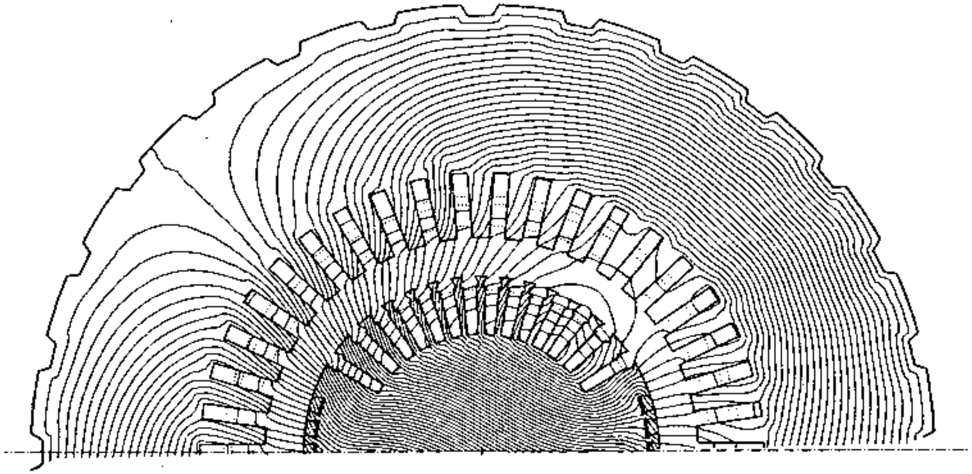
4. Excitation of synchronous machines

- No-load and short-circuit characteristic

- Determination of necessary field ampere-turns

- Phasor diagram of saturated synchronous machines

- *POTIER* reactance



4. Excitation of synchronous machines

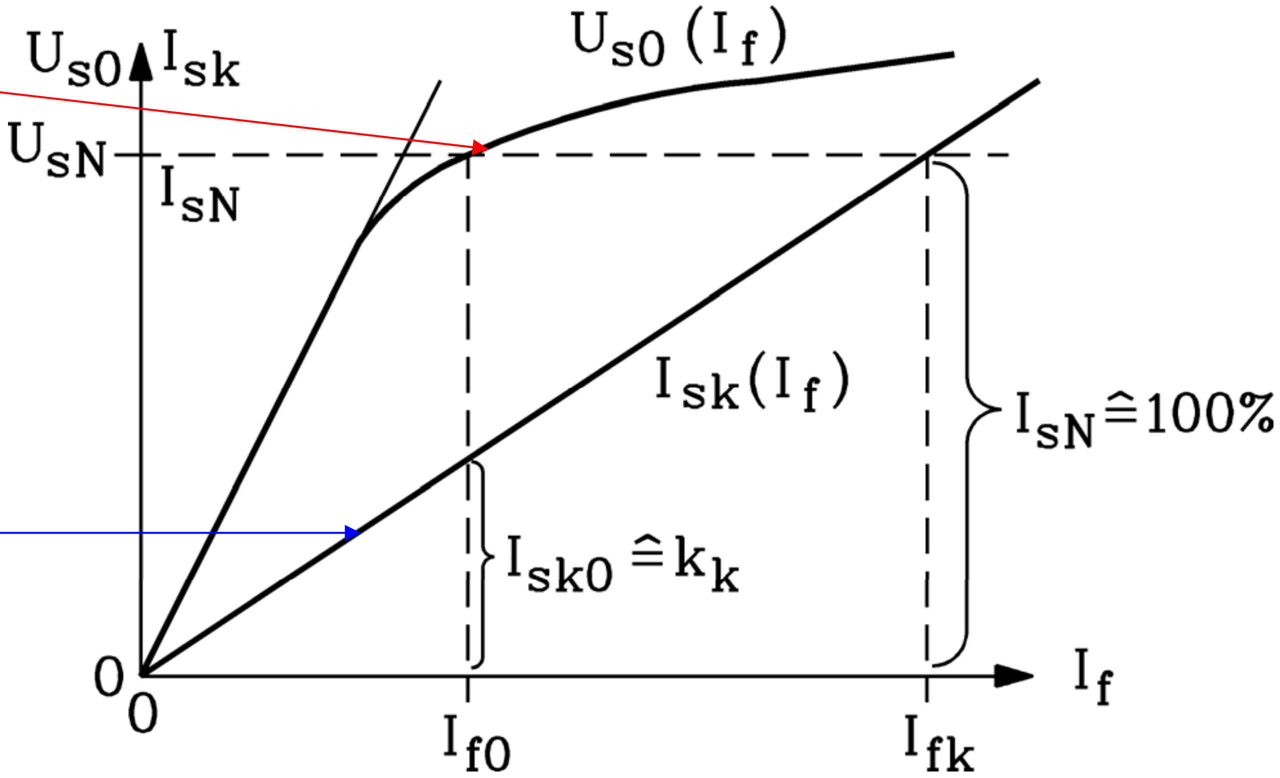
4.1 No-load and short-circuit characteristic

