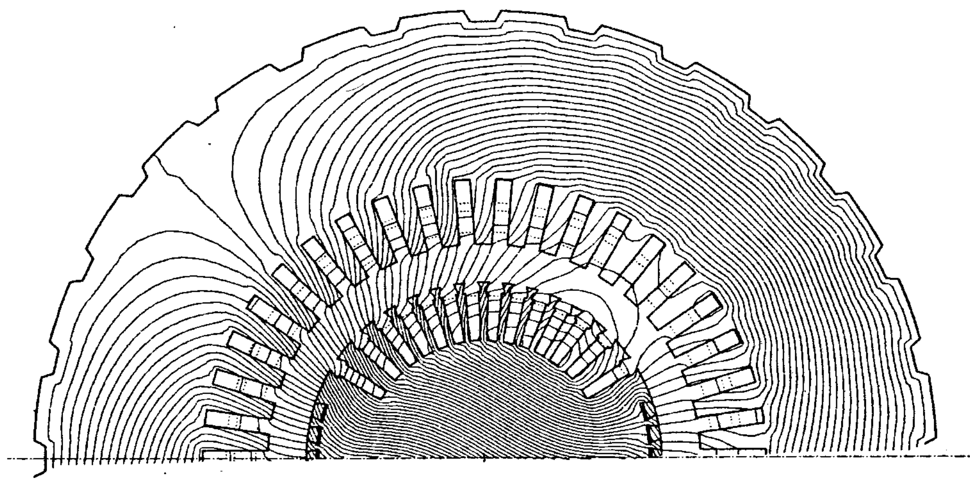
4.1 No-load and short-circuit characteristic

4.2 Determination of necessary field ampere-turns

4.3 Phasor diagram of saturated synchronous machines

4.4 *POTIER* reactance

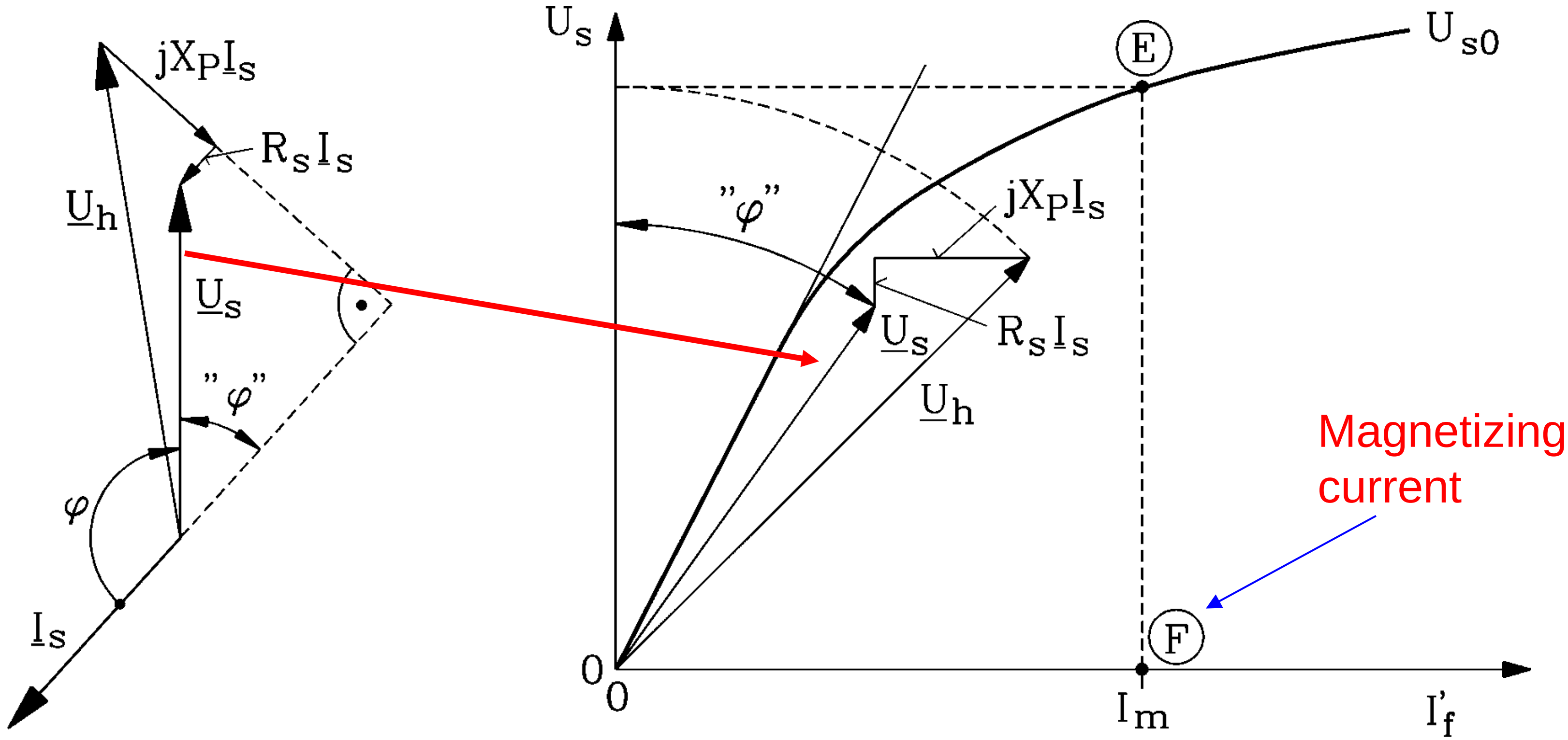
4.5 Stator current root locus



Source: Neidhöfer, G., BBC, Switzerland

4.2 Determination of necessary field ampere-turns

Calculation of magnetizing current, considering main flux saturation:



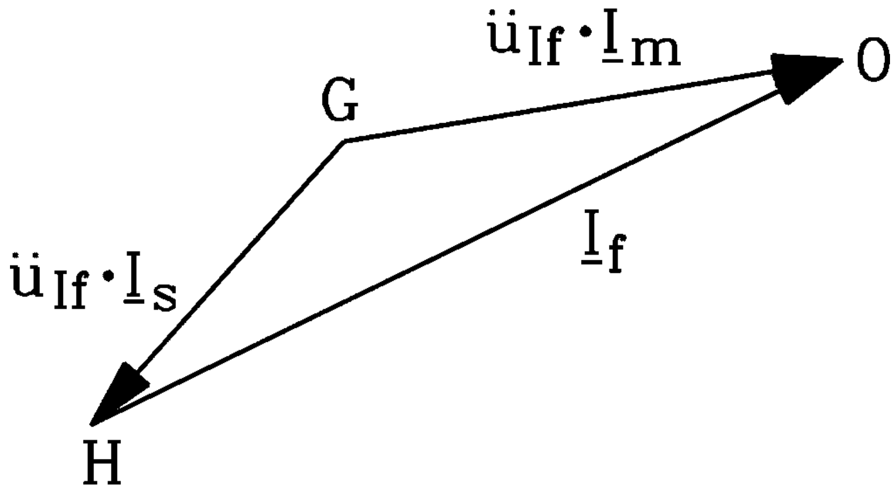
Magnetic point of operation *E* of main air gap flux linkage Ψ_h is determined by internal voltage:

$$\underline{U}_h = j\omega\underline{\Psi}_h$$

This is given for any arbitrary load (U_s, I_s, φ) and determines magnetizing current: $\underline{U}_h = jX_h\underline{I}_m$

4. Excitation of synchronous machines

Determination of field current I_f from phasor diagram

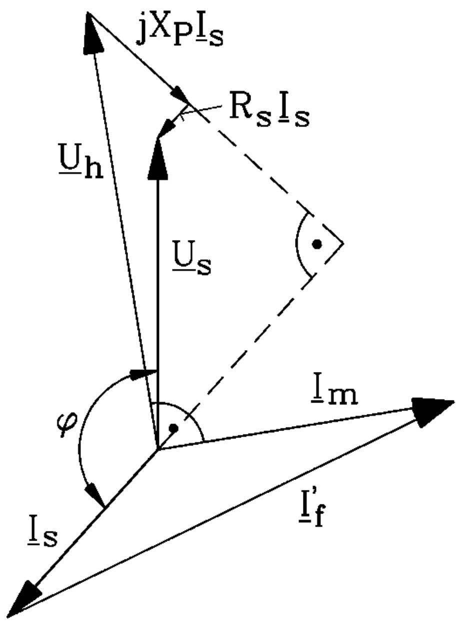


- In order to get field current I_f from I_m, we need to know addition of stator and rotor current.

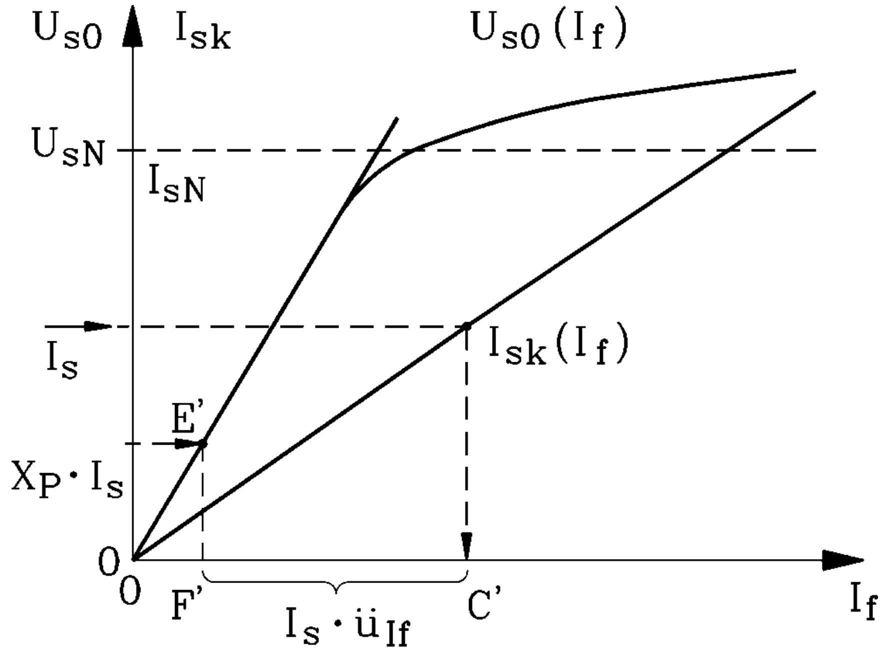
- From phasor diagram we get I'_f. With knowledge of $ü_{If}$ we calculate I_f.

