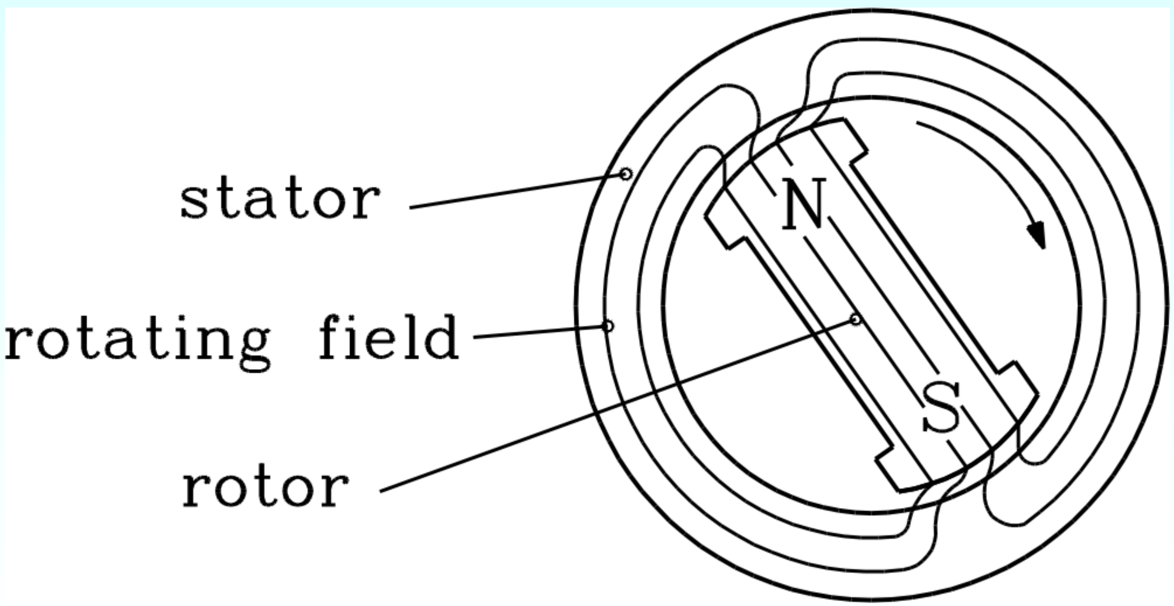
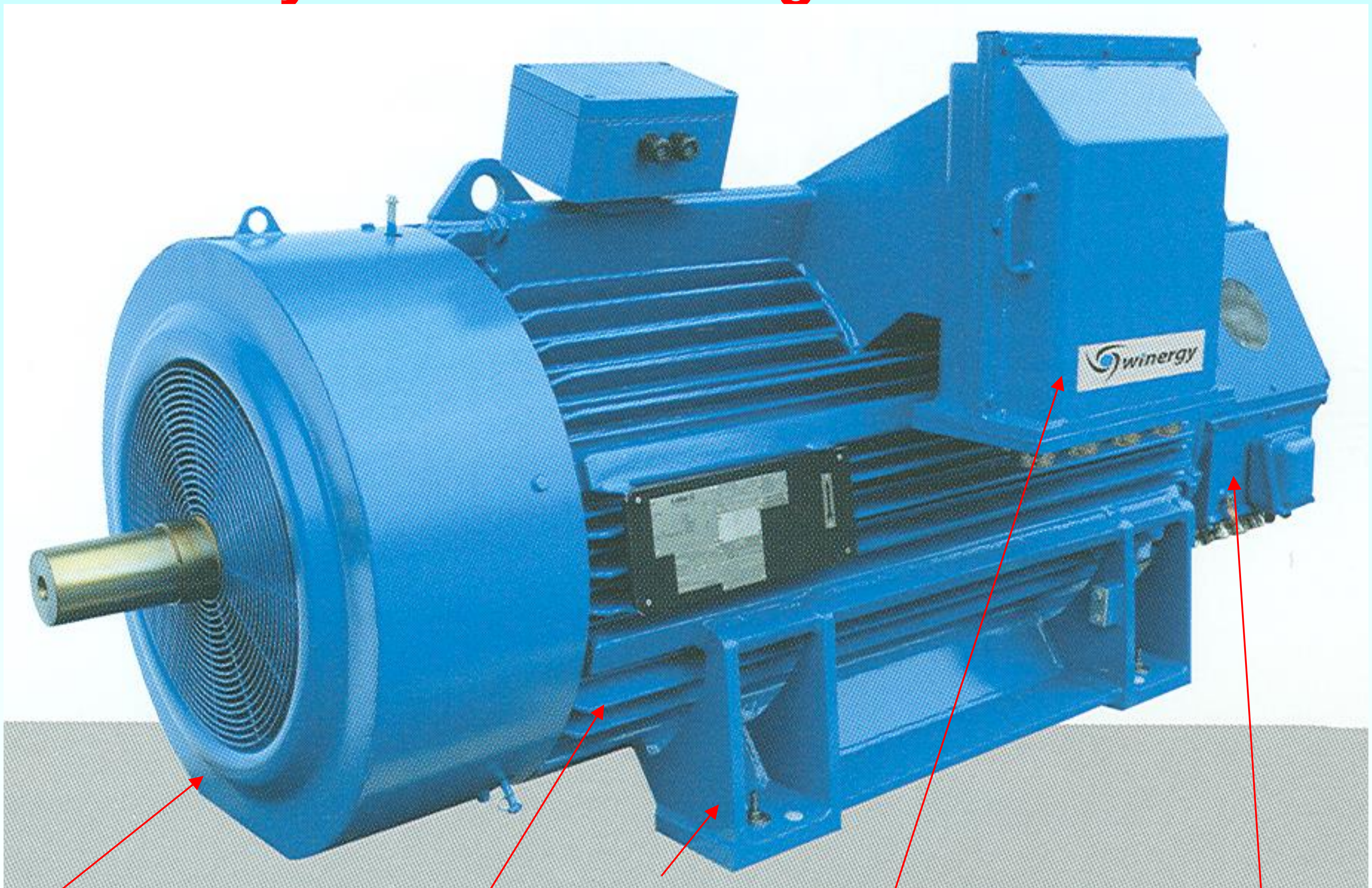
# 2. Rotating Fields in Electric Machines



# Doubly-fed induction generator for wind power




Totally enclosed doubly-fed induction generator

Air-cooled with iron-cast cooling fin housing

600 kW at 1155/min

Source:

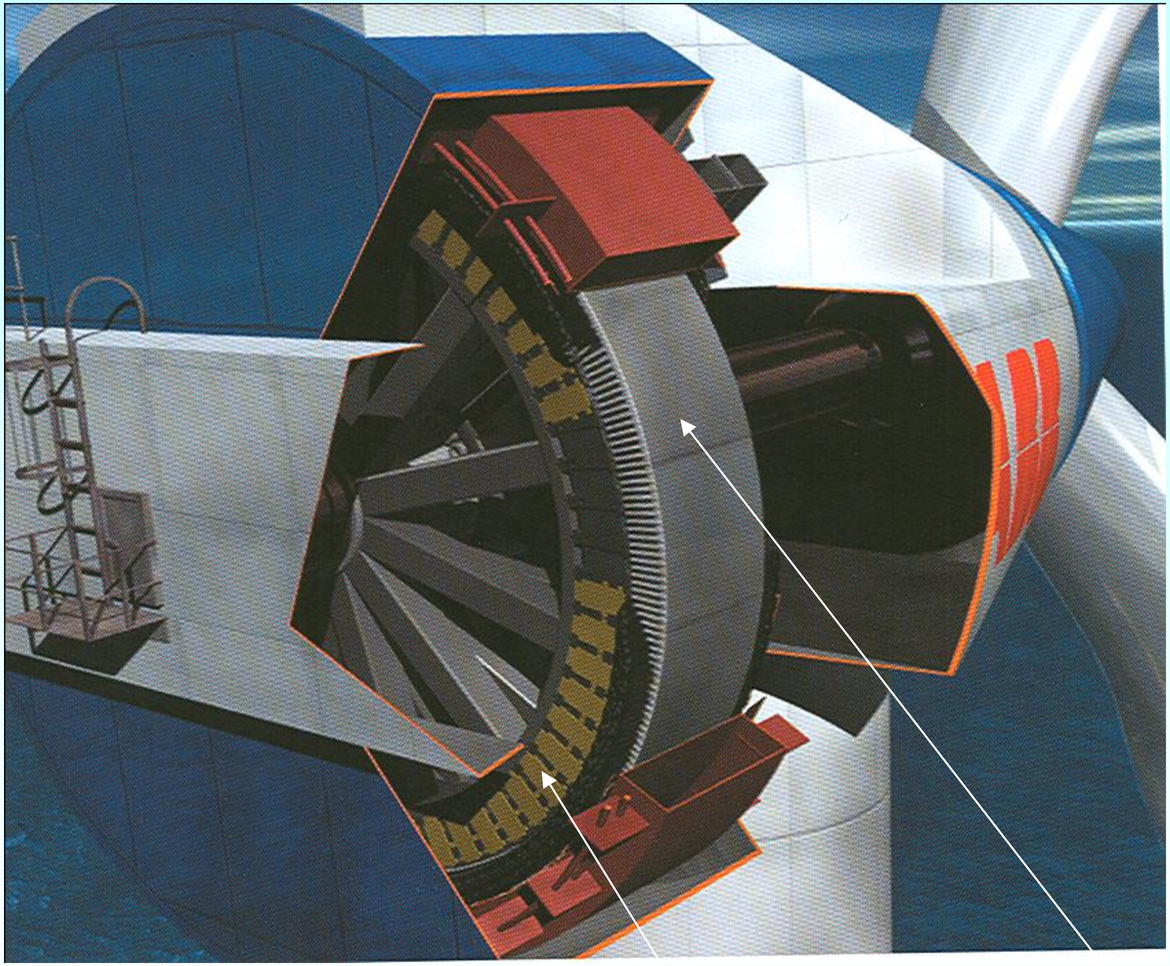
Winergy

Germany

Fan hood   Cooling fins   Feet   Power terminal box   Slip ring

Shaft mounted fan inside   terminal box

# Gearless permanent magnet wind generator



Magnet rotor high voltage stator with winding

*Source: ABB, Sweden*

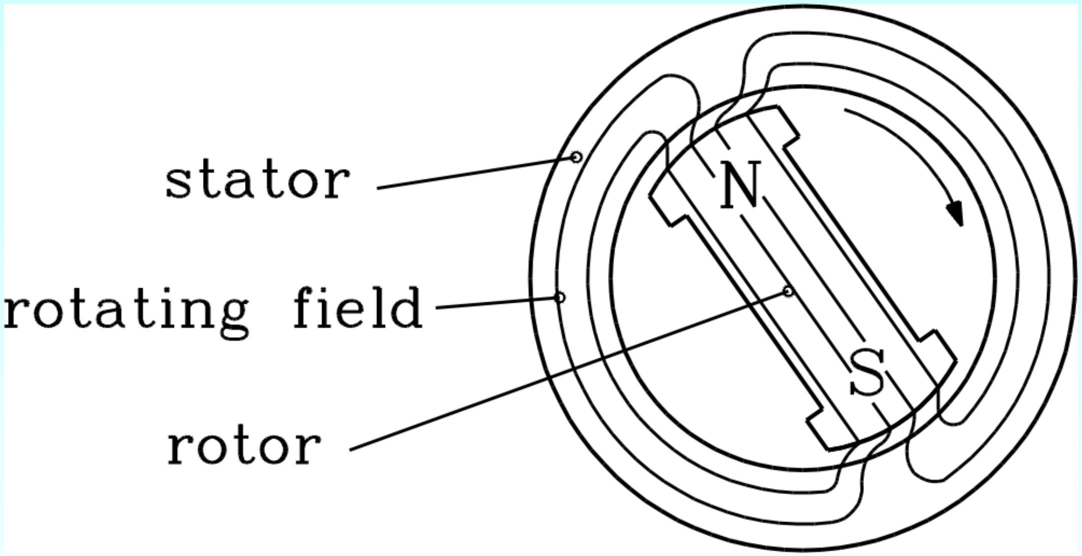
High pole count synchronous generator for low speed operation.