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}



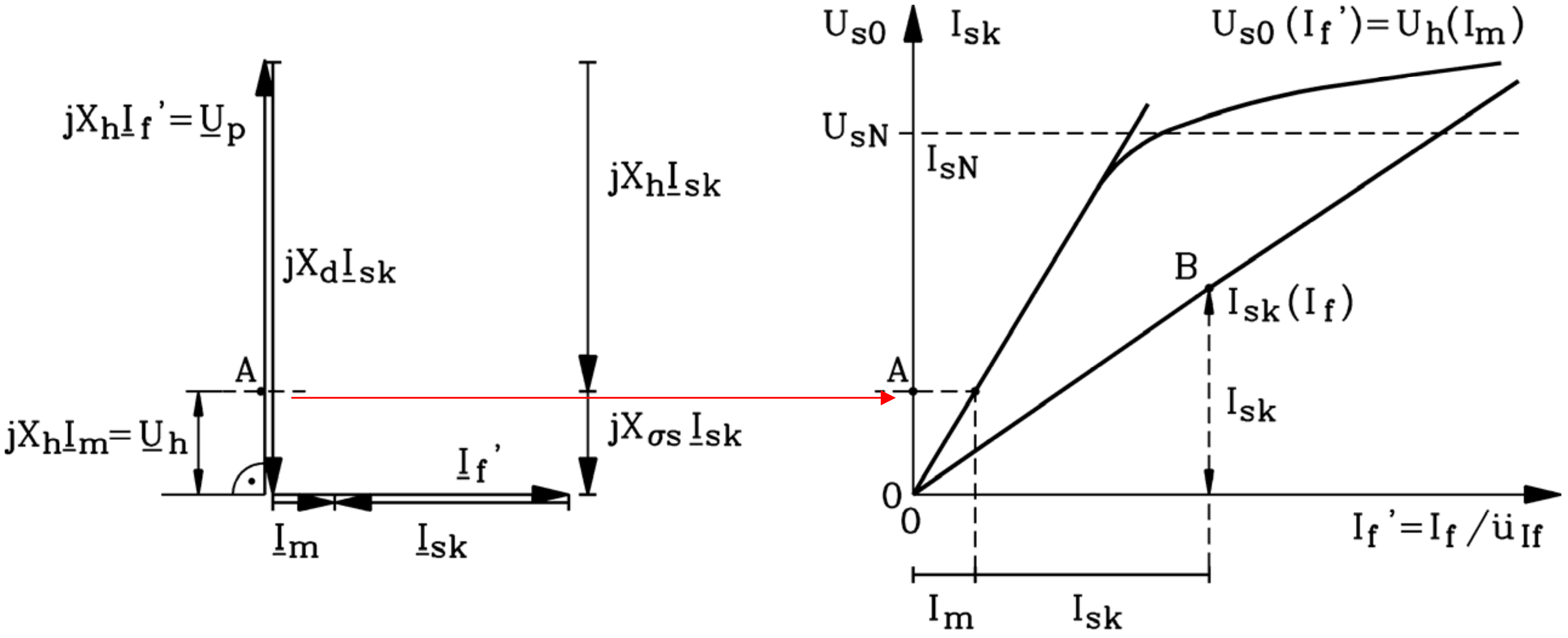
Synchronous reactance x_d (per unit):

$x_d = X_d / Z_N = 1/k_k$

k_k: No-load/short-circuit ratio

4. Excitation of synchronous machines

Saturation at no-load, <u>no</u> 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 <u>unsaturated.</u>

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 $\underline{I}'_f$:** $\boxed{\underline{U}_p = jX_h \underline{I}'_f}$

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

- **$\underline{I}'_f$ 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.**

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

Example: Turbine generator:

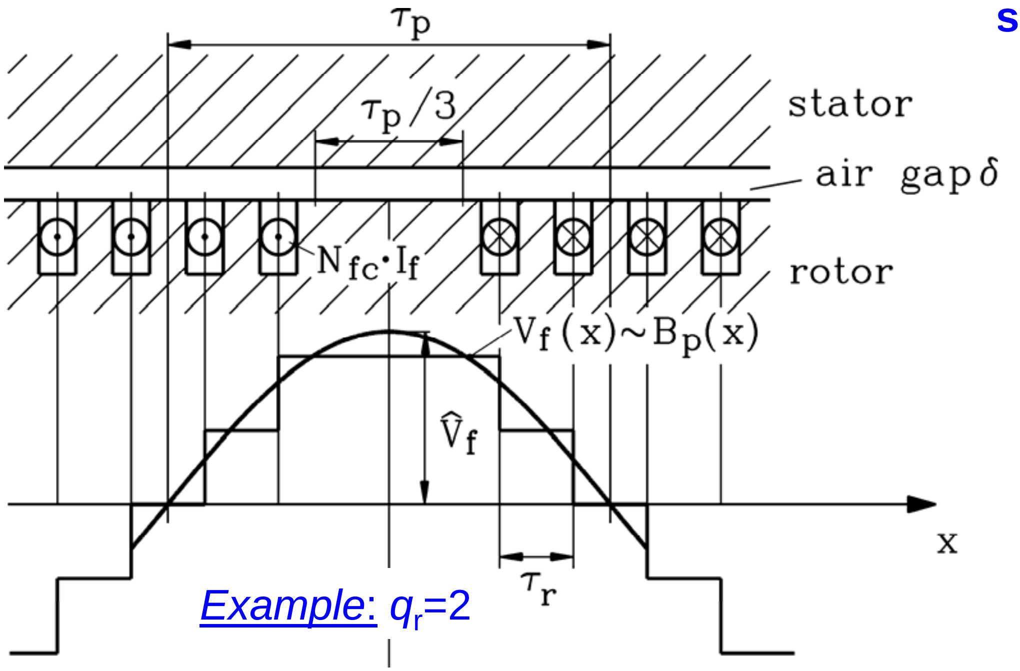
Rotor m.m.f. fundamental: $\hat{V}_f = \frac{2}{\pi} \cdot \frac{N_f}{p} \cdot k_{wf} \cdot I_f$

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: $\boxed{\ddot{u}_{If} = \frac{m_s N_s k_{ws} \sqrt{2}}{2 N_f k_{wf}}}$

4. Excitation of synchronous machines

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** ($\mu = 1$):