Calculation of necessary field current for load point (U_s, I_s, φ)

A)



B)



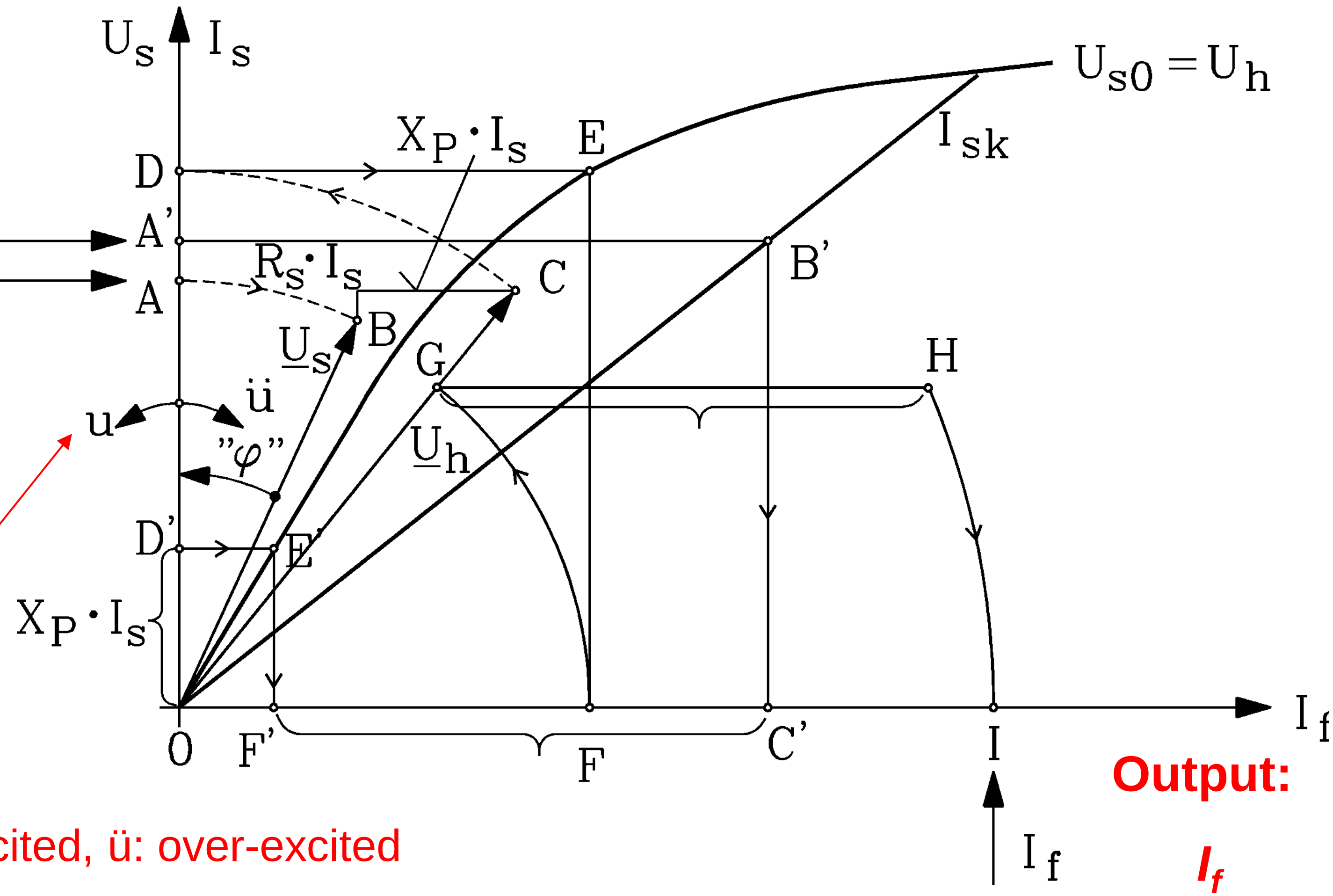
A) In order to get field current I_f from I_m, we need to know addition of stator and rotor current. From phasor diagram we get I'_f. With knowledge of $\ddot{u}_{If}$ we calculate I_f.

B) If machine is already built and measured, we can take $\ddot{u}_{If}$ from short-circuit characteristic. It is the distance between F´and C´, if the curve is given in dependence of I_f.

Calculation of field current for load point (U_s, I_s, φ) in ONE diagram

Input:

U_s, I_s, φ



Output:

I_f

u: under-excited, ü: over-excited

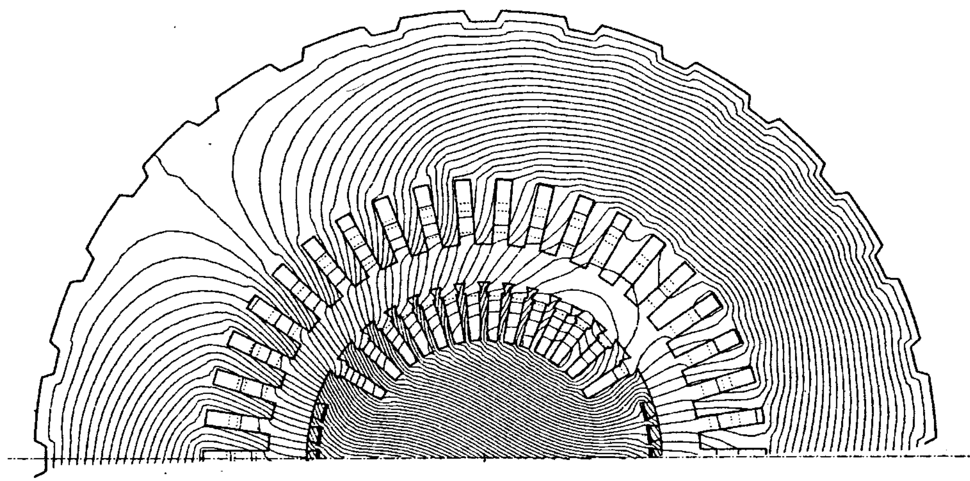
Summary:

Determination of necessary field ampere-turns

- Magnetic point of operation is determined by internal voltage U_h
- Magnetizing current is read from the no-load characteristic $U_{\mathrm{h}}(I_{\mathrm{m}}) \hat{=} U_{\mathrm{s0}}(I_{\mathrm{f}})$
- Equivalent current I'_f from phasor diagram
- Transfer ratio needed for determination of the excitation current
  - May be taken from the no-load/short-circuit characteristic

- Usually calculation is done in ONE diagram

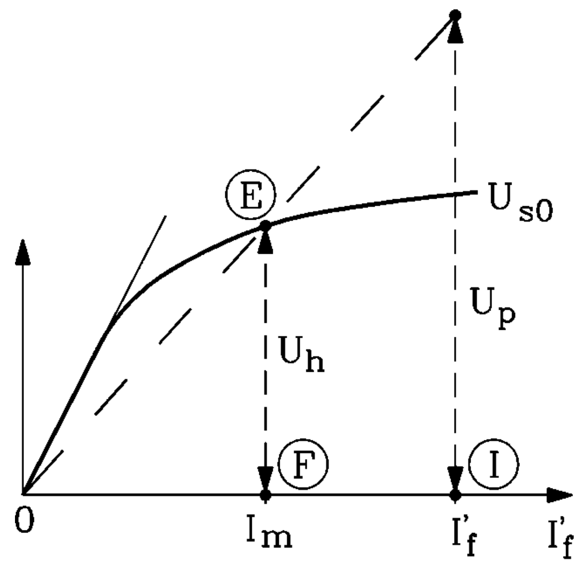
4. Excitation of synchronous machines

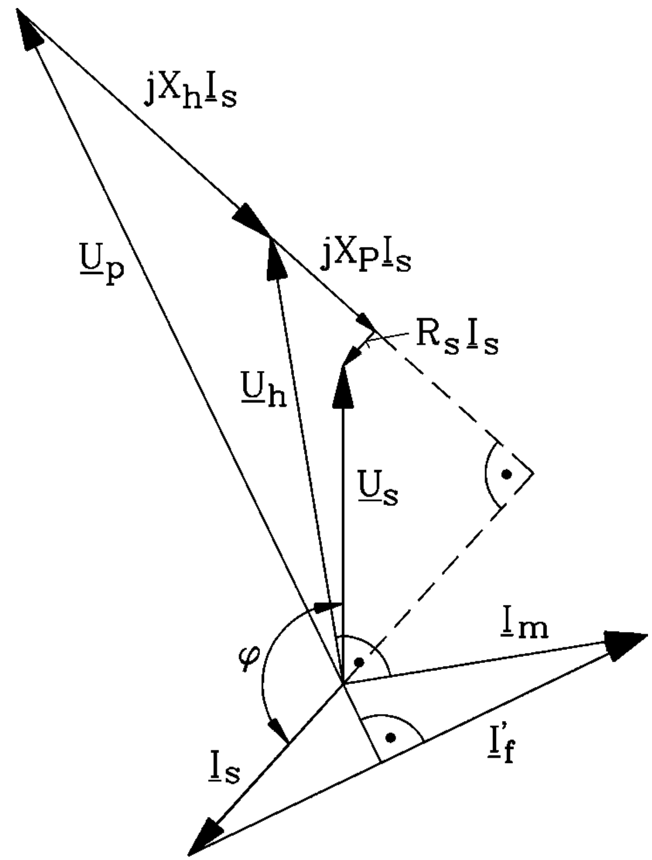


Source: Neidhöfer, G., BBC, Switzerland

4. Excitation of synchronous machines

4.3 Phasor diagram of saturated synchronous machines





Magnetic characteristic is linearized in magnetic operation point E to determine (fictive) back EMF for saturated load operation point.

