3. Three phase winding technology

Source: VATech Hydro, Austria
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: $Q = m \cdot 2p \cdot q = 3 \cdot 12 \cdot 3 = 108$

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 ("2nd plane").
Example: Single layer winding with short and long coils

Unrolled winding system gives “winding scheme”: here a four-pole machine: $2p = 4$, $m = 3$, $q = 2$, $Q = 24$

Winding manufactured with concentric coils.

“Long coils”: Winding overhang 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!
Stator three phase single-layer winding of induction machine

Source: ELIN EBG Motors, Austria
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!
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)!).
High voltage form wound stator coil with several turns $N_c$ for two-layer winding

Source: VATech Hydro, Austria
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 $S < mq = 3 \cdot 2 = 6$: $S = 1, 2, 3, 4, 5$.
  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 $W/\tau_p = 5/6$. 
Inserting form-wound two-layer winding in induction generator stator

Source: Winergy, Germany

Winding overhang
Stator iron stack
Coil ends
Inserting form-wound two-layer winding in stator slots

Source: ABB, Switzerland
Stator three phase two-layer winding of induction generator

Source: Winergy
Germany
Rotor three phase two-layer winding of slip ring induction generator

Source: Winergy
Germany
Inserting of impregnated form wound coils in the stator slots of a synchronous hydro generator with high pole count

Ventilation duct
Tooth
Slot
Massive iron clamping finger
Pressing plate
1\textsuperscript{st} layer
2\textsuperscript{nd} layer
winding overhang

Source: VATech 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** $N$:

  \[
  N = \frac{pqN_c}{a} \quad \text{Single-layer winding} \\
  N = \frac{2pqN_c}{a} \quad \text{Two-layer winding}
  \]

- **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: $N = \frac{4 \cdot 2 \cdot 11}{1} = 88$
Variants of cooling of winding and iron stack

Heat flow density
(W/cm²)

Indirect air-cooled stator winding
Stator iron stack packets
Directly air-cooled rotor pole winding
Air/hydrogen water
Directly cooled hollow conductors

For comparison:
Heat transfer of flat iron
Rated voltage $U_n$ of stator winding increases with increasing apparent power $S_n$ to limit rated current $I_n$. 

![Diagram showing the relationship between $U_n$, $S_n$, and $I_n$.]
Welded stator housing of synchronous hydro generator

Source: VATech Hydro, Austria
Stacking of stator iron sheets of synchronous hydro generator

Source: VATech Hydro, Austria
Pressing of laminated stator iron core with hydraulic cylinders

Source: VATech Hydro, Austria
Insulation of high voltage stator winding (one turn = stator bar) with insulation robot

Big generators:
Only one turn per coil.
Coil is split into 2 halves = 2 bars.

Here visible: Insulating one bar for a 2-pole turbine generator with glass-fibre band with mica layer for high voltage insulation.

Source:
VATech Hydro, Austria
Insulation of high voltage stator winding (one turn = stator bar) with insulation robot

Source: VATech Hydro, Austria
Resin impregnated coils are heated in the oven to dry and harden the insulation.

Source: VATech Hydro, Austria
High voltage stator winding of synchronous hydro generator - Pressing of winding bars in the slots

Source: VATech Hydro, Austria