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

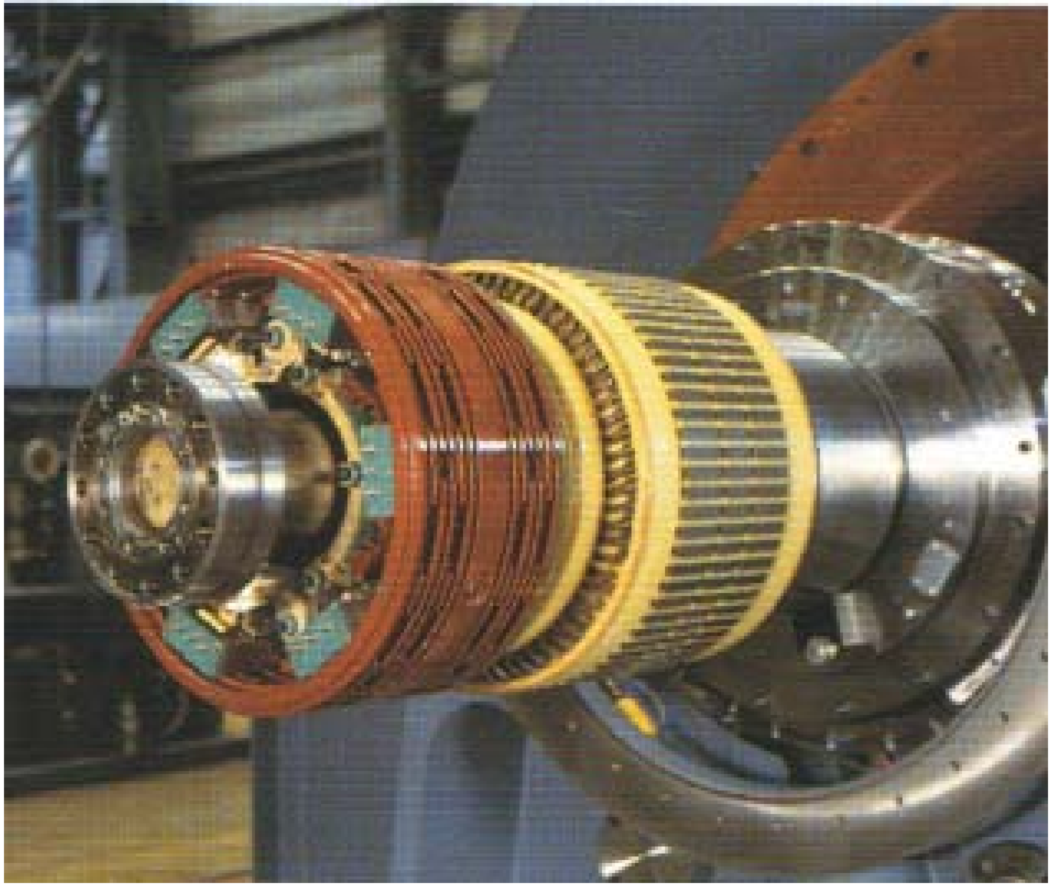
$$\hat{B}_p = \mu_0 \frac{\hat{V}_f}{\delta} , \quad N_f = 2p \cdot q_r \cdot N_{fc}$$

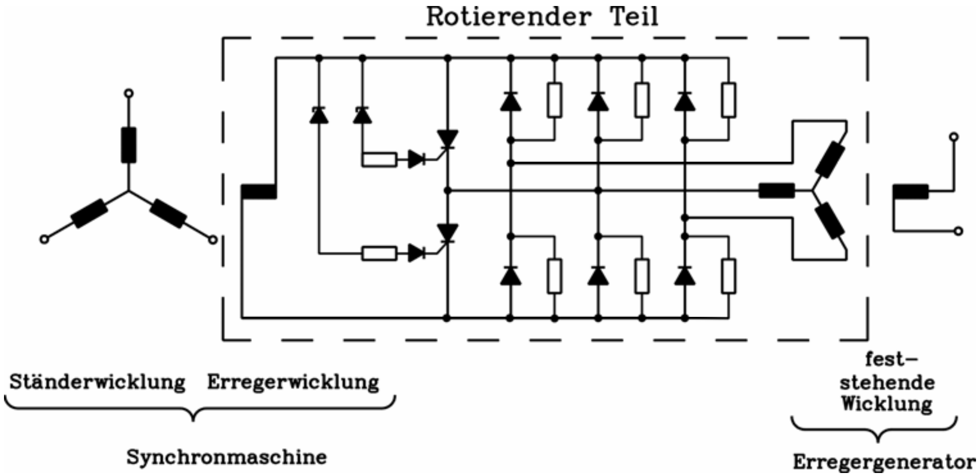
$$k_{p,f} = \sin\left(\frac{W}{\tau_p} \cdot \frac{\pi}{2}\right) = \sin(\pi/3) = \frac{\sqrt{3}}{2}$$

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

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

Brushless excitation armature and diode wheel

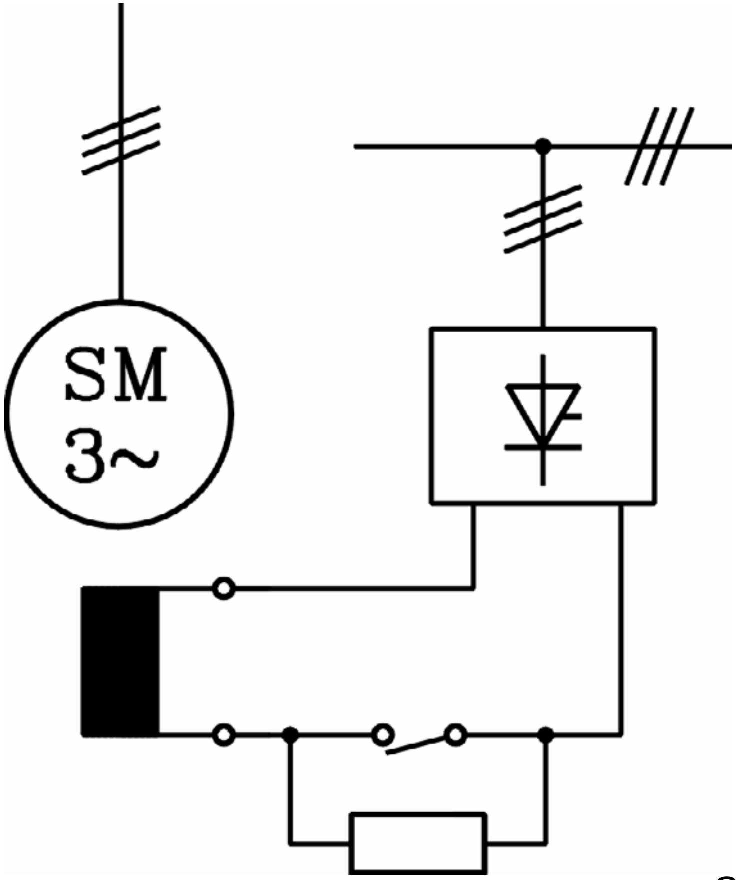




Source:

Siemens AG, Mülheim/Ruhr, Germany

Static excitation collector via two slip rings and carbon brushes



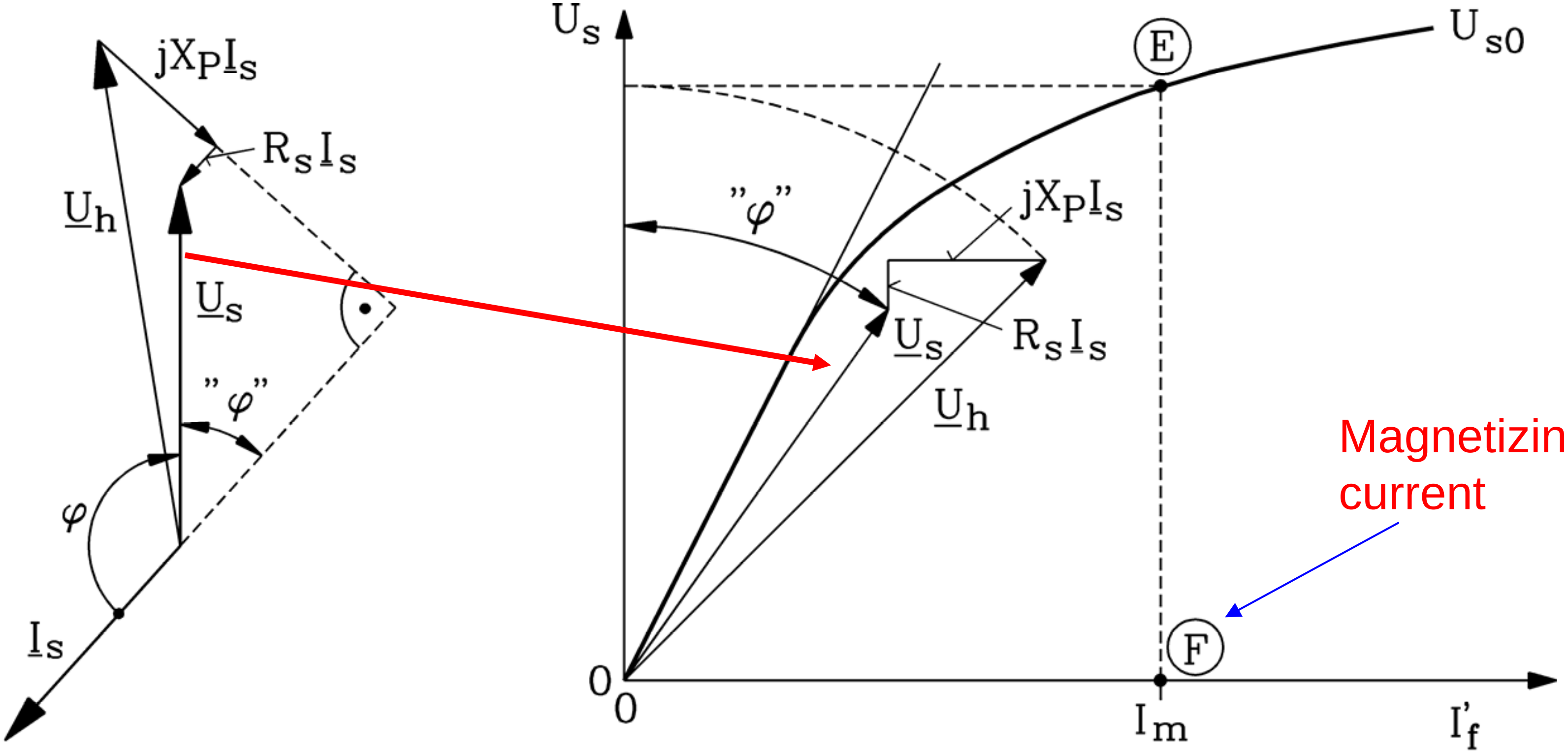
Source:

*Siemens AG,
Mülheim/Ruhr,
Germany*

4. Excitation of synchronous machines

4.2 Determination of necessary field ampere-turns

Calculation of magnetizing current, considering main flux saturation:



Magnetizing current

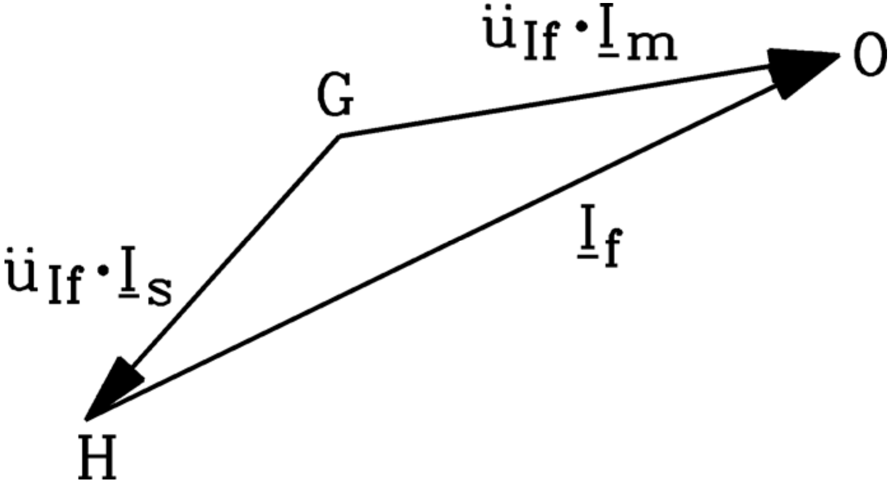
Magnetic point of operation *E* of main air gap flux linkage Ψ_h is determined by internal voltage:

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

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



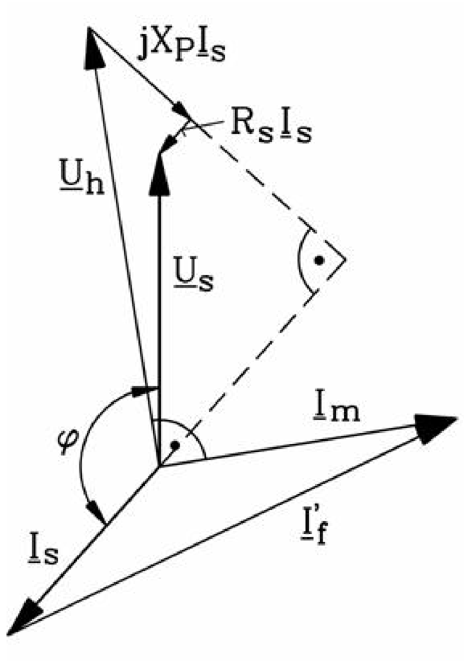
- In order to get field current I_f from I_m, we need to know addition of stator and rotor current.

- From phasor diagram we get I'_f. With knowledge of $\ddot{u}_{If}$ we calculate I_f.

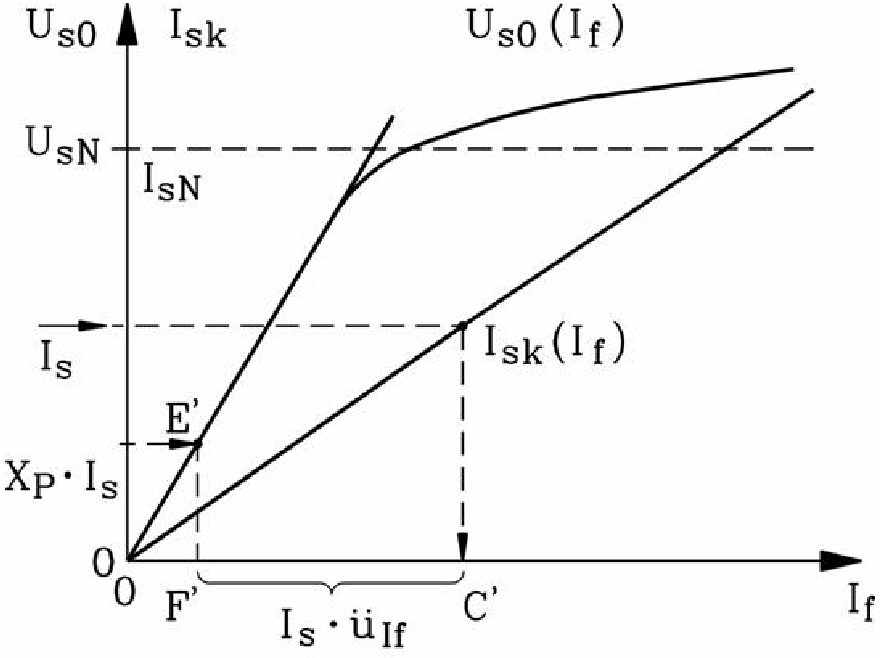
4. Excitation of synchronous machines

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 $ü_{If}$ we calculate I_f.

B) If machine is already built and measured, we can take $ü_{If}$ from short-circuit characteristic.

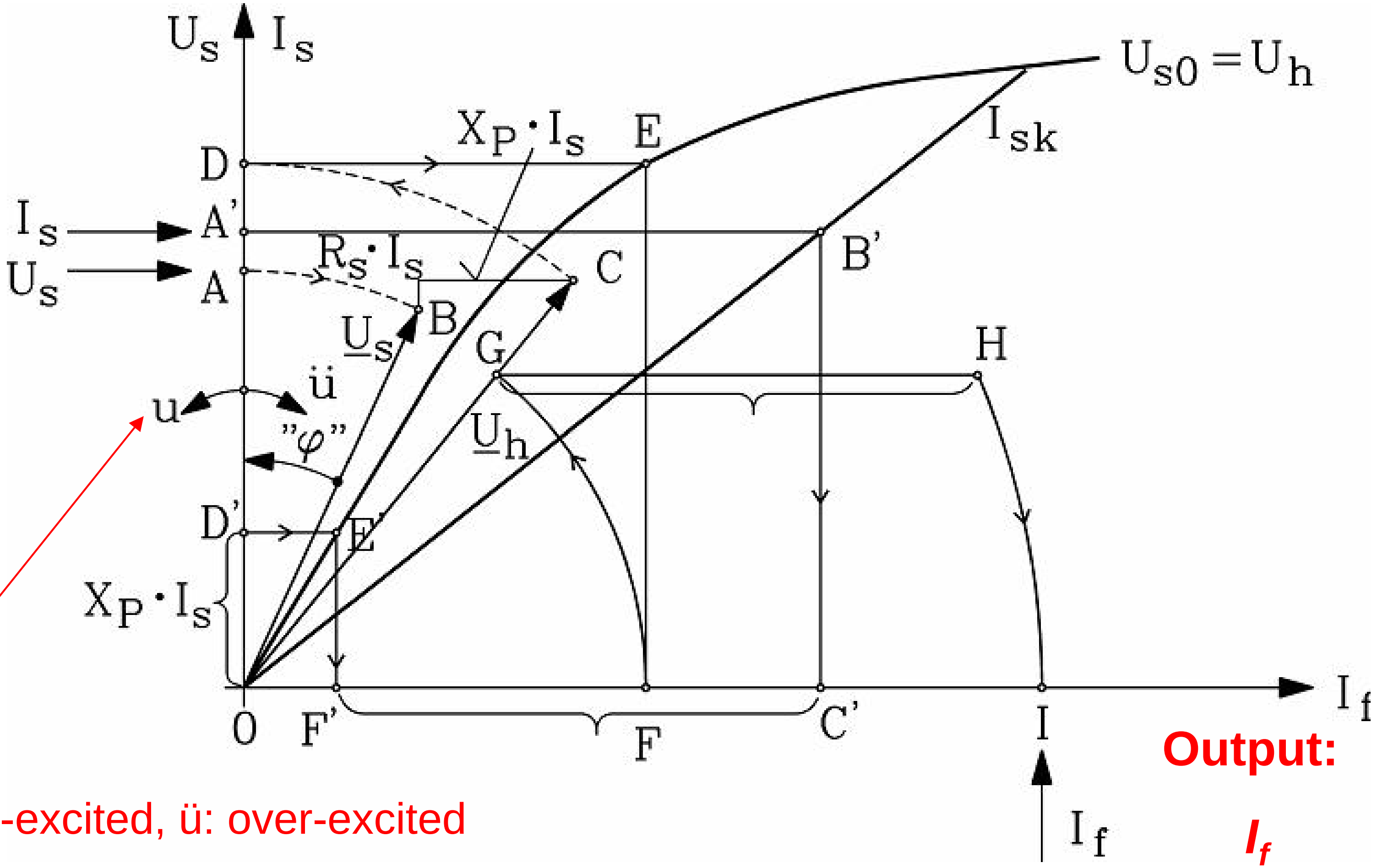
It is the distance between F´and C´, if the curve is given in dependence of I_f.