Summary:

Phasor diagram of saturated synchronous machines

- Linearization of the magnetic characteristic
- Fictive back EMF in saturated load operation
- In case of load shedding: Terminal voltage is real no-load voltage, not fictive back EMF

4. Excitation of synchronous machines

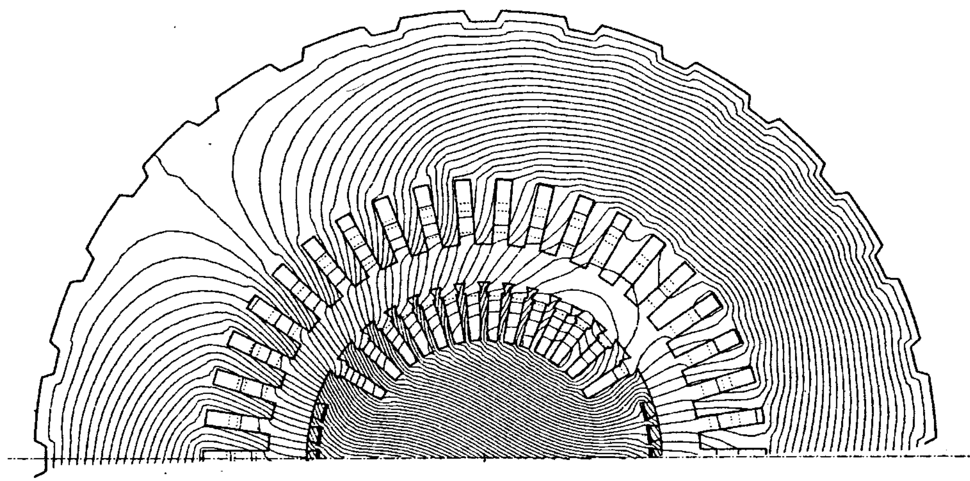
4.1 No-load and short-circuit characteristic

4.2 Determination of necessary field ampere-turns

4.3 Phasor diagram of saturated synchronous machines

4.4 *POTIER* reactance

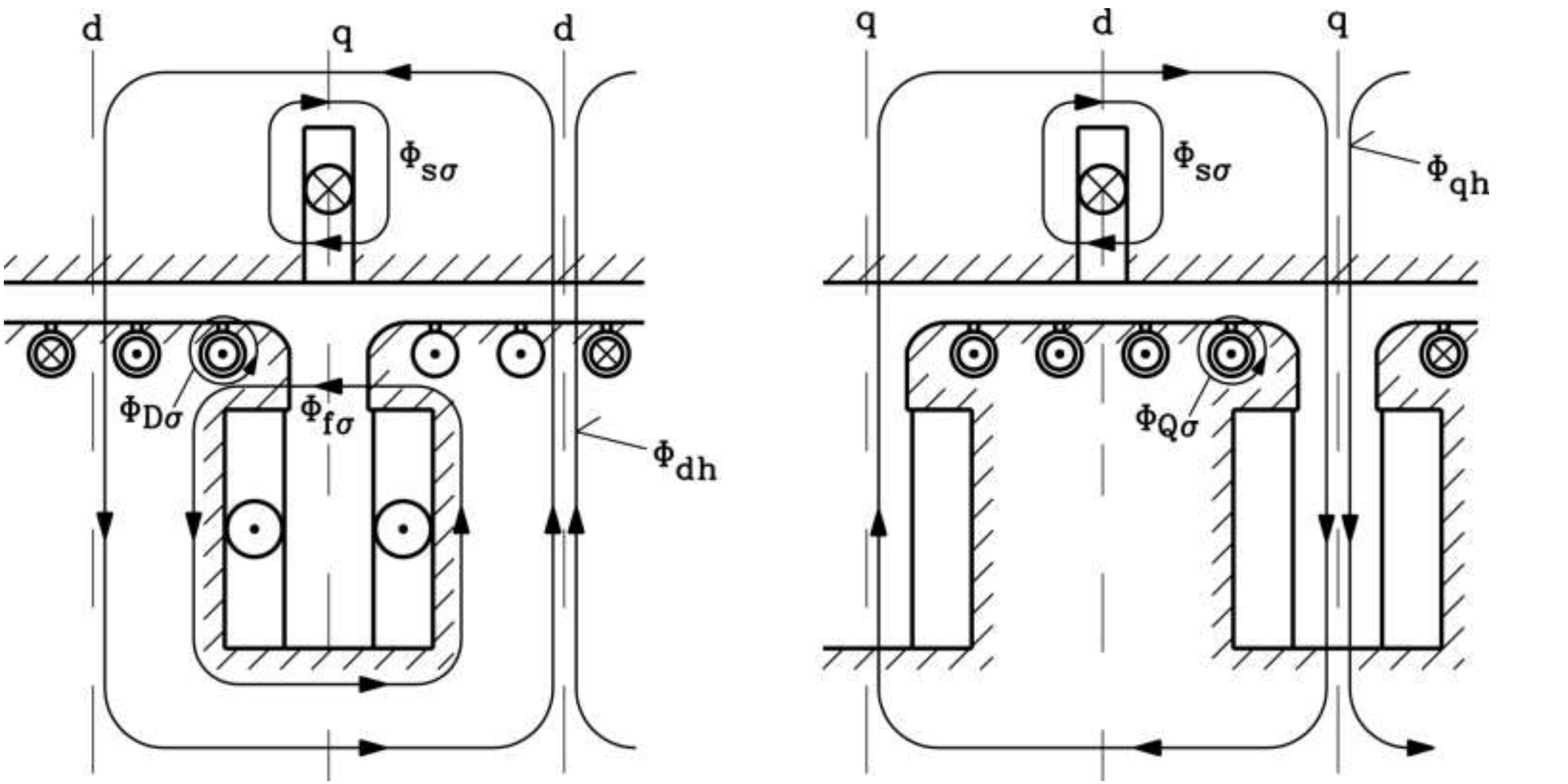
4.5 Stator current root locus



Source: Neidhöfer, G., BBC, Switzerland

4. Excitation of synchronous machines

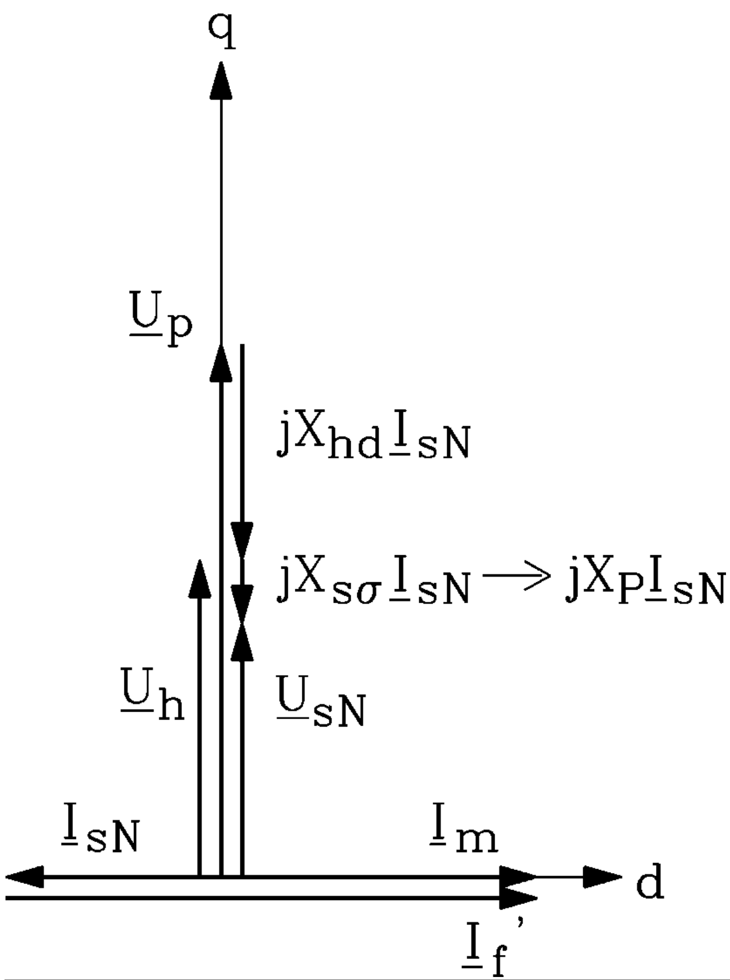
4.4 *POTIER* reactance



In d-axis rotor stray flux $\Phi_{f\sigma} \sim I_f$ is ADDING to main flux Φ_h, so it will increase pole shaft iron saturation.

Especially at over-excitation (big $\Phi_{f\sigma} \sim I_f$) this saturation may become very high.

Worst-case over-excitation (maximum $\Phi_{f\sigma} \sim I_f$) at pure inductive load of synchronous generator