Generator is integrated into turbine construction.

Gearless: Big turbine torque = generator torque, so generator needs big diameter

# AC Rotating field machines: Basic principle

- AC rotating field machines: Induction machines, synchronous machines
- **Example:** Salient pole rotor synchronous machine: Working principle: 2-pole rotating field



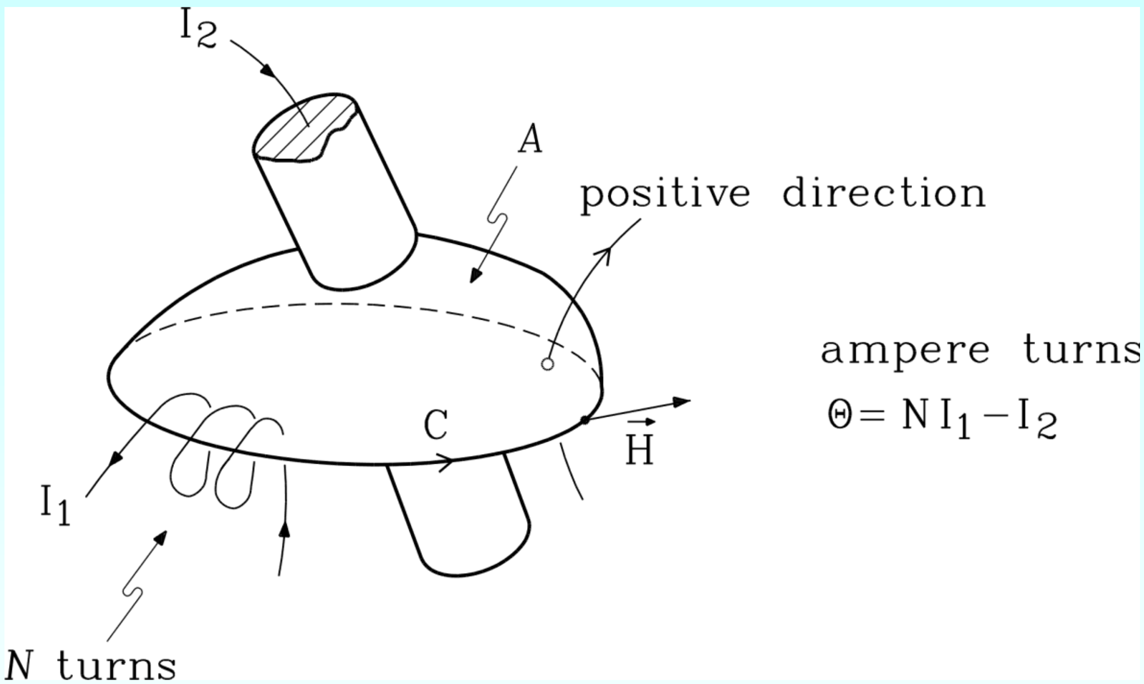

- 3-phase sinus current system (rms $I_s$) in stator 3-phase winding excites rotating stator field.
- Exciting rotor winding ("**salient poles**") fed via 2 slip rings with DC current: "**field current $I_f$**"
  A 2-pole rotor magnetic DC field is excited.
- The 2-pole stator rotating field pulls via magnetic force the rotor **SYNCHRONOUSLY**.
- For calculating the operational performance of **AC rotating field machines** the calculation of the rotating field and its effects (voltage induction, torque generation) is needed. We use *AMPERE´*s law, *FARADAY´*s induction law, winding schemes and *FOURIER*-analysis.

# *AMPERE´s* law: Excitation of magnetic field by electric current

***Example:***

Two different currents $I_1$, $I_2$ with two different numbers of turns 1 and $N$ and two different flow directions:

**Ampere turns $\Theta$ :**
**$\Theta = N I_1 - I_2$**



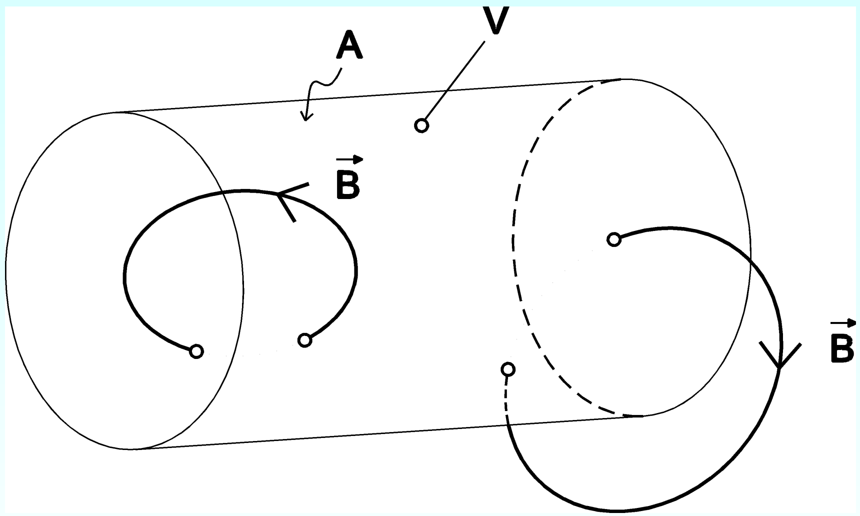

$$\oint_C \vec{H} \cdot d\vec{s} = \Theta$$

- **The integration of magnetic field strength *H* along closed loop (curve *C*), which spans the area *A*, is equal to the resulting current flow (Ampere turns $\Theta$) penetrating through the area *A*.**
- **Positive field direction is connected to positive current flow direction by RIGHT HAND RULE.**

# Law of magnetic flux on closed surfaces

- The total magnetic flux $\Phi$ on closed surface $A$ of volume $V$ is **always ZERO** !

$$\oint_A \vec{B} \cdot d\vec{A} = \Phi = 0$$

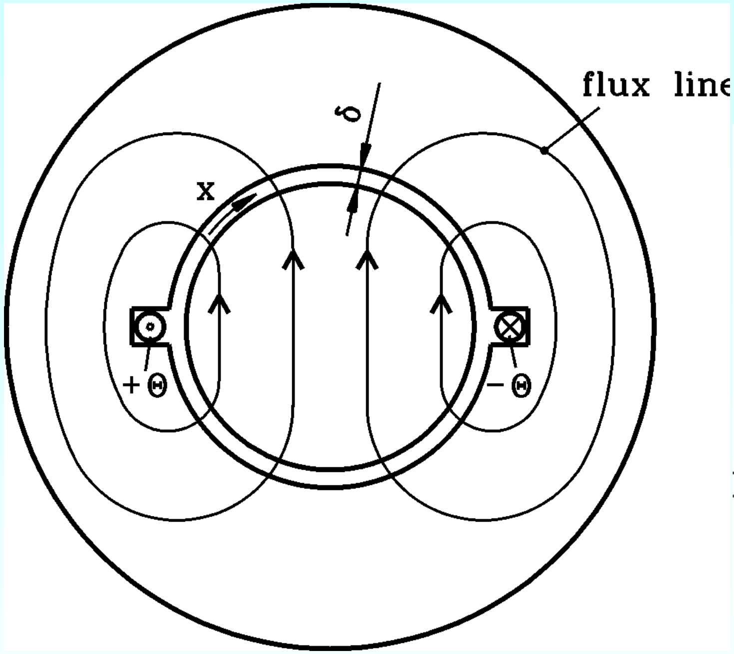


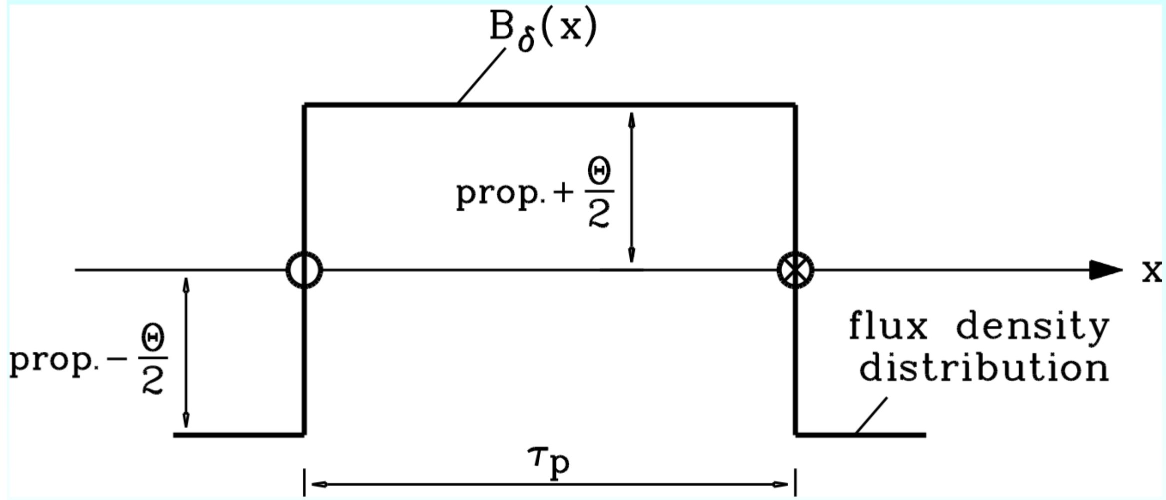

***B*:Magnetic flux density**

- **Normal component of *B*-vector** on both sides of surface *A* is identical: $B_{n,1} = B_{n,2}$
- Magnetic field has always **north- AND south poles: NO magnetic monopoles !**
- Minimum pole number is 2: One north and one south pole (*Example:* Earth magnetic field !
- Number of magnetic poles 2*p* (**pole pair number** *p* = 1, 2, 3, ... means 2, 4, 6, ... poles).