4. Excitation of synchronous machines

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

Input:

U_s, I_s, φ



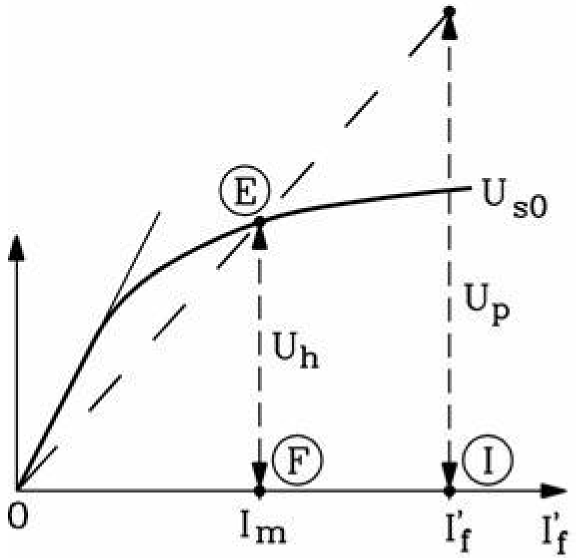
Output:

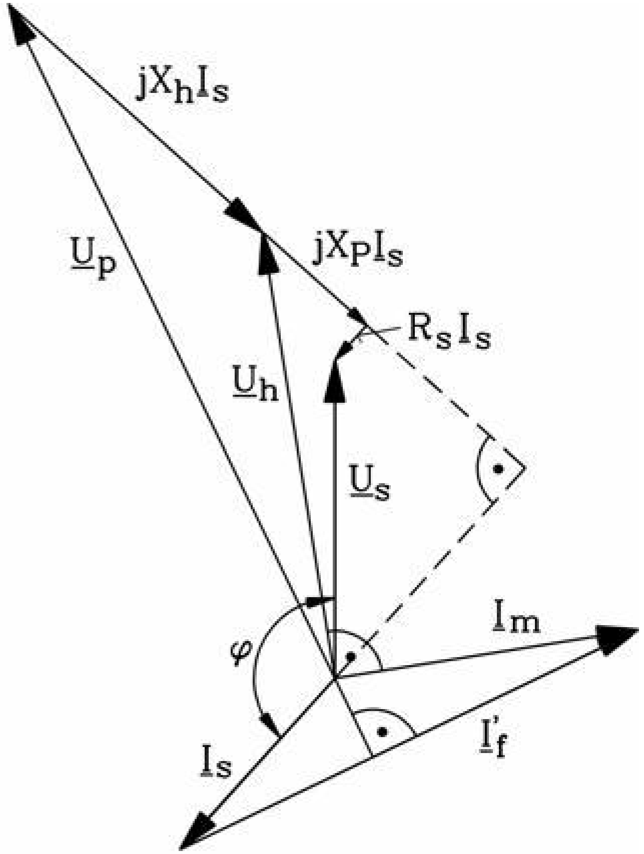
I_f

u: under-excited, ü: over-excited

4. Excitation of synchronous machines

4.3 Phasor diagram of saturated synchronous machines

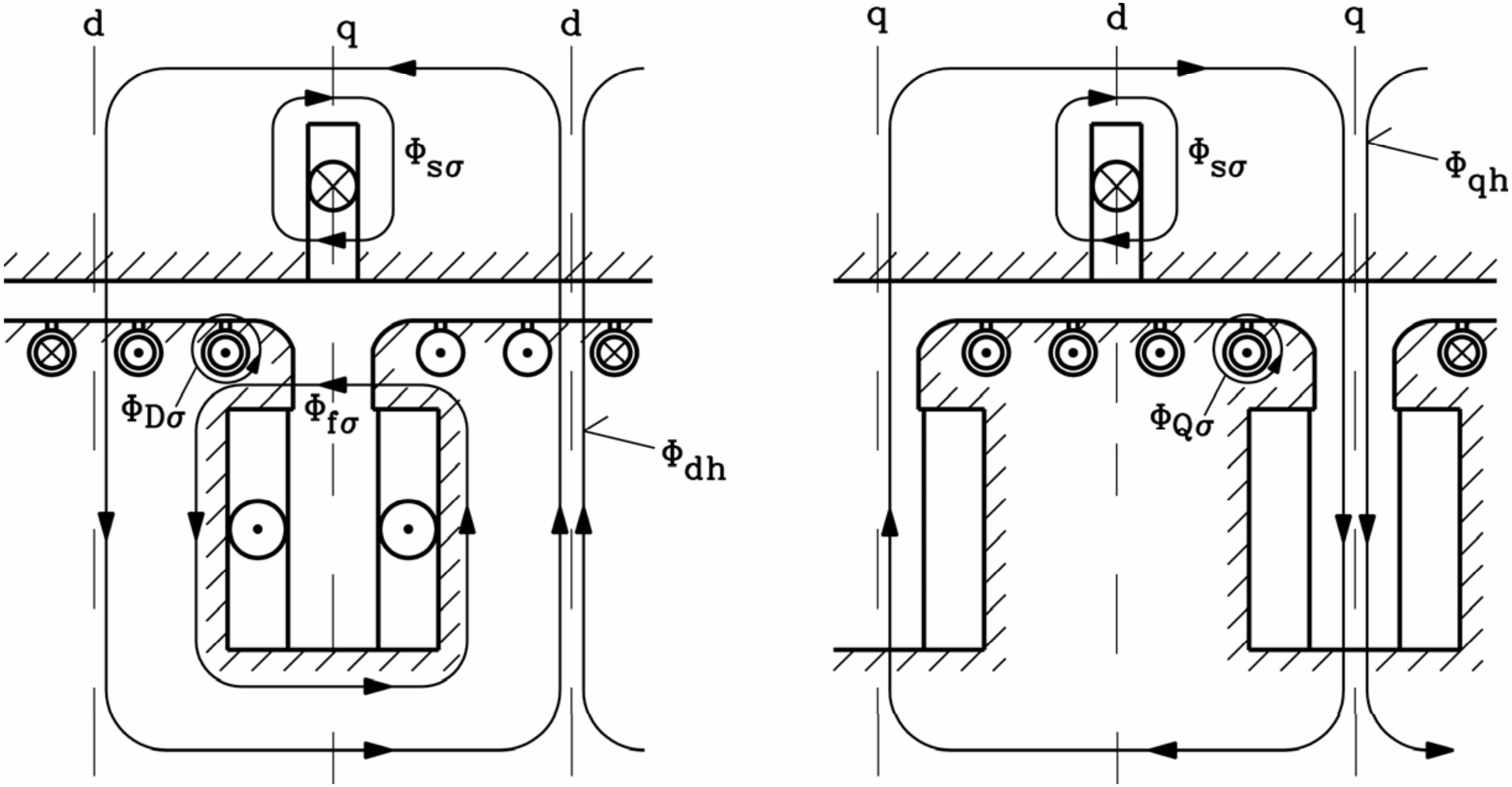