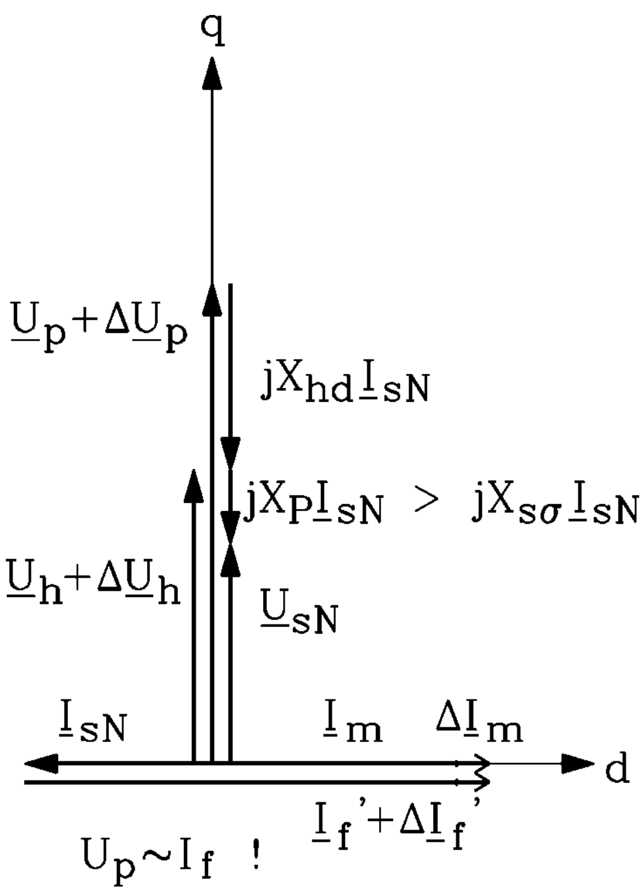


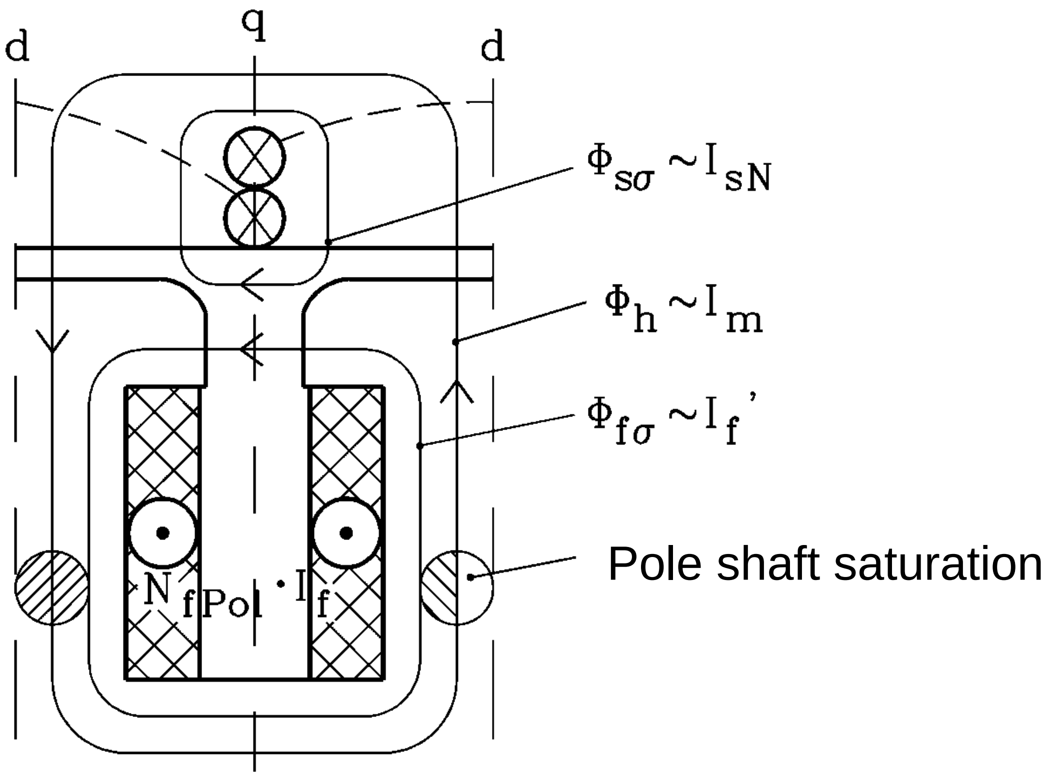
Phasor diagram for pure inductive load of generator at rated voltage and current:
$U_s = U_N$, $I_s = I_N$, $\cos\varphi = 0$ *over-excited*

Due to this big rotor stray flux the rotor iron saturates strongly, yielding an increased demand of excitation ampere-turns ΔI_f.

$$\oint_C \vec{H} \bullet d\vec{s} = 2N_{f,pole} \cdot I_f \rightarrow 2N_{f,pole} \cdot (I_f + \Delta I_f)$$

Increased demand of field current is considered in phasor diagram by *POTIER* reactance X_P instead of stator leakage reactance $X_{s\sigma}$





$N_{fPol} \cdot I_f$ **is maximum** at pure rated inductive load

POTIER reactance X_P

- Increased iron saturation will lead to decrease in main reactance.

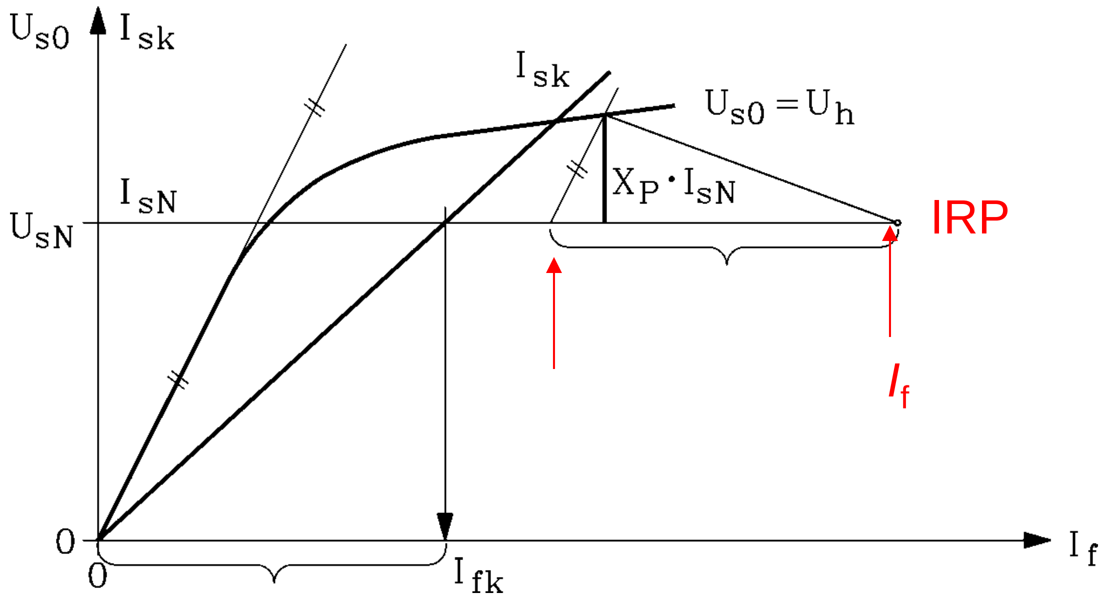
- Usually this influence is not considered by reducing main reactance, but by introducing *POTIER* reactance !

- Increased field current gives (at fictively constant main reactance X_{hd}) a fictively increased back EMF U_p. This has to be compensated by a fictively increased leakage reactance $X_{\sigma s}$, which is called ***POTIER*-reactance X_P :**

$$U_p = X_{hd} I'_f \quad \Rightarrow \quad \Delta U_p = X_{hd} \Delta I'_f \quad \Rightarrow \quad \Delta U_h = X_{hd} \Delta I_m$$

$$X_P > X_{s\sigma}$$

Measuring *POTIER* reactance with method of *FISCHER-HINNEN*



- No-load & short-circuit characteristic are measured and field current for pure inductive rated load **(IRP)**
- **Magnetic point of operation E of internal voltage U_h includes terminal voltage U_{sN} and voltage drop $X_P I_{sN}$**
- Substracting from field current I_f the stator current $I_{sN} \cdot \ddot{u}_{If}$ yields magnetizing current $I_m \cdot \ddot{u}_{If}$, so we get $U_h(I_m) = U_{s0}(I_m)$ from no-load characteristic.
- $I_{sN} \cdot \ddot{u}_{If}$ is visible in short-circuit characteristic. There iron is unsaturated, so $X_P I_N = X_{\sigma s} I_N$.
- Paralleling unsaturated no-load characteristic and ampere-turns of short-circuit conditions is also possible to determine U_h, instead of taking $I_{sN} \cdot \ddot{u}_{If}$ (which needs knowledge of $\ddot{u}_{If}$)

Summary:

POITIER reactance

- Rotor stray flux is adding to main flux in d-axis
- Increased iron saturation of the pole shafts
- Increased demand of excitation ampere turns
- Worst case: Over-Excited pure inductive load
- The influence is considered by introducing *POTIER* reactance $X_P > X_{s\sigma}$
- Measurement via the method of *FISCHER-HINNEN* for pure inductive rated load (IRP)

4. Excitation of synchronous machines

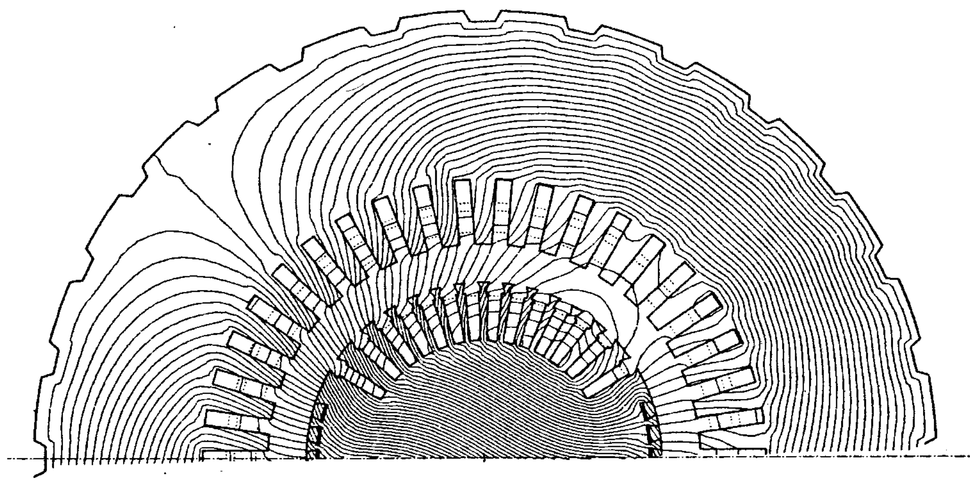
4.1 No-load and short-circuit characteristic