# Magnetic field of current excited coil in air gap

- *AMPERE´s law:* $\oint_C \vec{H} \cdot d\vec{s} = 2H_{Fe}\Delta_{Fe} + 2H_\delta \delta = 2H_\delta \delta = \Theta$




- $B_\delta = B_{Fe} \Rightarrow H_{Fe} = B_{Fe}/\mu_{Fe} = 0$ ($\mu_{Fe} = \infty$) and $H_\delta = B_\delta/\mu_0$ ($\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am)
- **Field vectors** $\vec{H}, \vec{B}$ in air gap: only dominating radial components considered !
- Number of turns of coil $N_c$, coil current $I_c$ : $B_\delta = \mu_0 H_\delta = \mu_0 \dfrac{\Theta}{2\delta} = \mu_0 \dfrac{N_c I_c}{2\delta}$

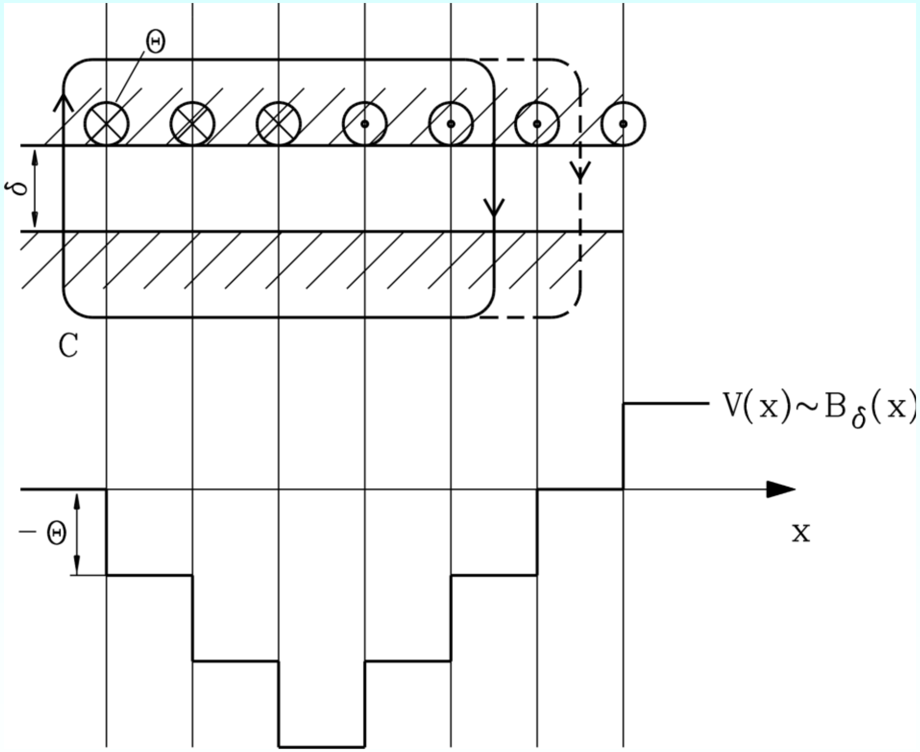
# Magnetomotive "force" $V(x)$ and current layer $A(x)$

- As $H_{Fe} = 0$ ($\mu_{Fe} \to \infty$): field lines of $H_\delta$ start and end at iron surfaces:

  **"magnetomotive force $V$"** in air gap: $V_\delta = H_\delta \cdot \delta$ ; $B_\delta(x) = \mu_0 \dfrac{V_\delta(x)}{\delta}$

- **"current layer" $A(x)$**: $A = \lim_{b \to 0} \dfrac{\Theta}{b}$ in slot region, $A = 0$ in tooth region

  $b$: slot width: here $b = 0$ for simplification !




- Calculation of $B_\delta$ with use of current layer $A(x)$:

$$B_\delta(x) = \mu_0 H_\delta(x) = \frac{\mu_0}{\delta}\int_0^x A(x)dx = \frac{\mu_0}{\delta}\left(V(x) - V_0\right)$$

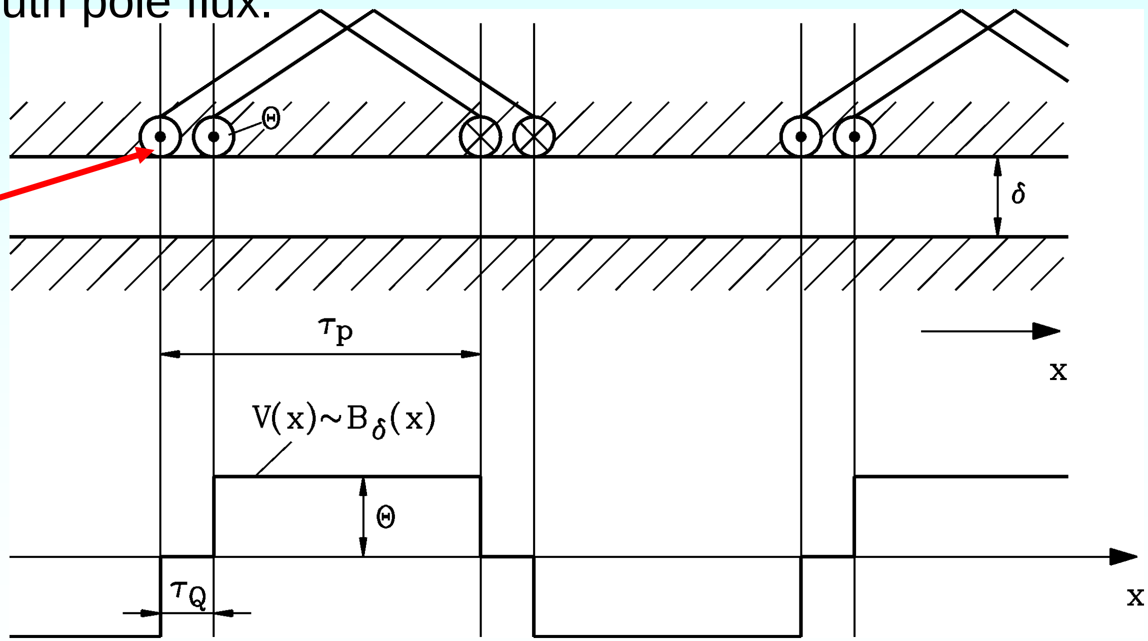
- **Total magnetic flux** at closed surface $A_H$ surrounding rotor in air gap is zero $\Rightarrow$ This determines integration constant $V_0$.

$$\oint_{A_H} \vec{B} \cdot d\vec{A} = l_{Fe} \int_{x=0}^{2p\tau_p} B_\delta(x)dx = 0$$

# Magnetic air gap field of group of coils

- **Coil group:** The windings per pole are given by more than one coil. Coils are connected in series ($q$ coils per group).
- Coil groups distanced by one **pole pitch** $\tau_p$ distributed along machine circumference.
- **"Concentrated" Ampere-turns** per coil is $\Theta$.
- **Magnetic air gap field** of coil group is **symmetrical to abscissa** = field curve $B_\delta(x)$ above and below abscissa $x$ is identical.
- Flux per pole and per axial length = Area beneath field curve: positive & negative areas are equal: north pole flux = south pole flux.

*Example:* "Number of coils per pole and phase" $\boldsymbol{q = 2}$.



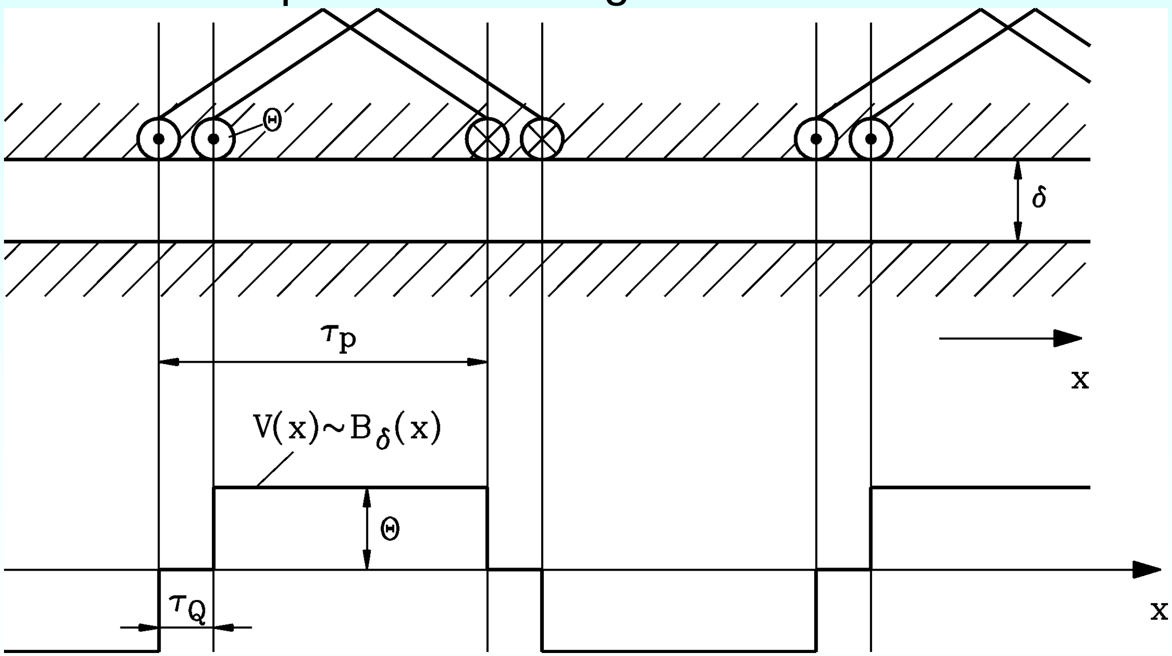
# Magnetic alternating field (AC field)

- Feeding the coil groups with sinusoidal alternating current $i_c$:

  Amplitude $\hat{I}_c$, frequency $f$, angular frequency $\omega = 2\pi f$, $T = 1/f$ : period of oscillation

$$i_c(t) = \hat{I}_c \cos \omega t \qquad B_\delta(x,t) = B_\delta(x) \cos \omega t$$

- Air gap field oscillates also sinusoidal with time, BUT maintains **its spatial distribution (its shape =** its distribution along $x$) ! The amplitude of (radial) field component at locus $x$ changes with time between positive and negative maximum value.



# *TESLA*'s idea for rotating (moving) magnetic air gap field

- THREE windings ("phases") U, V, W with positive and negative current flow direction = **6 zones** with notation +U, -W, +V, -U, +W, -V form a WINDING BELT.
- Zones with positive current flow direction chosen so, that phase V is shifted with respect to phase U by $2\tau_p/3$ , and phase W by $4\tau_p/3$.
- Winding belt phases U, V, W fed with 3 sinus currents: Each AC current time-shifted with $T/3$ phase shift: $i_U(t)$, $i_V(t)$, $i_W(t)$ ( = symmetrical 3-phase AC CURRENT SYSTEM).