Magnetic characteristic is linearized in magnetic operation point E to determine (fictive) back EMF for saturated load operation point.

4. Excitation of synchronous machines

4.4 *POTIER* reactance

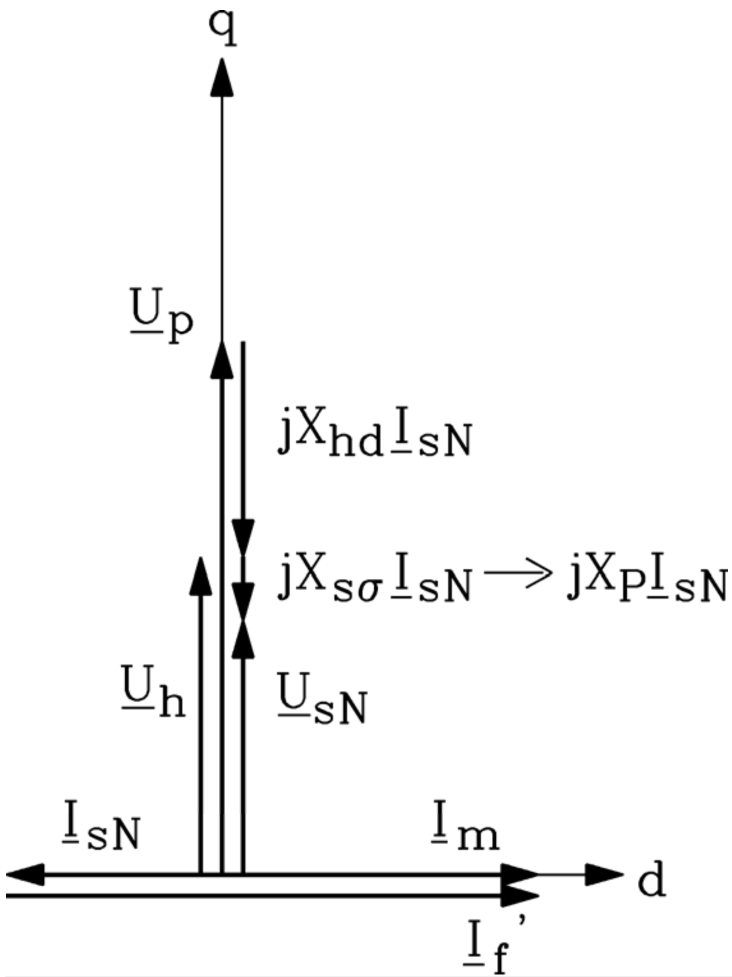


In d-axis rotor stray flux $\Phi_{f\sigma} \sim I_f$ is ADDING to main flux Φ_h, so it will increase pole shaft iron saturation.