4.2 Determination of necessary field ampere-turns

4.3 Phasor diagram of saturated synchronous machines

4.4 *POTIER* reactance

4.5 Stator current root locus

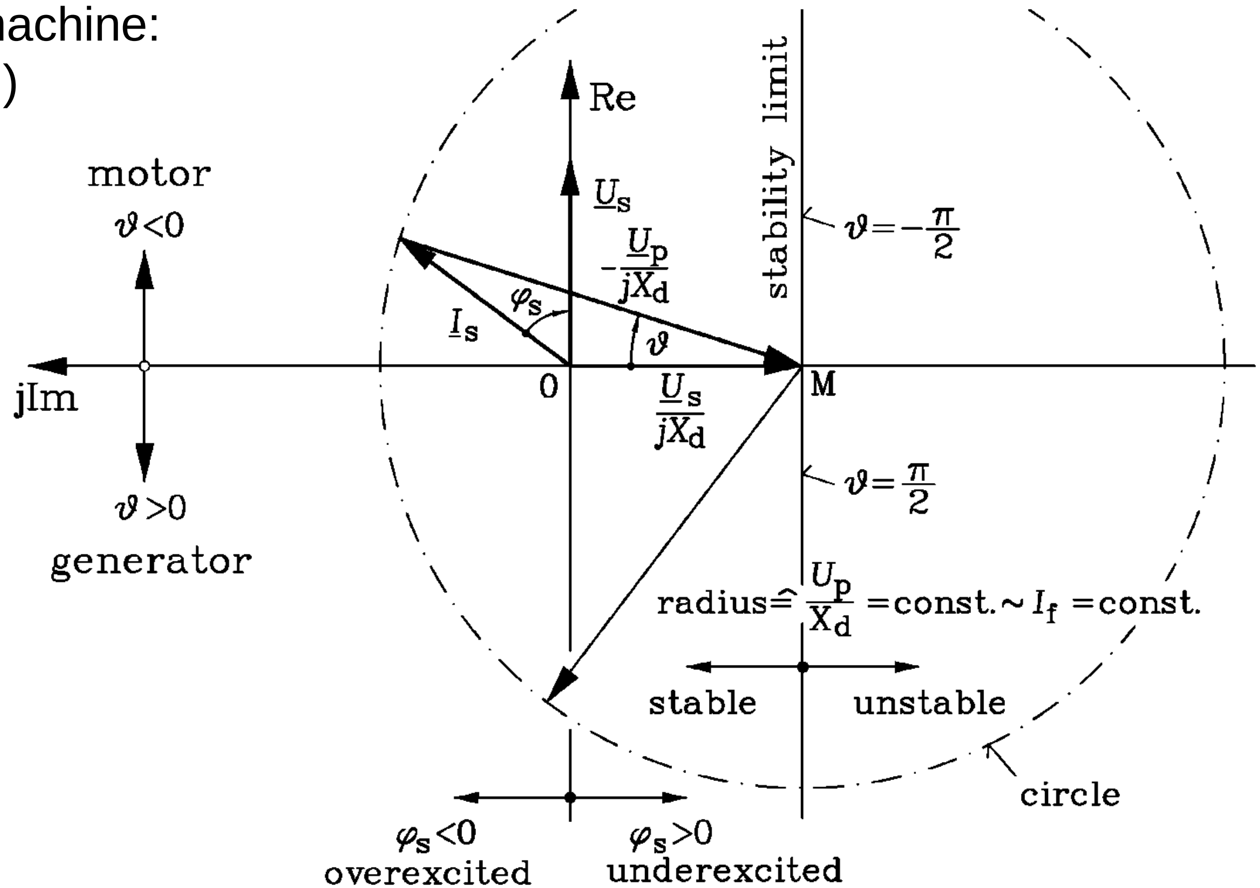


Source: Neidhöfer, G., BBC, Switzerland

4.5 Stator current root locus

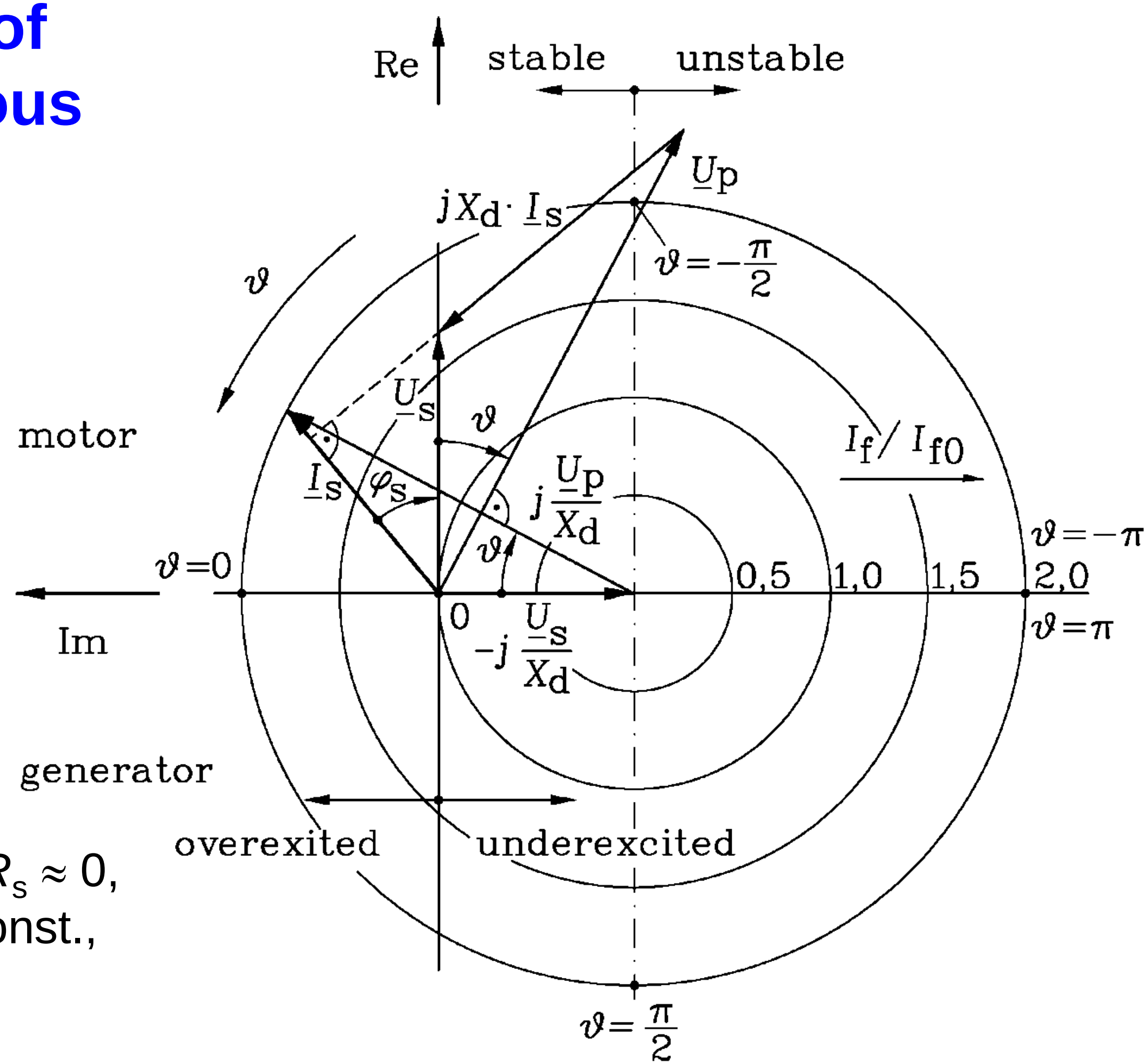
Cylindrical rotor synchronous machine:
($R_s \approx 0$, $\underline{U}_s$ = const., $\underline{U}_p$ = const.)

$$\underline{I}_s(\vartheta) = -j\frac{U_s}{X_d} + j\frac{U_p}{X_d}e^{j\vartheta}$$



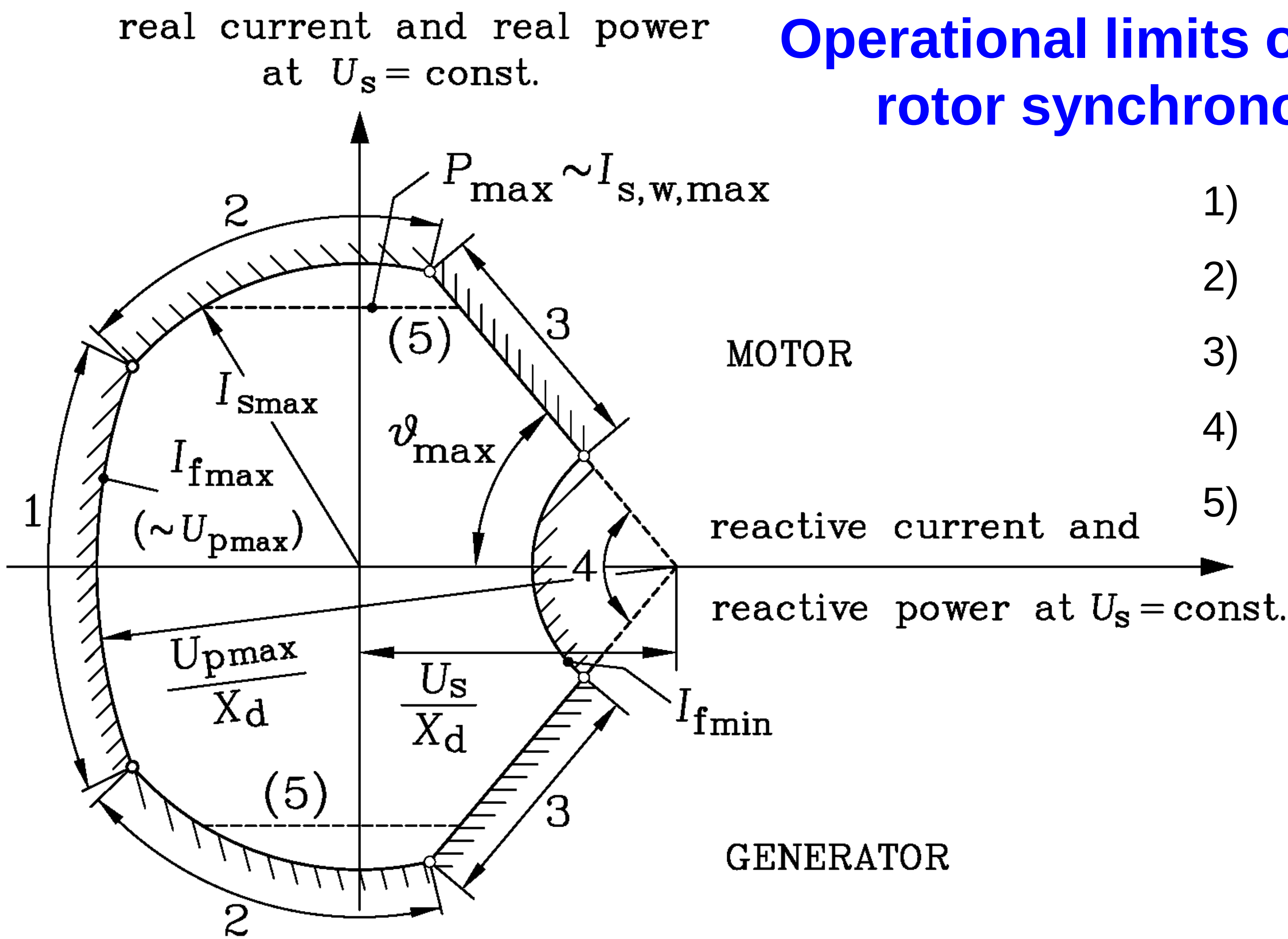
4. Excitation of synchronous machines

Stator current root locus of cylindrical rotor synchronous machine



- neglected stator winding resistance $R_s \approx 0$,
- stator grid voltage is constant $\underline{U}_s$ = const.,
- different excitation levels $I_f \sim \underline{U}_p$