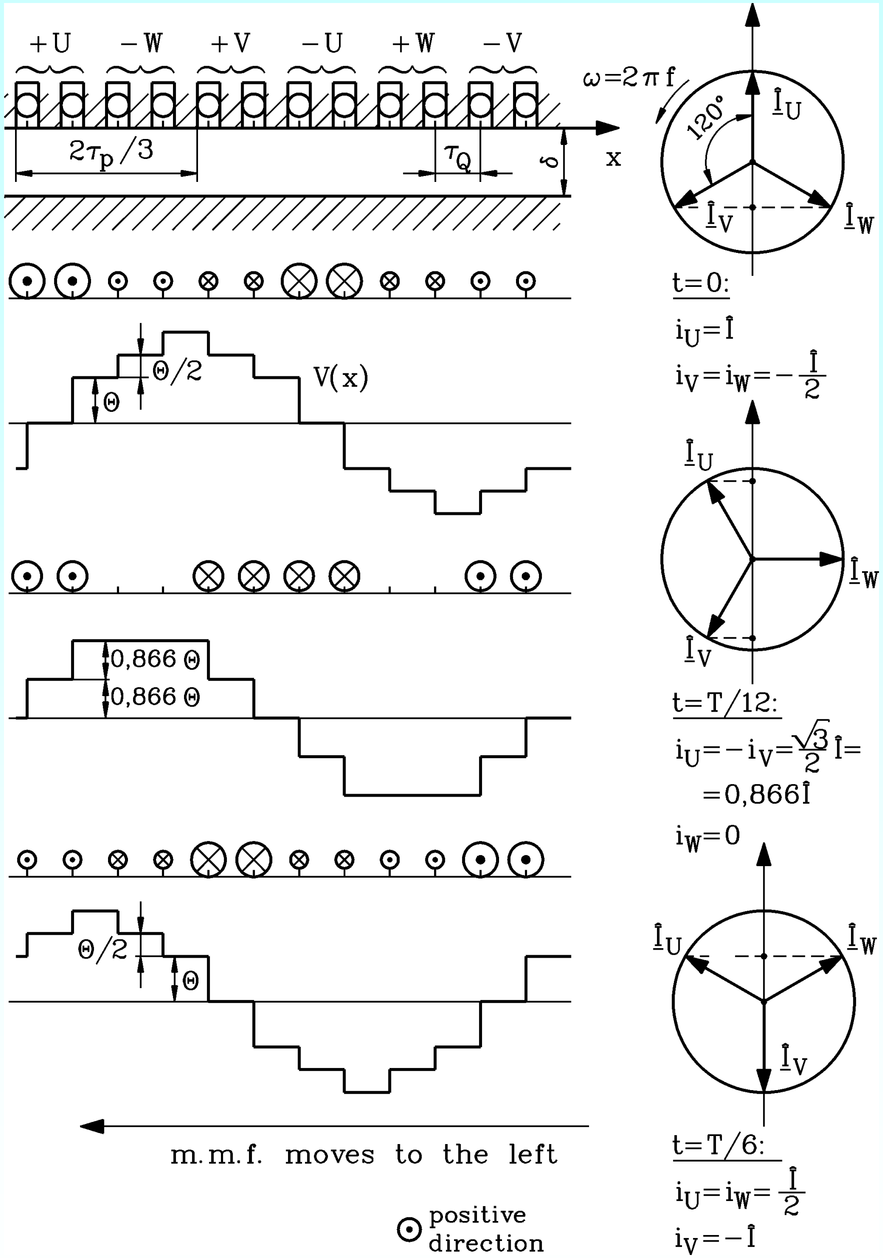
$$i_U(t) = \hat{I}\cos(\omega t + \varphi)$$

$$i_V(t) = \hat{I}\cos(\omega t + \frac{\omega \cdot T}{3} + \varphi)$$

$$i_W(t) = \hat{I}\cos(\omega t + \frac{\omega \cdot 2T}{3} + \varphi)$$

- We use **complex phasor calculus for sinusoidal AC currents & voltages:**

$$i(t) = \mathrm{Re}\left\{\underline{I} \cdot \sqrt{2} \cdot e^{j\omega t}\right\} = \mathrm{Re}\left\{I \cdot e^{j\varphi} \cdot \sqrt{2} \cdot e^{j\omega t}\right\} = \hat{I}\cos(\omega t + \varphi) \quad \Rightarrow \quad \underline{I} = I \cdot e^{j\varphi}$$




# Magnetic moving field

- Field curve moves with increasing time $t$ to the left !
- After time $T$ the field curve has passed the distance $2\tau_p$
- Velocity of <u>linear</u> movement is called

$$v_{syn}=\frac{2\tau_p}{T}=2f\tau_p$$

**synchronous velocity !**

**Synchronous rotational speed $n_{syn}$**

in case of <u>rotating</u> field arrangement:

$$\omega_{syn}=2\pi n_{syn}=\frac{v_{syn}}{d_{si}/2}=\frac{v_{syn}}{p\tau_p/\pi}=\frac{2\pi f}{p}$$

$$n_{syn}=\frac{f}{p}$$

# Linear machines

- **Linear** movement, e.g. drive system for magnetically levitated Hi-speed train (MagLev)
- Cruising speed of MAGLEV train *TRANSRAPID :*

  *Data:* $\tau_p$ = 258 mm, $f$ = 270 Hz (Maximum frequency of feeding inverter)

  $v_{syn} = 2 f \tau_p = 2 \cdot 270 \cdot 0.258 = \underline{139.3}$ m/s = 501.6 km/h

# Rotating field machines

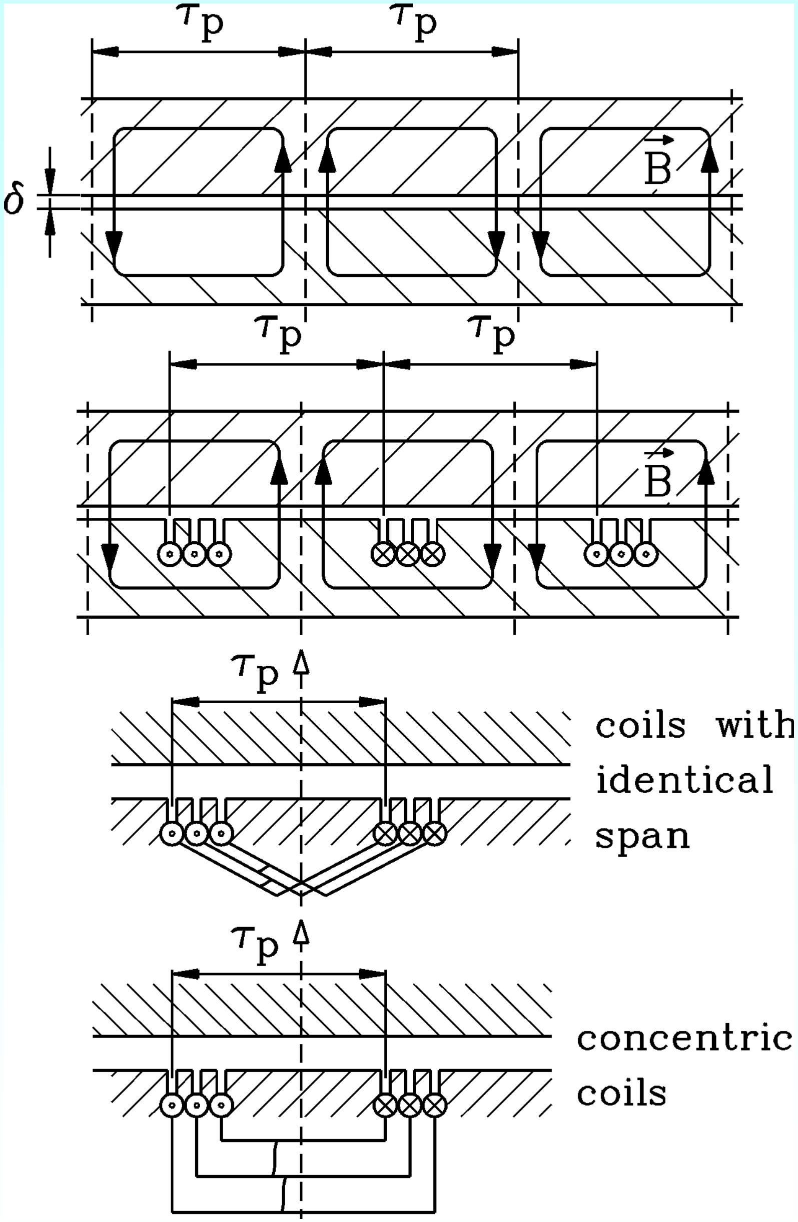
- **Rotating part of machine** ( = Rotor) at $f$ = 50 Hz:

  Two-pole machine ($2p$ = 2): Magnetic field rotates with $n_{syn}$ = 50 Hz = 3000/min

  Sixty-pole hydro generator ($2p$ = 60): Magnetic field rotates with $n_{syn}$ = 100/min

| | $2p$ | - | 2 | 4 | 6 | 8 | 10 | 12 | 14 |
|---|---|---|---|---|---|---|---|---|---|
| $f$ = 50 Hz | $n_{syn}$ | 1/min | 3000 | 1500 | 1000 | 750 | 600 | 500 | 428.6 |
| $f$ = 60Hz | $n_{syn}$ | 1/min | 3600 | 1800 | 1200 | 900 | 720 | 600 | 514.2 |

- Changing direction of rotation of magnetic field by changing connection of two terminals !




# Single layer winding

- Per slot only one coil side is placed.
- Coils manufactured as:
  - **a) Coils with identical coil span**: $W = \tau_p$
  - **b) Concentric coils**

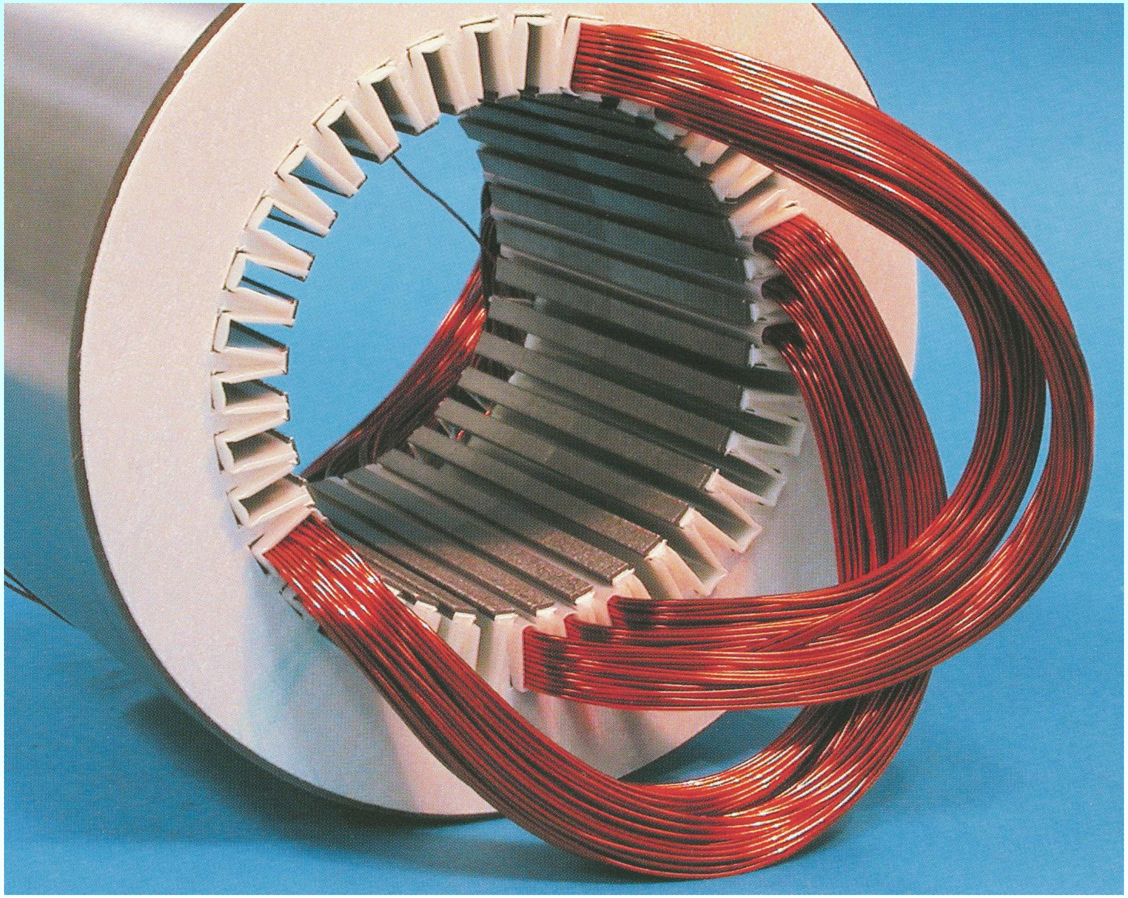
*Example:*

Three-phase, 12-pole machine with $q = 3$ coils per pole and phase:
Total slot number: $Q = m \cdot 2p \cdot q = 3 \cdot 12 \cdot 3 = \underline{108}$

North- and south pole are generated by **ONE coil group per phase**.