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

4. Excitation of synchronous machines

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



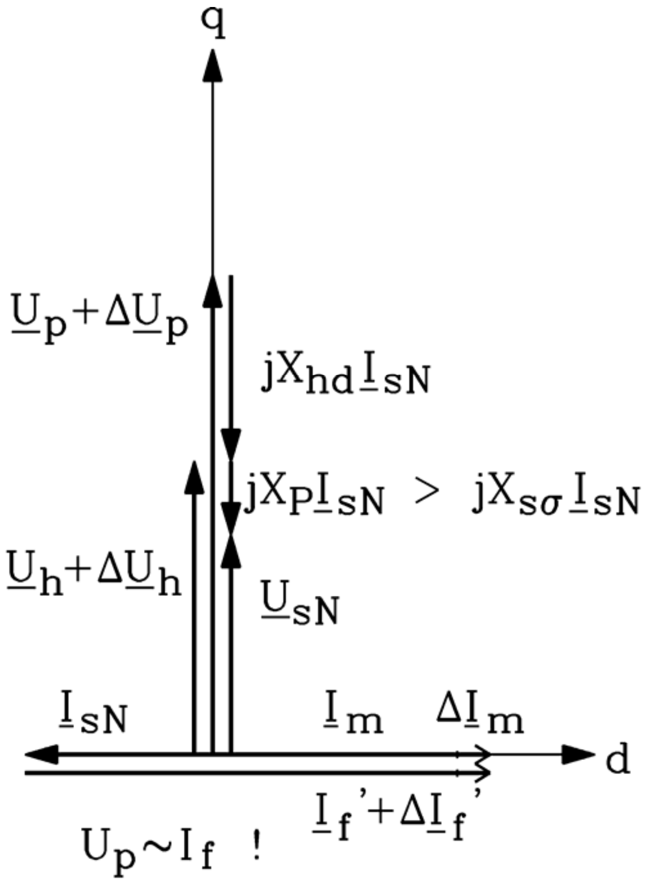
Phasor diagram for pure inductive load of generator at rated voltage and current:
$U_s = U_N$, $I_s = I_N$, $\cos\varphi = 0$ *over-excited*

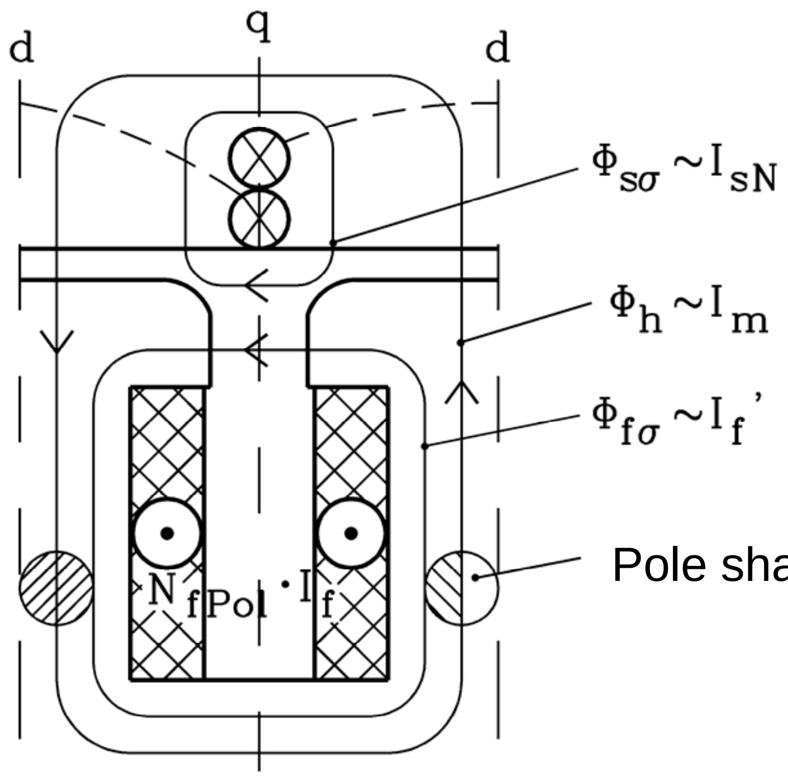
Due to this big rotor stray flux the rotor iron saturates strongly, yielding an increased demand of excitation ampere-turns ΔI_f.

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

4. Excitation of synchronous machines

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





Pole shaft saturation

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

4. Excitation of synchronous machines

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 !

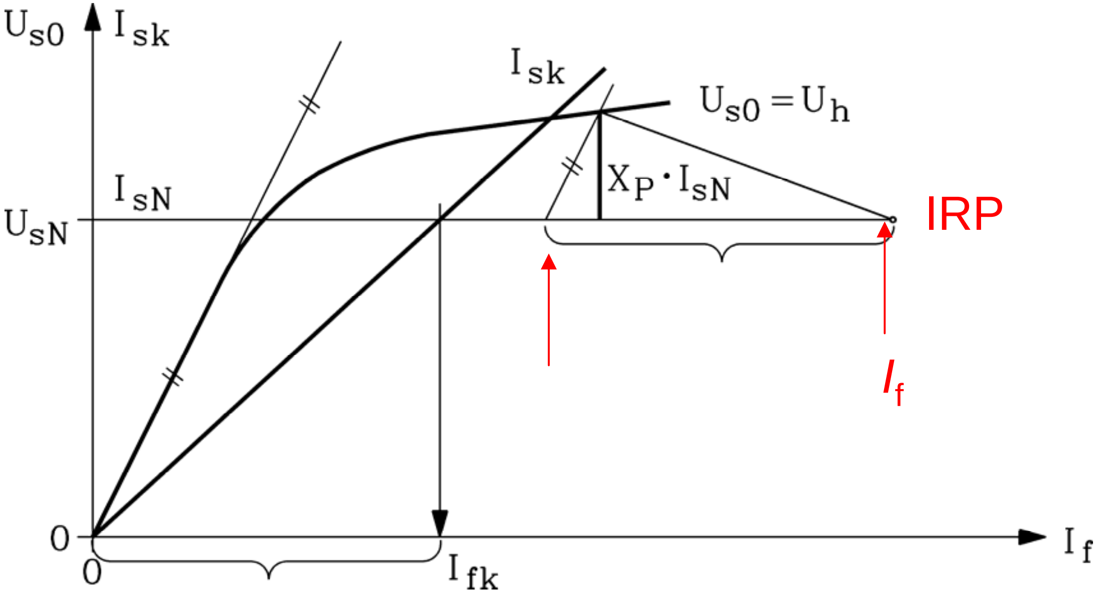
- Increased field current gives (at fictively constant main reactance X_{hd}) a fictively increased back EMF U_p. This has to be compensated by a fictively increased leakage reactance $X_{\sigma s}$, which is called ***POTIER*-reactance X_P :**

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

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

4. Excitation of synchronous machines

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 $\ddot{u}_{If}$)