4. Excitation of synchronous machines

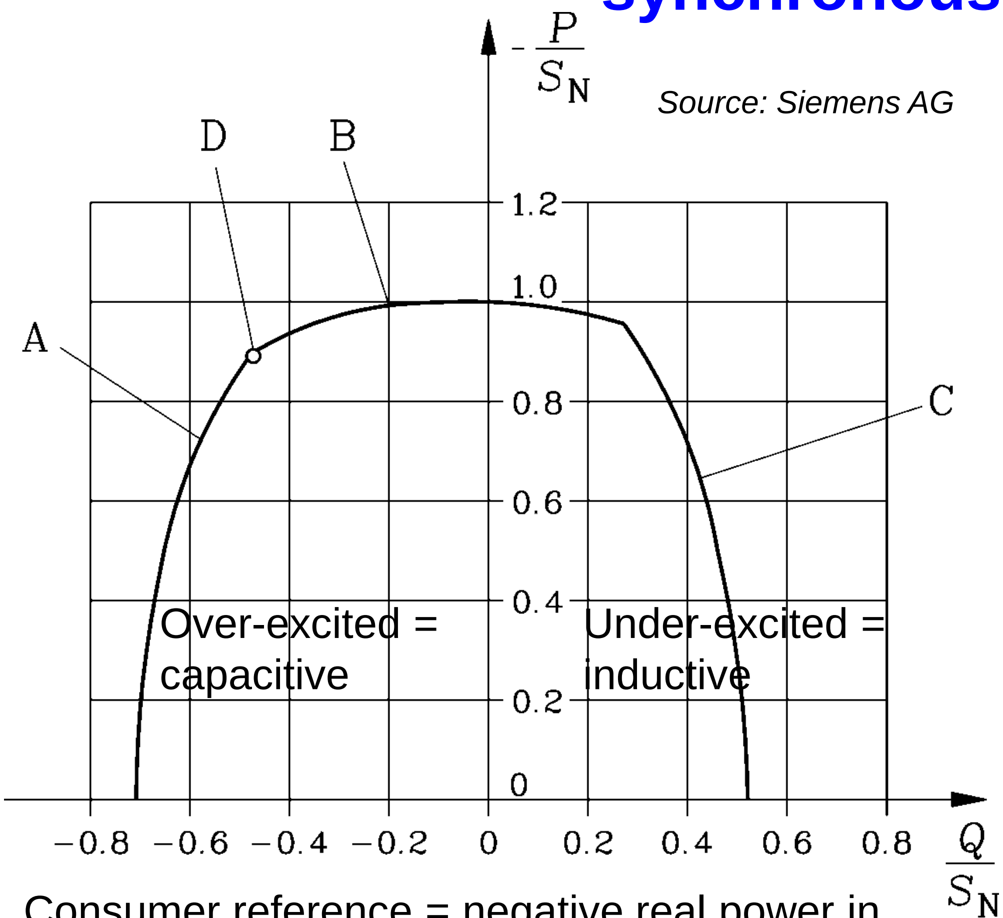


Operational limits of the cylindrical rotor synchronous machine

1) Max. exciter current
2) Max. stator current
3) Max. load angle (< 90°)
4) Minimum exciter current
5) Max. real power

Source: Kleinrath, H.; Grundlagen el. Maschinen, Akad. Verlagsgesellschaft

Real and reactive power limits of the cylindrical rotor synchronous machine



Consumer reference = negative real power in generator mode

$$P = m_s U_{sN} I_s \cos\varphi_s = m_s U_{sN}\,\mathrm{Re}\{\underline{I}_s\} \sim \mathrm{Re}\{\underline{I}_s\}$$

$$Q = m_s U_{sN} I_s \sin\varphi_s = m_s U_{sN}\,\mathrm{Im}\{\underline{I}_s\} \sim \mathrm{Im}\{\underline{I}_s\}$$

$$S_N = m_s U_{sN} I_{sN}$$

$$P / S_N = \mathrm{Re}\{\underline{I}_s / I_{sN}\} \qquad Q / S_N = \mathrm{Im}\{\underline{I}_s / I_{sN}\}$$

The power limit is directly proportional to the stator current limit !

Example: 2-pole turbine generator

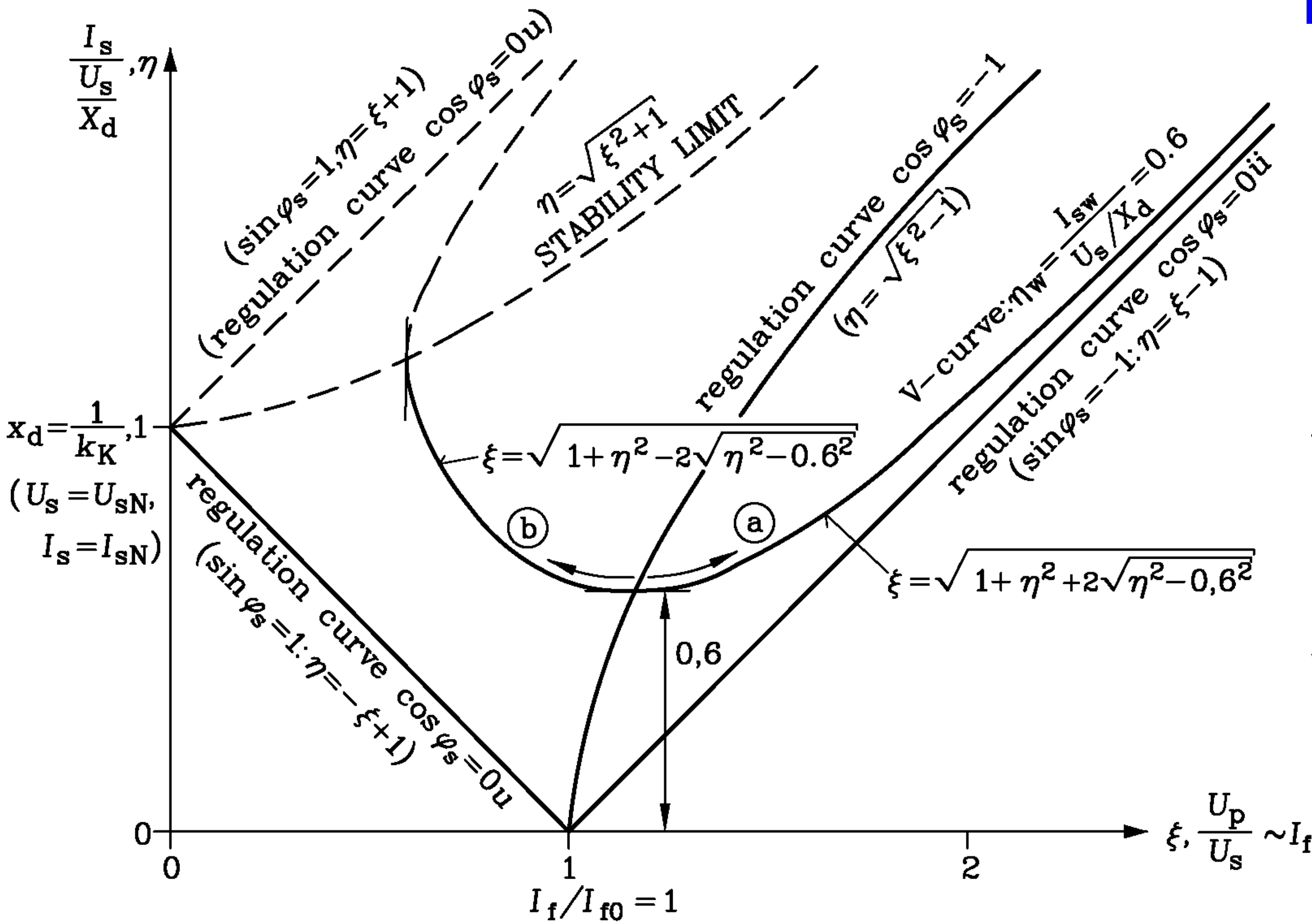
A: Thermal limit of exciter winding ($I_{f,max}$)

B: Thermal limit of stator winding ($I_{s,max}$)