**Problem with single layer windings:**
Crossing of coils in winding overhang part, as all coils are lying in the same plane. Thus some coils must be bent upward in winding overhang region **("2$^{nd}$ plane").**

# Single layer winding – Inserting of coils



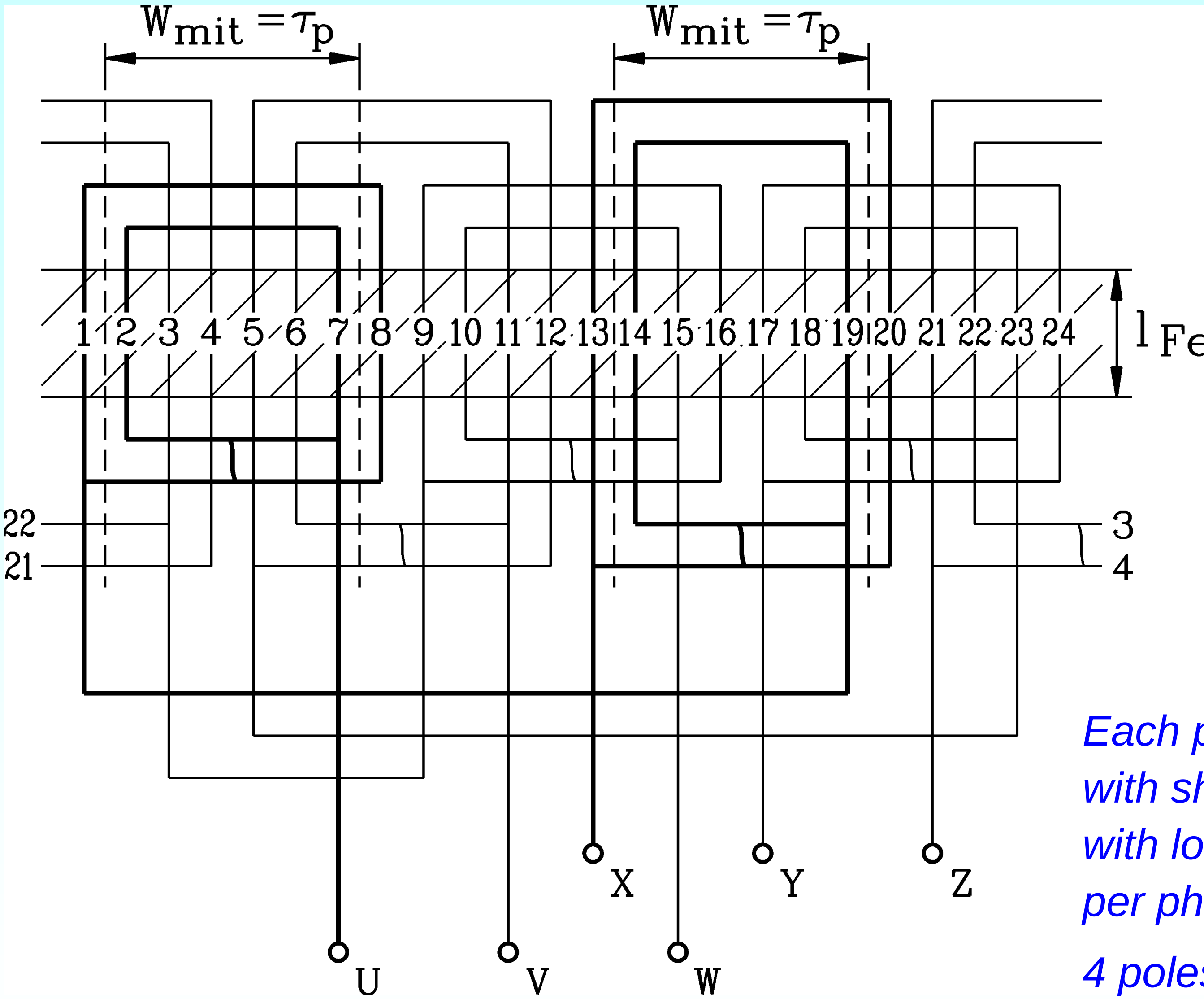
*Source: Krempel, Germany*

***<u>Example:</u>* *Inserting round wire coils:***

Round wire coils - concentric, $q$ = 3 coils per group, two-pole winding

36 slots, six-phase winding $m = 6$, $Q = 2p \cdot m \cdot q = 2 \cdot 6 \cdot 3 = 36$

# *Example:* Single layer winding with short and long coils



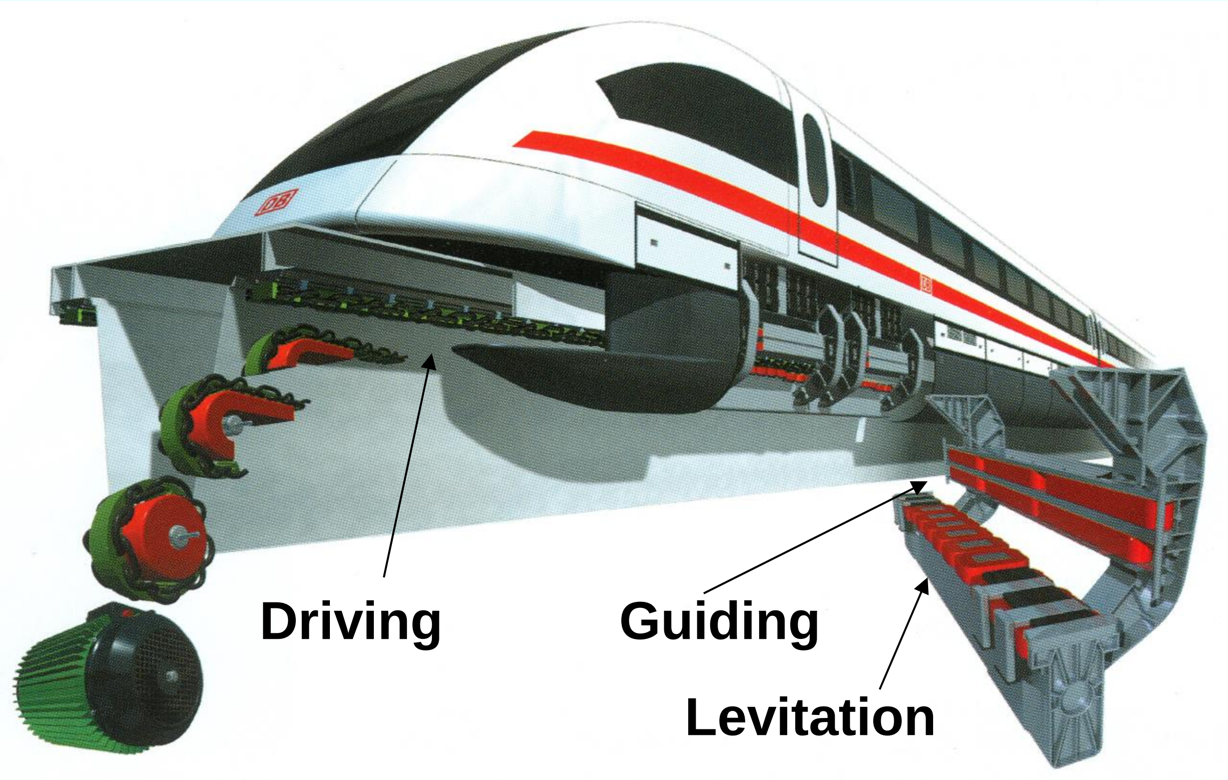

Unrolled winding system gives "winding scheme": here: four-pole machine: $2p = 4$, $m = 3$, $q = 2$, $Q = \underline{24}$

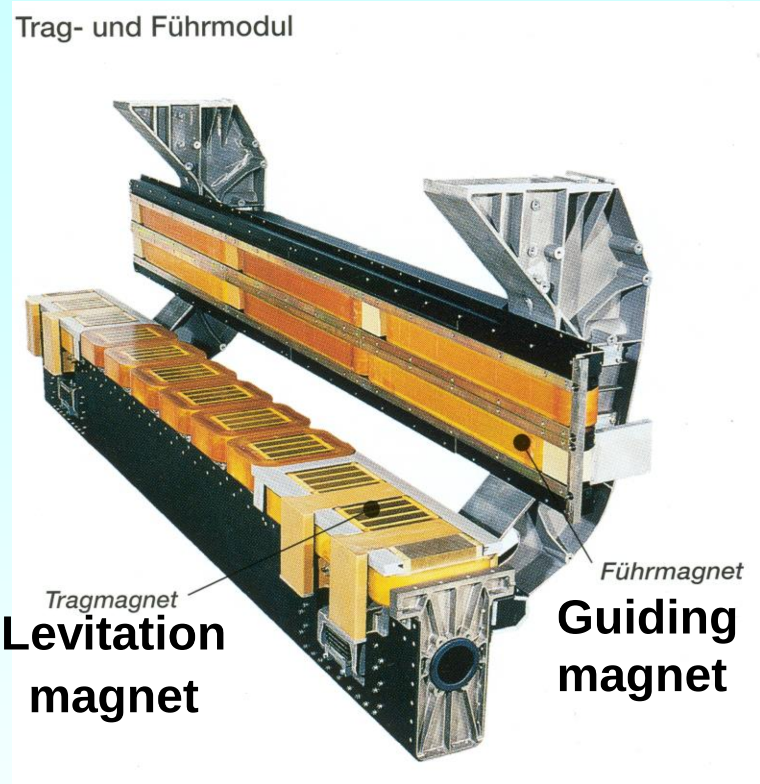
Winding manufactured with concentric coils.