C: Distance to stability limit

D: Rated power: $\cos\varphi_s$ = -0.9 overexcited

4. Excitation of synchronous machines



$$\mathrm{Re}\{\underline{I}_s\} = I_s \cos\varphi_s$$

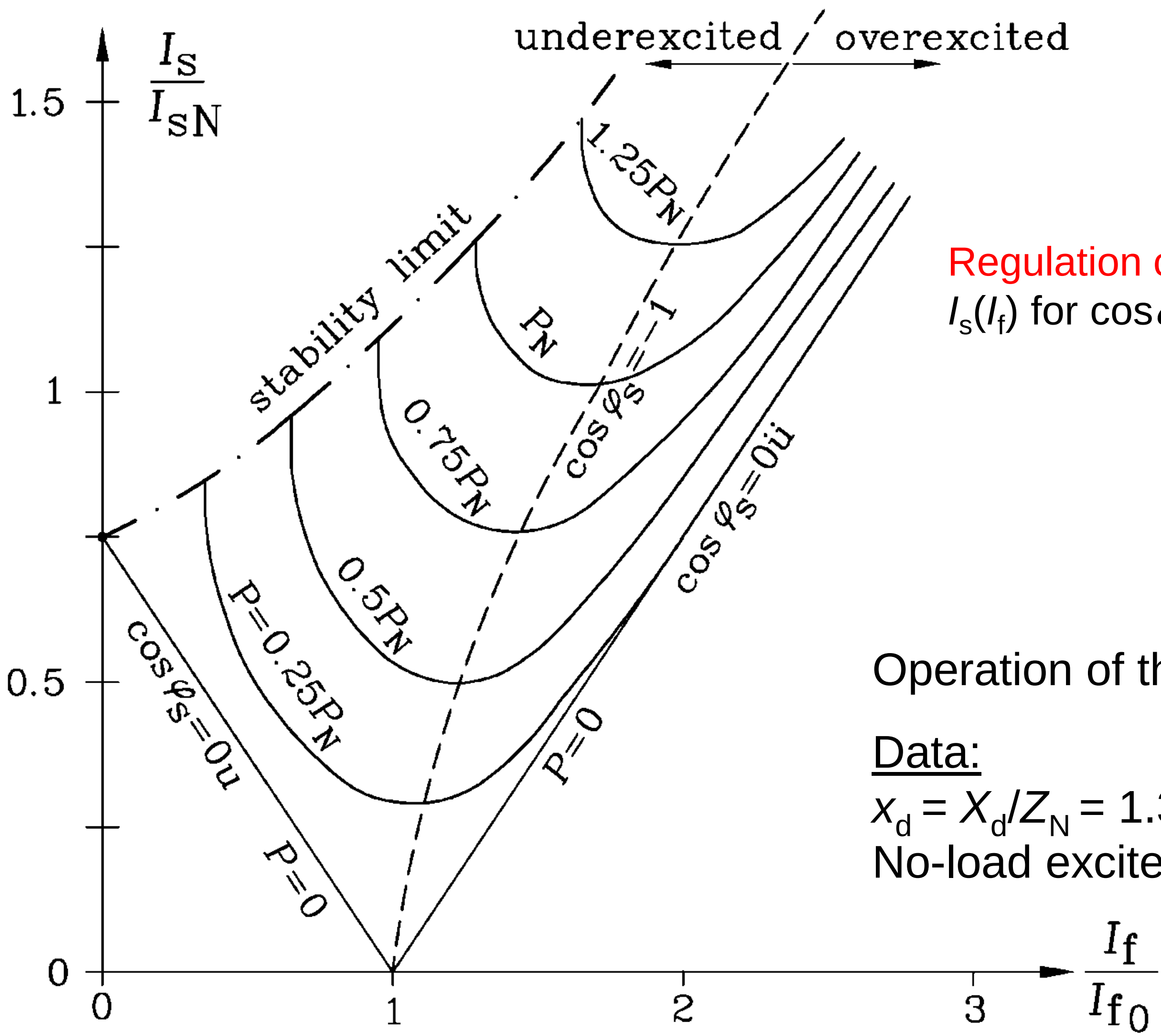
Regulation curves and V-curves of a cylindrical rotor synchronous generator

Curves can be directly taken from the stator current root locus diagram:

Regulation curves:
$I_s(I_f)$ for $\cos\varphi_s$ = const.

V-curves:
$I_s(I_f)$ for $\mathrm{Re}\{\underline{I}_s\}$ = const.

4. Excitation of synchronous machines



Regulation curves and V-curves of a synchronous motor

Regulation curves:
$I_s(I_f)$ for $\cos\varphi_s$ = const.

V-curves:
$I_s(I_f)$ for $\mathrm{Re}\{\underline{I}_s\}$ = const.

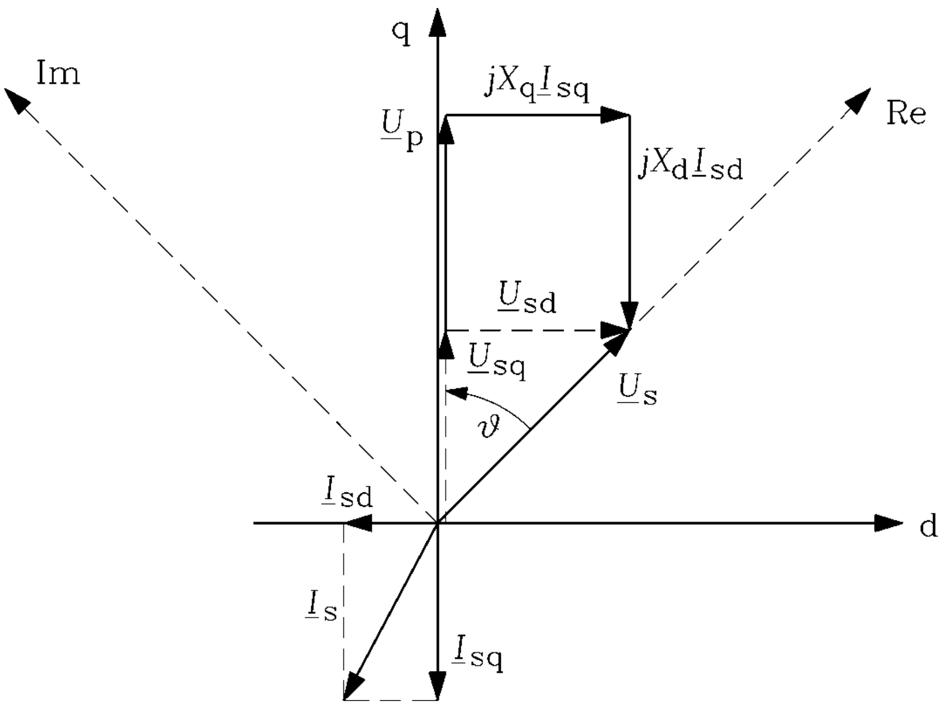
$$P = m_s U_{sN} \mathrm{Re}\{\underline{I}_s\} = const.$$

Operation of the motor at the rigid grid: U_s = const.

Data:
$x_d = X_d/Z_N = 1.33$, $k_K = 1/x_d = 0.75$,
No-load exciter current: I_{f0}

Source: AEG

Construction of the stator current root locus of a salient pole synchronous machine, $R_s = 0$ (1)



$$\underline{U}_p = U_p \cdot e^{j\vartheta}$$

$$\underline{U}_{sq} = U_s \cdot \cos\vartheta \cdot e^{j\vartheta} = U_s \cdot \frac{e^{j\vartheta} + e^{-j\vartheta}}{2} \cdot e^{j\vartheta}$$

$$\underline{U}_{sd} = U_s \cdot \sin\vartheta \cdot (-j) \cdot e^{j\vartheta} = U_s \cdot \frac{e^{j\vartheta} - e^{-j\vartheta}}{2j} \cdot (-j) \cdot e^{j\vartheta}$$

$$\underline{U}_{sq} = \underline{U}_p + jX_d \underline{I}_{sd}$$

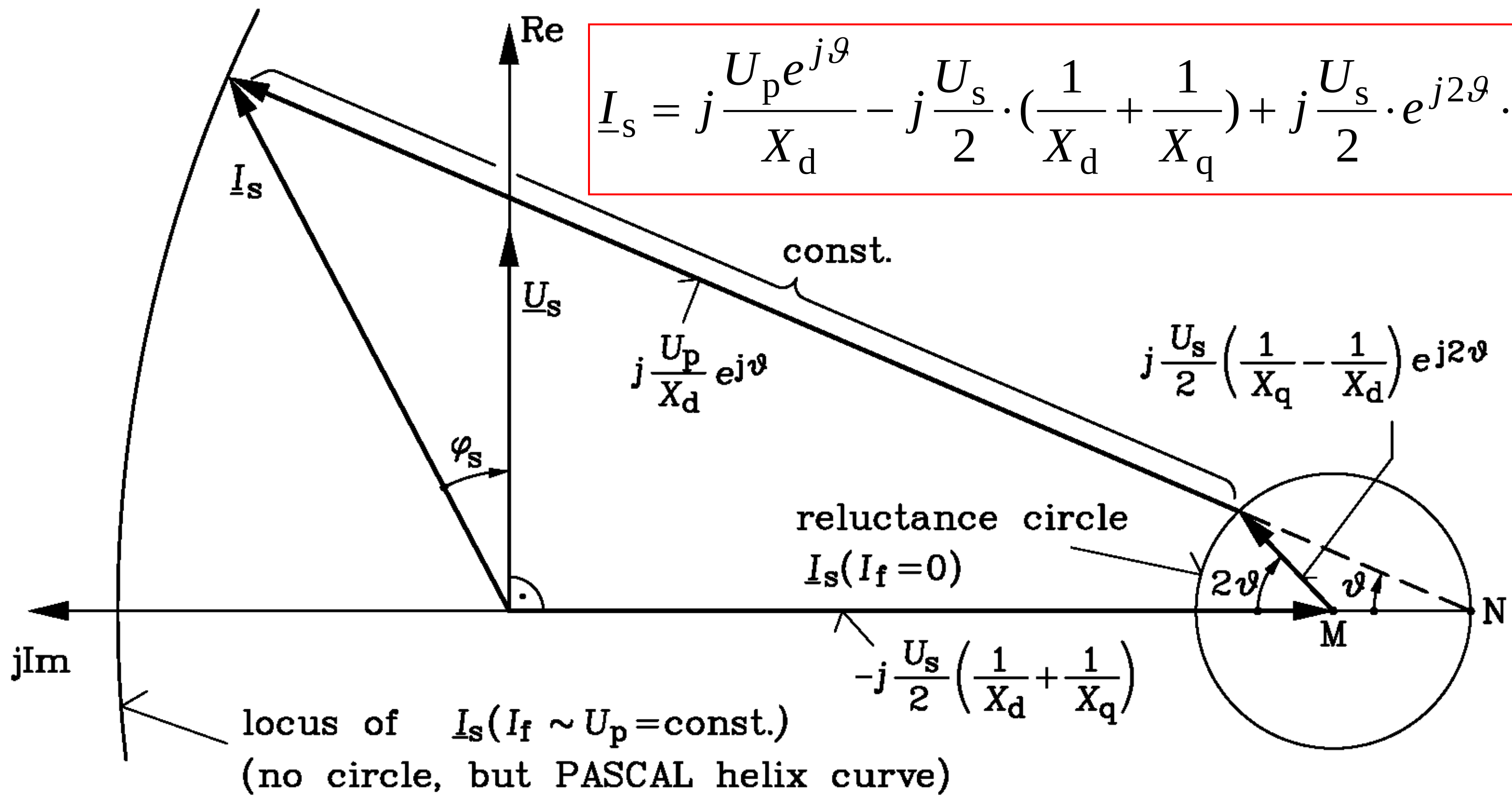
$$\underline{I}_{sd} = \frac{\underline{U}_{sq} - \underline{U}_p}{jX_d} = \frac{je^{j\vartheta}}{X_d} \cdot \left(U_p - U_s \cdot \frac{e^{j\vartheta} + e^{-j\vartheta}}{2} \right)$$

$$\underline{U}_{sd} = jX_q \underline{I}_{sq} \quad \Rightarrow \quad \underline{I}_{sq} = \frac{\underline{U}_{sd}}{jX_q} = \frac{je^{j\vartheta}}{X_q} \cdot U_s \cdot \frac{e^{j\vartheta} - e^{-j\vartheta}}{2}$$

$$\underline{I}_s = \underline{I}_{sd} + \underline{I}_{sq} = j\frac{U_p e^{j\vartheta}}{X_d} - j\frac{U_s}{2} \cdot \left(\frac{1}{X_d} + \frac{1}{X_q}\right) + j\frac{U_s}{2} \cdot e^{j2\vartheta} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d}\right)$$

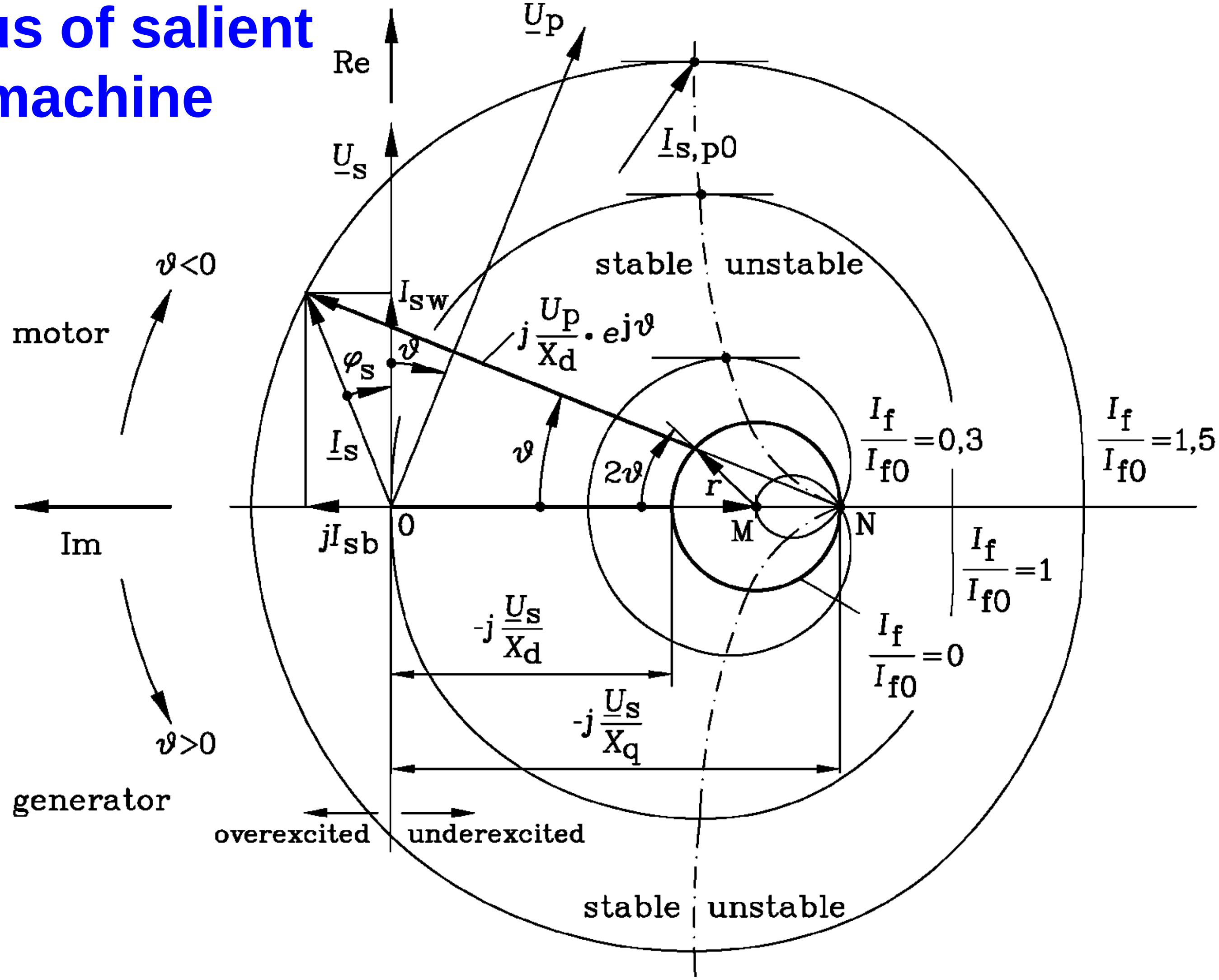
Construction of the stator current root locus of a salient pole synchronous machine, $R_s = 0$ (2)

$$\underline{I}_s = j\frac{U_p e^{j\vartheta}}{X_d} - j\frac{U_s}{2}\cdot\left(\frac{1}{X_d}+\frac{1}{X_q}\right) + j\frac{U_s}{2}\cdot e^{j2\vartheta}\cdot\left(\frac{1}{X_q}-\frac{1}{X_d}\right)$$

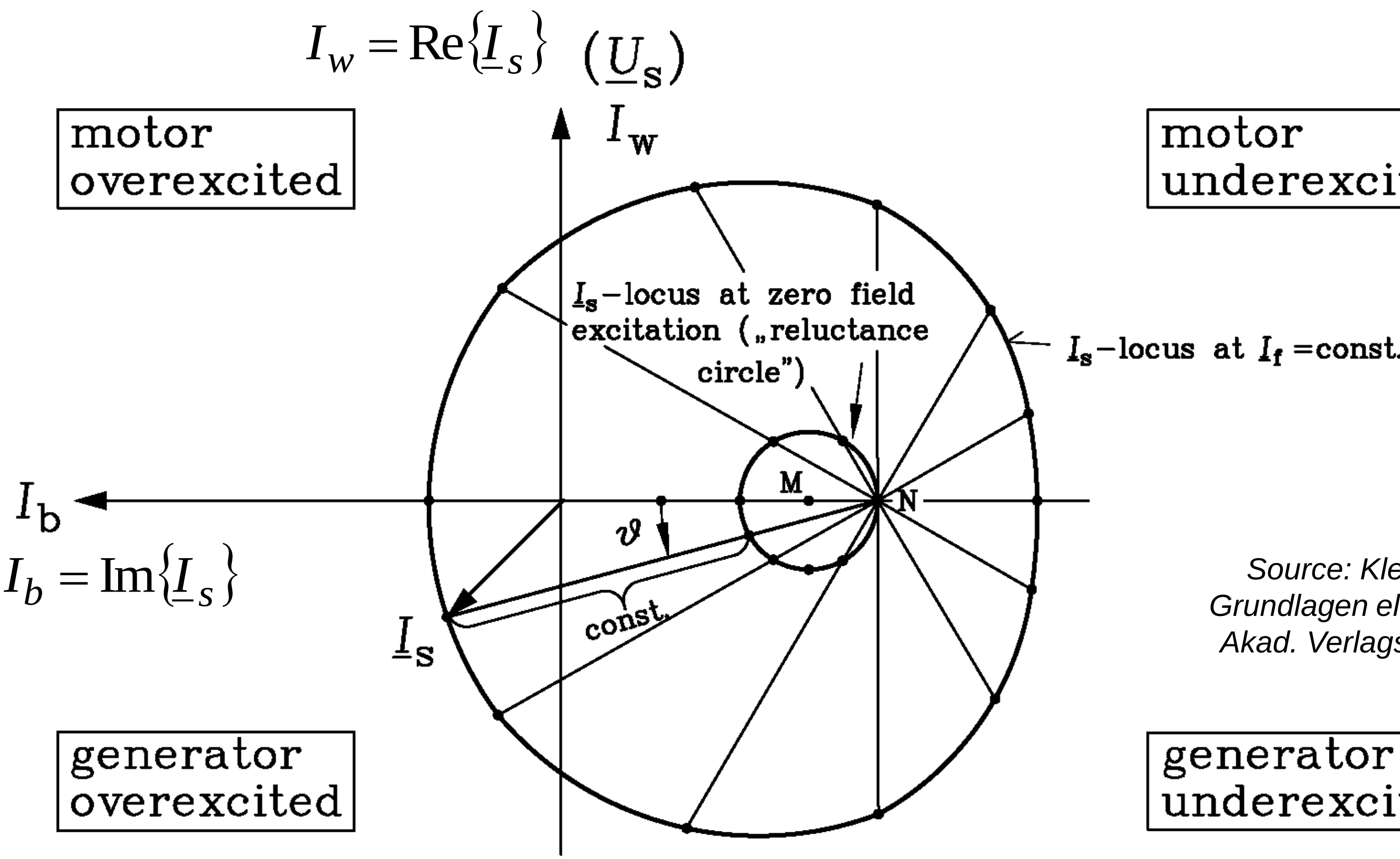


Stator current root locus of salient pole synchronous machine

- neglected stator winding resistance $R_s \approx 0$,
- stator grid voltage is constant $\underline{U}_s$ = const.,
- different excitation levels $I_f \sim \underline{U}_p$



Stator current root locus of salient pole synchronous machine



Source: Kleinrath, H.; Grundlagen el. Maschinen, Akad. Verlagsgesellschaft

Summary:

Stator current root locus

- Cylindrical rotor machine: circle with radius proportional to I_f (for $R_s = 0$)
- Operational limits:
  min./max. exciter current, max. stator current, max. load angle, max. real power, stability limit

- Salient pole machine: *Pascal* limacons
- For zero excitation: Reluctance circle

- Regulation curves: $I_s(I_f)$ for $\cos\varphi_s$ = const.
- V-Curves: $I_s(I_f)$ for $\mathrm{Re}\{\underline{I}_s\}$ = const.