***"Long coils":*** Winding over- hang part of coils is longer; so these coils may be bent upwards !

*Each phase has one pole pair with short and one pole pair with long coils ! So resistance per phase is equal, but minimum of 4 poles required !*

# Driving and levitation of TRANSRAPID

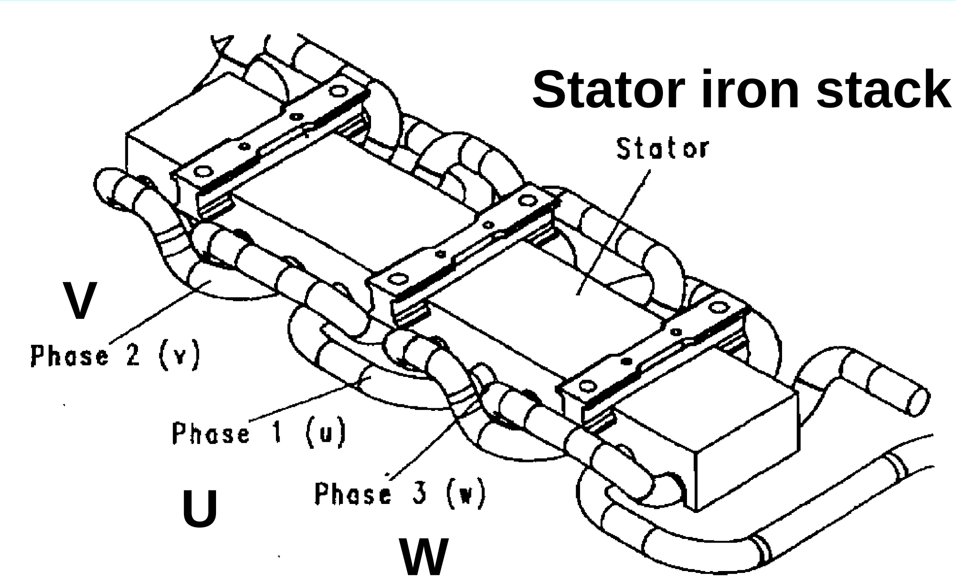


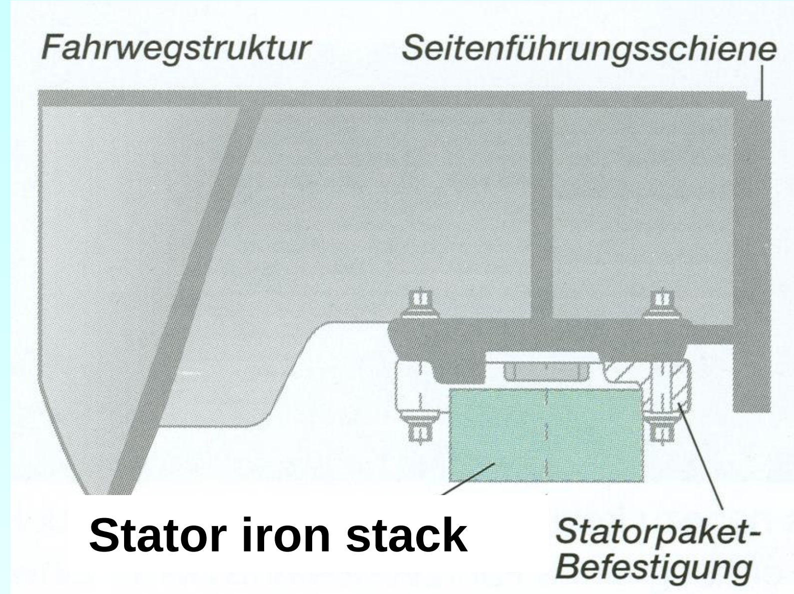




**The levitation magnets attract from below at an air gap of ca. 10 ...13 mm the vehicle to the stator of the synchronous linear motor, which is placed in the track. Thus the vehicle clearance ABOVE the track is about 150 mm.**

*Source: Siemens AG & Thyssen Krupp, Germany*

# Three phase long stator winding in stator iron stack




**Three winding „phases" U, V, W: wave-like placed aluminium-cables with one turn per coil and one slot per pole and phase.**

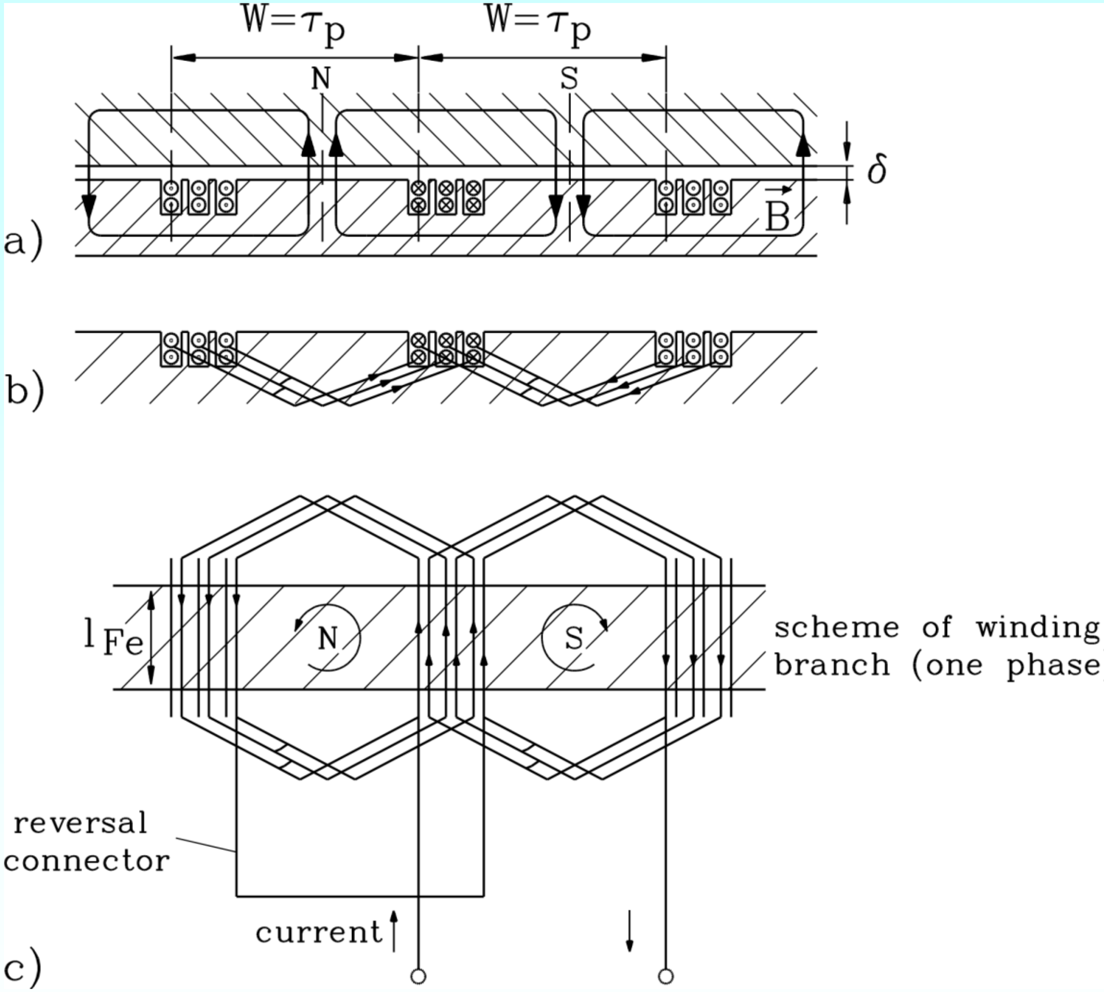
**Pole pitch: 258 mm, Units with 4 poles = 1032 mm, 24 units = 1 section = 24.768 m, Stack length 185 mm, two stators in parallel per track**

**Several sections form a feeding unit: in *Shanghai*: 0.9 ... 5.0 km**

**Ca. 180 poles fit under one vehicle of 46 m length.**

*Source: Thyssen Krupp, Germany*

# Two-layer winding

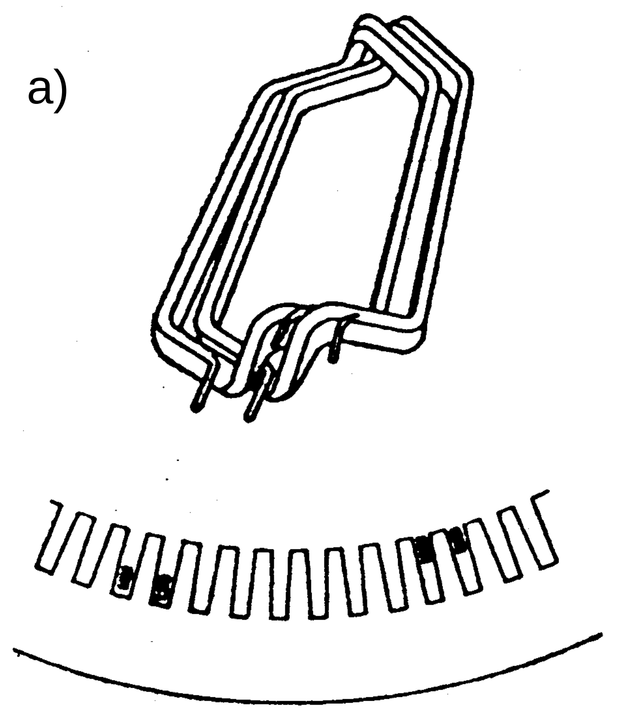


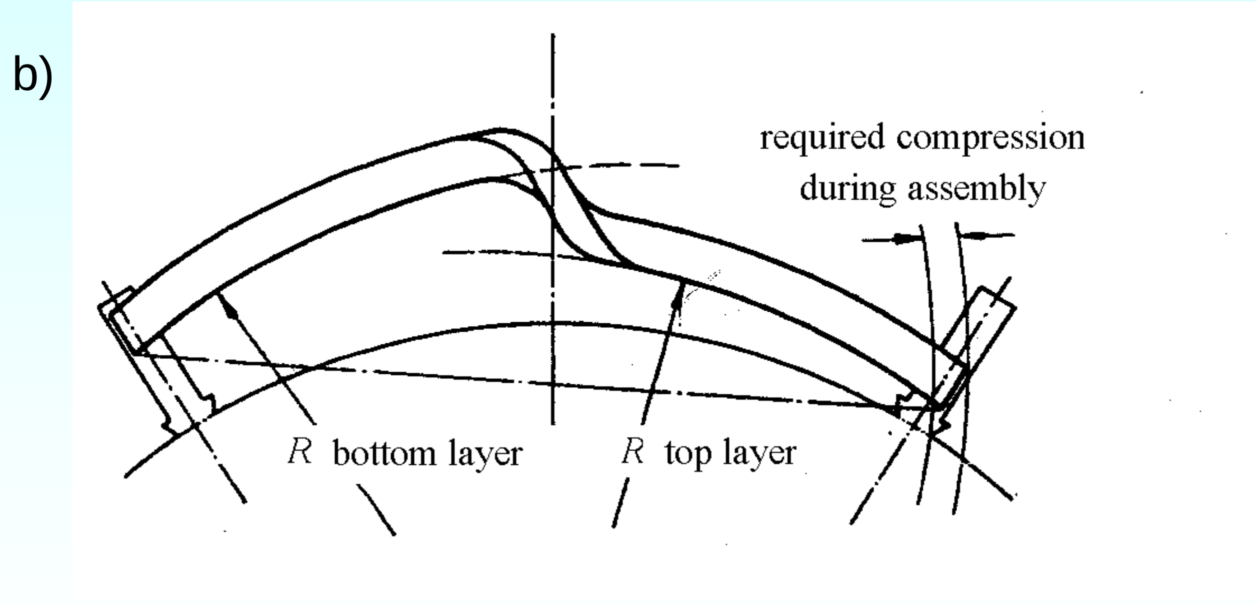

- Coils with **equal span**
- **Two-layer winding:** Per slot TWO coil sides are placed one above the other.
- North- and south pole are generated by **two** coil groups.
- Direction of current flow in N- and S-pole coils opposite !
- Changing of current flow direction by **reversal connector.**
- Bigger machine ratings typically above 500 kW: Profiled coil conductors (rectangular cross section), round wire with smaller machines !

- *Example:* For 4-pole machine we need four coil groups per phase !
  $q = 3$, $m = 3$, $Q = 2p.q.m = \underline{36}$

# Winding overhang of two-layer winding

- a) Two form wound coils before being put into the stator slots: Due to S-shape in winding overhang part of coils there are **NO** crossing points of the coils.
- b) Form wound coil with profiled conductor, placed in stator slot, with left coil side in lower and right coil side in upper layer. Manufacturing much more expensive than with round wire single-layer winding, therefore used usually only in bigger machines: e.g.**high voltage machines** up to 30 kV ("High voltage": $U$ > 1000 V (rms)!).




*Source: Hütte Energietechnik, Springer-Verlag*

# High voltage form wound stator coil with several turns $N_c$ for two-layer winding

Winding overhang

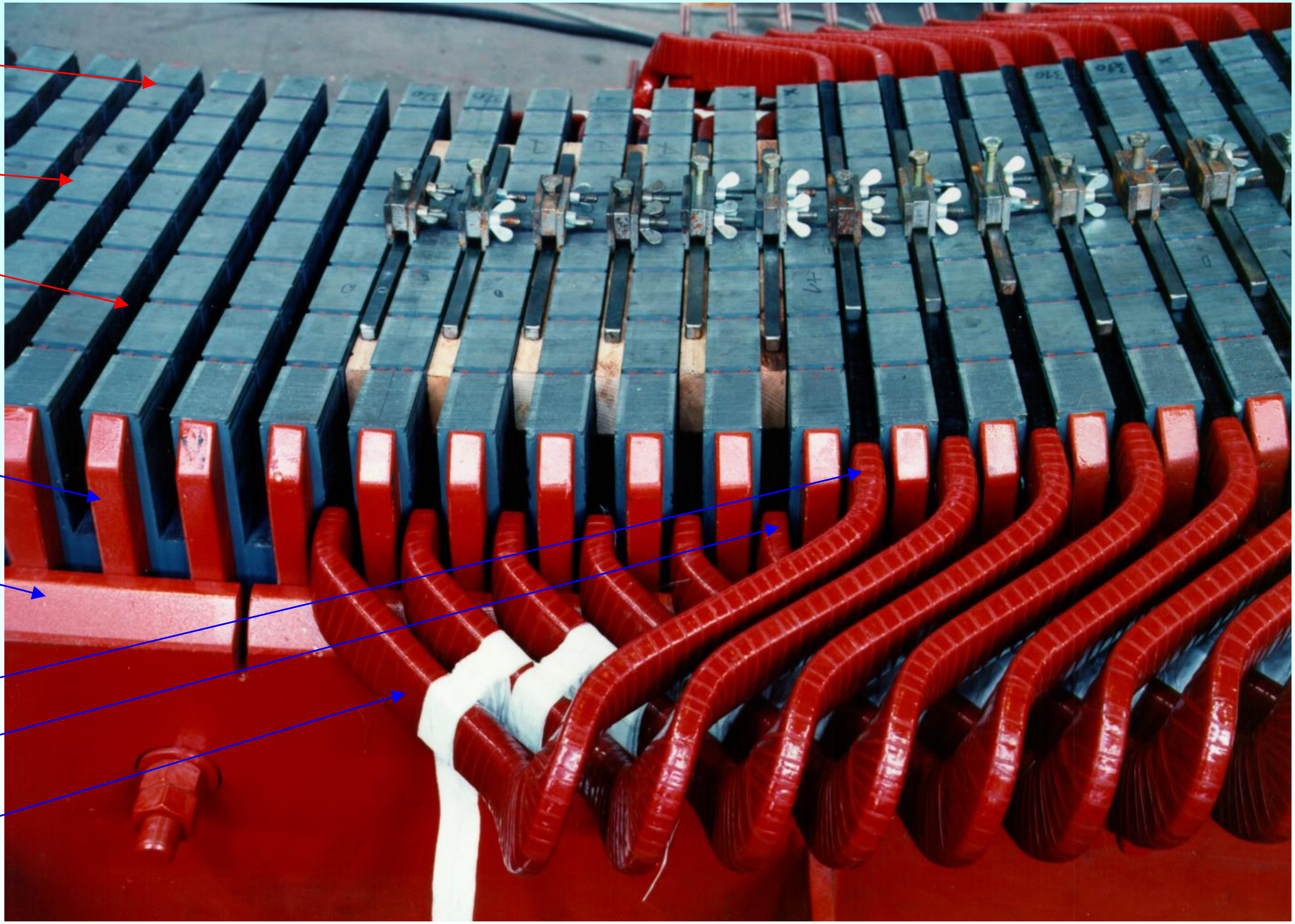
coil side, inserted in slot

coil terminals

*Source:*

*Andritz Hydro, Austria*

# Inserting of impregnated form wound coils in the stator slots of a synchronous hydro generator with high pole count




*Source:*

*Andritz Hydro, Austria*

# Series and parallel connection of coil groups

- **Series and parallel connection** of coil groups to get one winding phase

- *Example :* Eight-pole machine:
  *Two-layer winding*: 8 coil groups, which may be connected as follows:
  - $a$ = 1: Series connection of all 8 coil groups
  - $a$ = 2: 4 coil groups in series, then paralleling the two series sections
  - $a$ = 4: 2 coil groups in series,then paralleling the four series sections
  - $a$ = 8: All 8 coil groups are connected in parallel

  *Single-layer winding*: 4 coil groups, which may be connected as follows:
  - $a$ = 1: Series connection of all 4 coil groups
  - $a$ = 2: 2 coil groups in series, then paralleling the two series sections
  - $a$ = 4: All 4 coil groups are connected in parallel

- Resulting **number of turns per phase** *N:*

$$N = \frac{pqN_c}{a}$$ Single-layer winding

$$N = \frac{2pqN_c}{a}$$ Two-layer winding

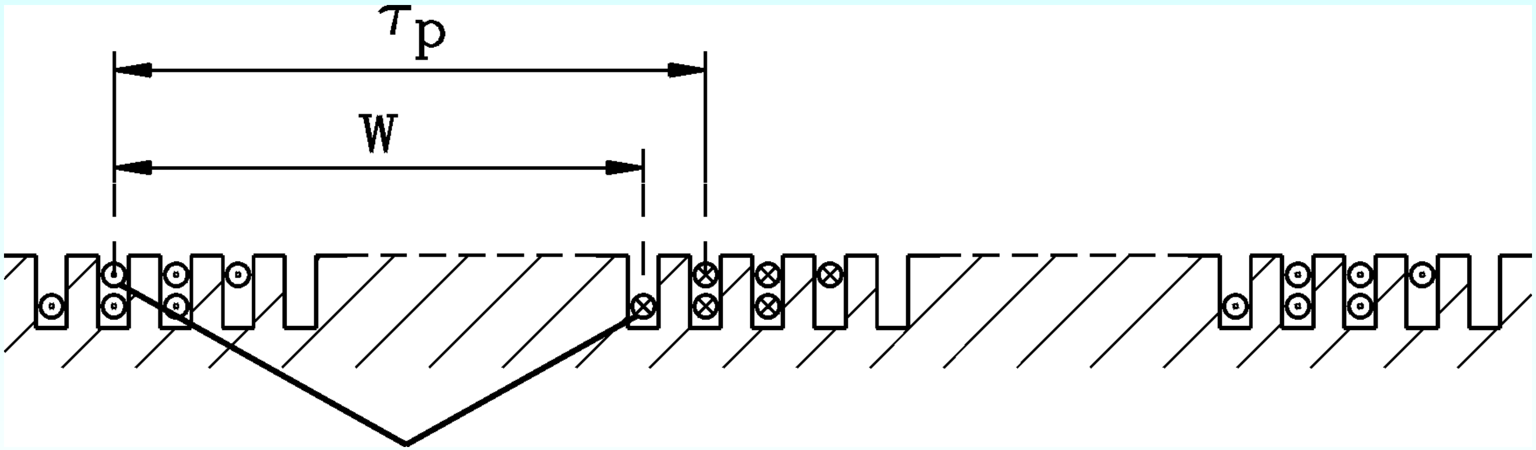
- *Example:* $2p = 4$, $q = 2$, eleven turns per coil ($N_c = 11$), series connection of all coil groups: $a = 1$: number of turns per phase: $N = 4 \cdot 2 \cdot 11/1 = 88$

# Pitching (chording) of coils $W < \tau_p$

- With **Two-layer windings: pitching of coils** is possible !
- Pitching = Shortening of coil span *W* , counted in number *S* of slot pitches

$$W = \tau_p \cdot \frac{m \cdot q - S}{m \cdot q} = \tau_p \cdot \frac{Y_Q}{m \cdot q}$$

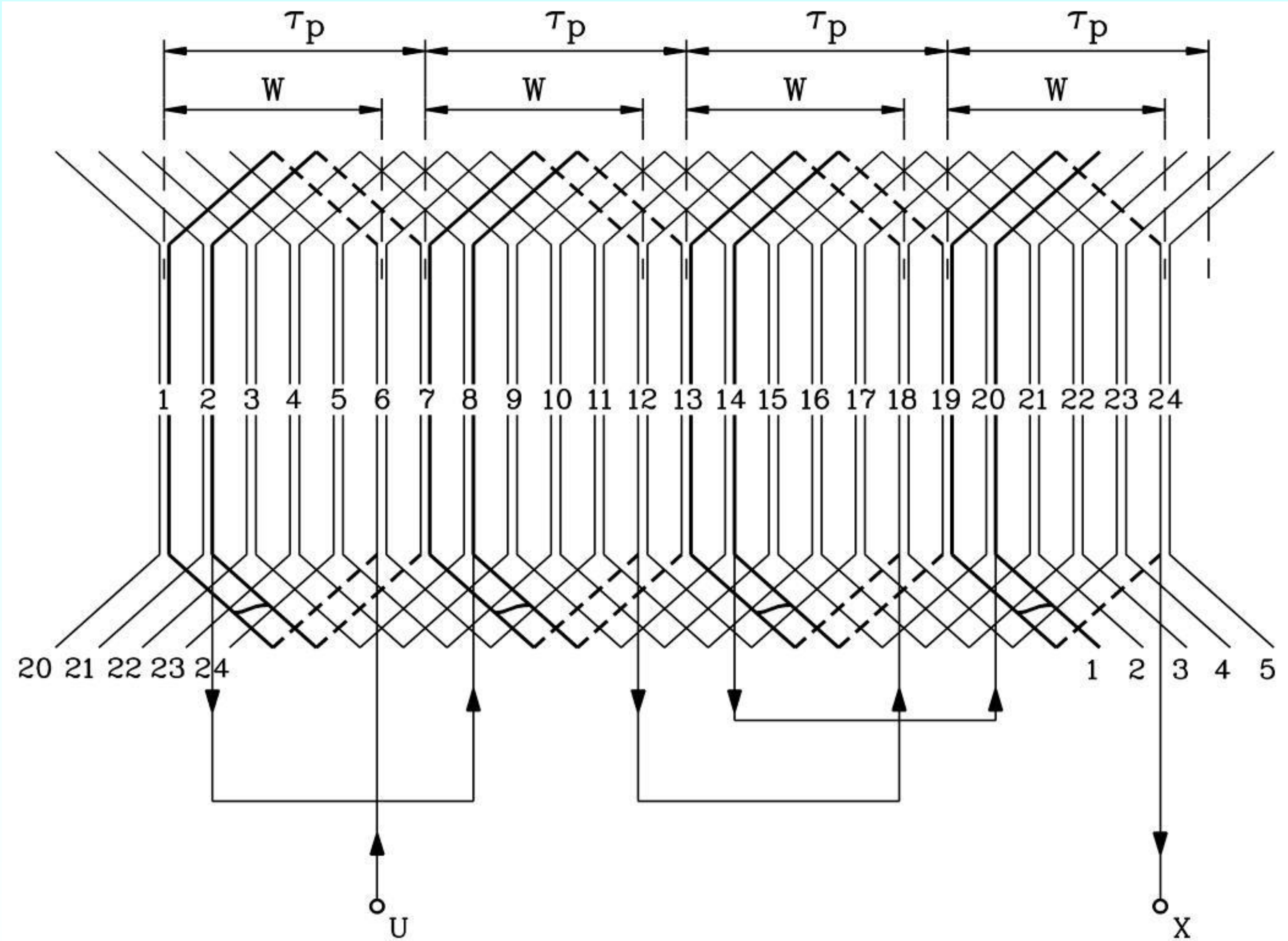
*S* : integer number




- Benefit of pitching: Shape of field curve fits better to ideal sinusoidal shape.
- *Example*: Four-pole machine: Data: $m = 3$, $Q = 24$, $q = 2$:
  Pitching is possible for $S < m \cdot q = 3 \cdot 2 = 6$: $S = 1, 2, 3, 4, 5$.
  e. g.: $S = 1$, hence pitching is $W/\tau_p = 5/6$.

# Example: Pitched Two-layer winding

- Four pole machine, $m$ = 3, $Q$ = 24, $q$ = 2: Pitching $W/\tau_p$ = 5/6.

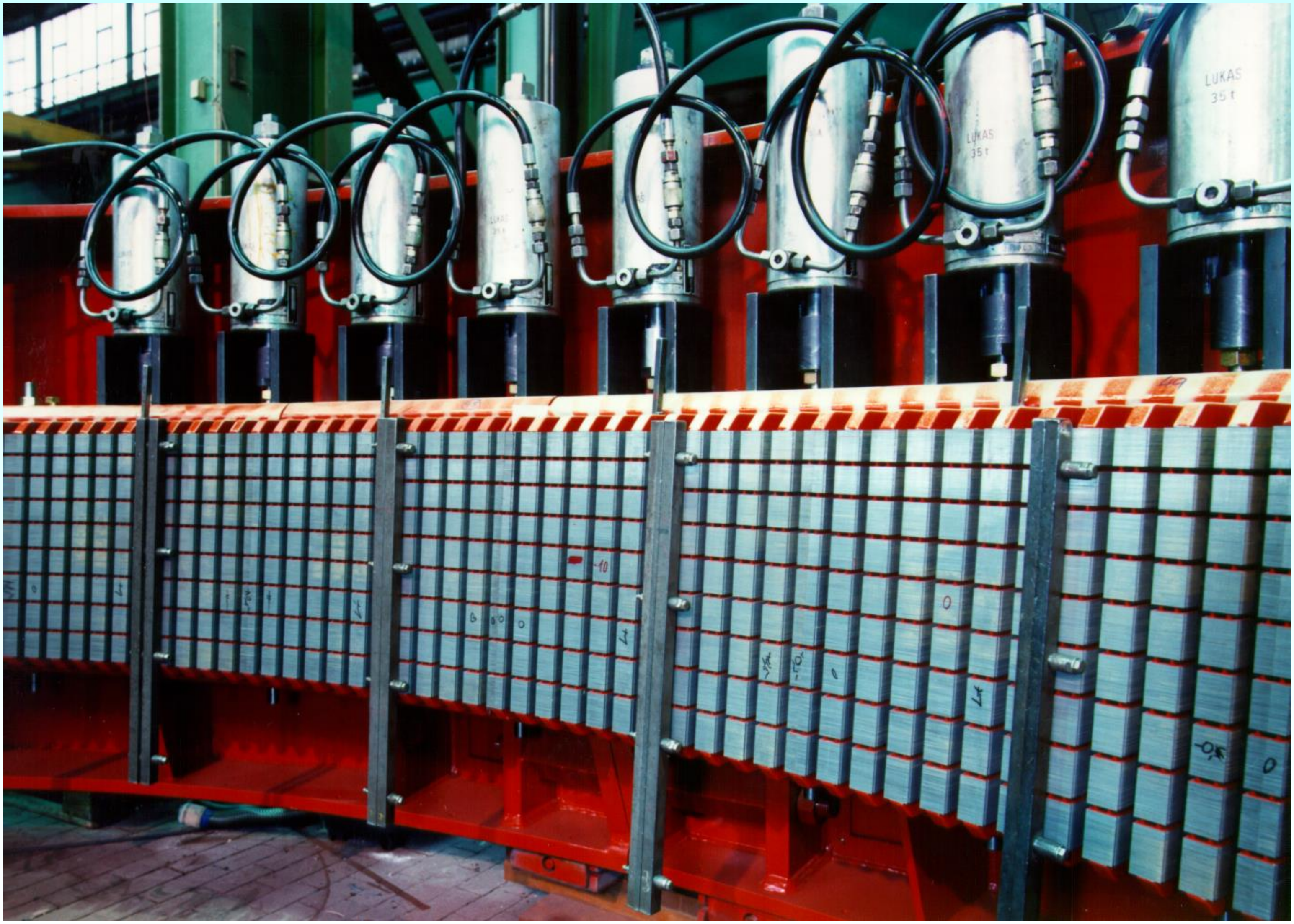


# Stacking of stator iron sheets of synchronous hydro generator

*Source:*

*Andritz Hydro, Austria*

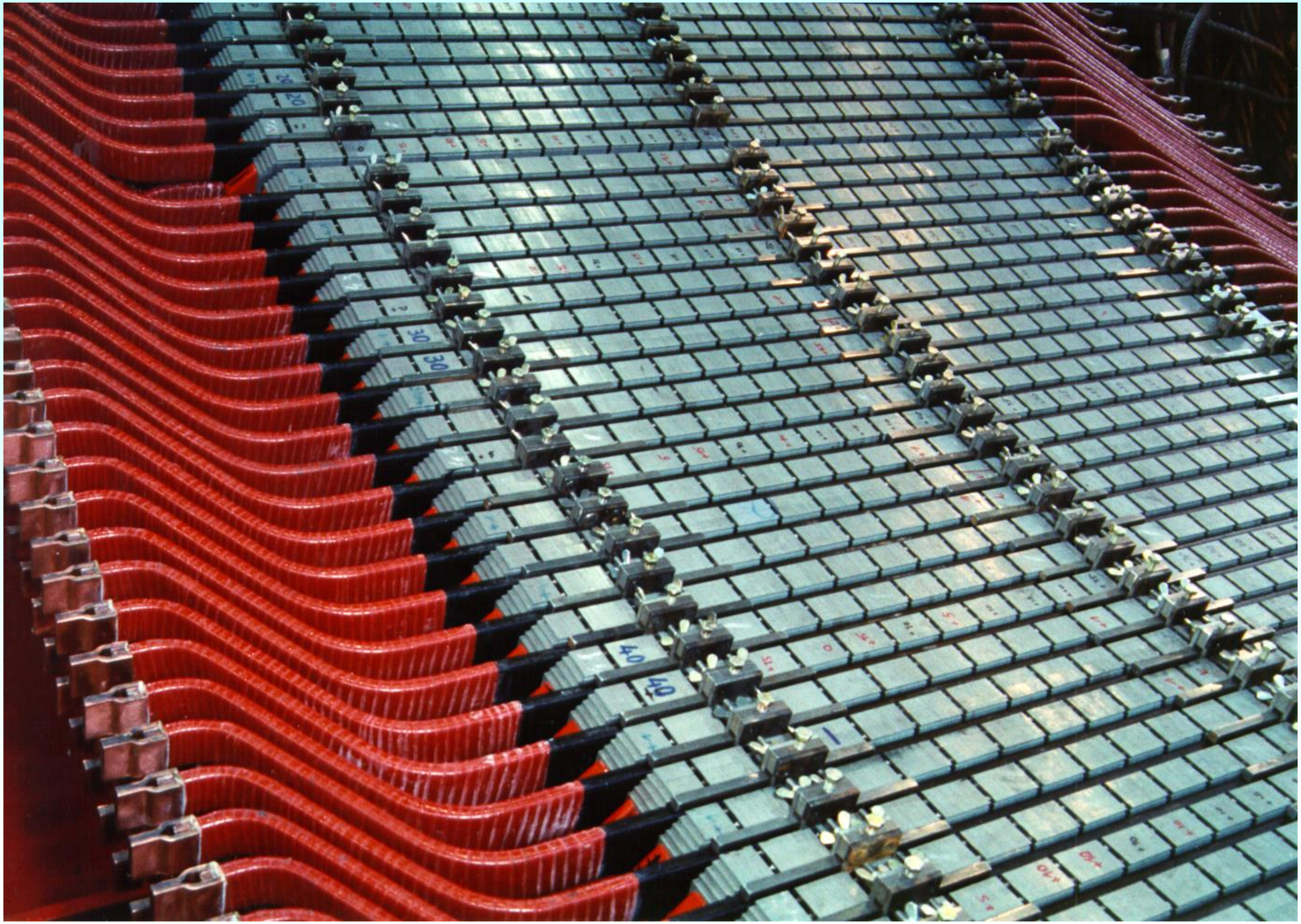
# Pressing of laminated stator iron core with hydraulic cylinders




*Source:*

*Andritz Hydro, Austria*

# High voltage stator winding of synchronous hydro generator - Pressing of winding bars in the slots



*Source:*

*Andritz Hydro, Austria*