Three-Phase Winding Design for Large Hydro-Generators

Georg Traxler-Samek, Michael Lecker

***Abstract*—High-voltage stator windings for large salient-pole synchronous machines in hydro power applications are designed based on manufacturing, maintenance, cost and electromagnetic performance issues. This paper discusses various aspects for designing standard three-phase windings and in particular presents a novel method for minimizing the number of external connections in wave winding application. A special section is dedicated to unbalanced winding parallel circuits due to coil bypass for quick repair in the case of bar or coil failures.**

***Index Terms*—Rotating machines, Windings, Synchronous machine**

I. Introduction

Three-phase stator windings for large salient-pole synchronous machines in hydro application in the Megawatt range (Fig. 1) have particular requirements due to the application of high-voltage technology with voltages in the range of $3 \dots 23$ kV. Some of the major aspects are

- Usage of open stator slots for being able to insert the winding bars resp. coils;
- Space requirements due to relative large insulation thicknesses for high voltage insulation;
- Maintenance and repair features (e.g. removal of some few bars for a quick repair of old machines after failure);
- Cost issues, e.g. decision between lap and wave winding;
- Special applications like unbalanced windings or zone short-pitching;
- Integer or fractional slot windings;

Winding design methology for integer as well as fractional slot windings is common and can be found in appropriate prominent literature, e.g. [1]–[7]. Winding design has strong influence on the machine performance [8], [9]. Stator winding magneto-motive force (mmf) harmonic field waves have a significant impact on power losses (e.g. pole face and damper winding losses) as well as — mainly for fractional slot windings — radial forces and vibrations [10]–[12]. The filter-effect of the winding can help to improve stator winding voltage harmonics [13]–[15].

Many recent publications deal with tooth-wound windings [16]–[18], these windings usually are not applied in large hydro generators with their high loss penalties due to the impact of harmonics on performance and losses.

Section II first summarizes the well-known state of the art in double-layer three-phase stator winding design for large hydro-generators with respect to special fractional slot windings and zone short-pitched wave windings. Section III presents a novel method for minimizing the number of external winding connections (pole jumpers) for wave winding types with a computation algorithm. Finally a special section is dedicated to coil bypass of damaged winding bars/coils, as it is used for short-term quick repair in the case of winding failures.

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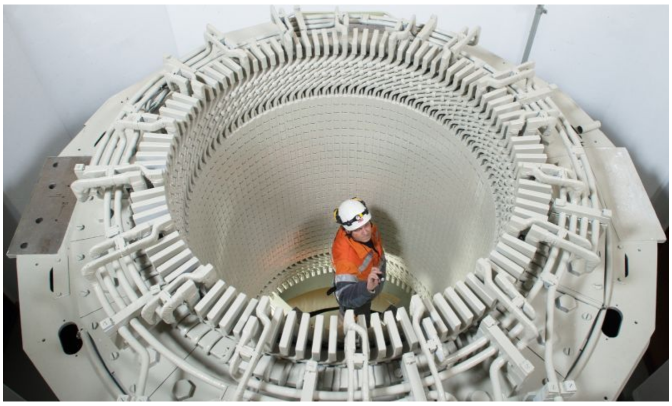

Fig. 1. Stator of a hydro-generator, view from connection-end (source: ANDRITZ Hydro AG Switzerland)

II. State of the Art in Three-Phase Double-Layer Winding Systems

A. Three-Phase Windings

It is well-known for standard three-phase machines ($m = 3$), that voltages and currents are each displaced by an electrical angle of $2\pi/3$, winding groups are arranged on the perimeter of the machine, each spatially shifted by a third of the wave length. Fig. 2 shows the winding diagram of a three-phase double-layer winding with $q = 3$ slots per pole and phase; the winding or coil pitch is $Y_1 = 7$.

An important characteristic figure for describing winding systems is the number of slots per pole and phase [19], [20],

$$q = \frac{q_1}{q_2} = \frac{Q}{2pm} \ , \qquad (1)$$

where Q is the total number of slots on the circumference of the machine and $2p$ the total number of poles. In general, q is a fraction, when $q_2 = 1$ we speak of an integer slot winding, for $q_2 > 1$ the winding is a fractional slot winding. Fig. 3 shows such a fractional slot winding with a number of slots per pole and phase of $q = 9/4$. This means, that e.g. on the

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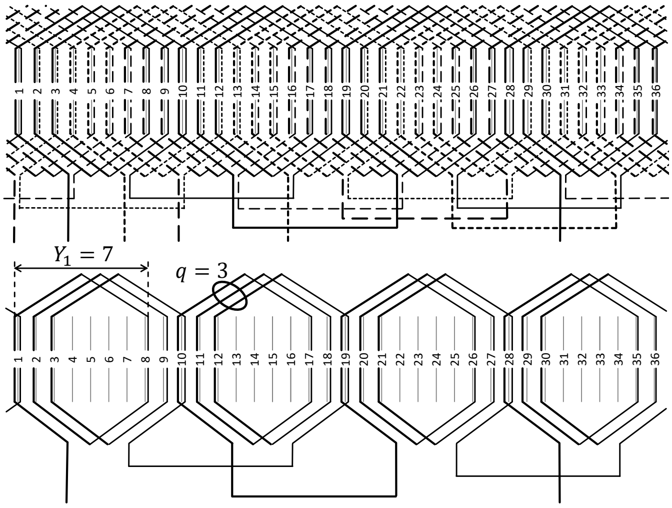

Fig. 2. Winding diagram, $m = 3$ phases, double-layer $N_L = 2$, $q = 3$ slots per pole and phase, winding pitch $Y_1 = 7$, including winding connections (pole jumpers); top: all three phases, bottom: first phase shown only

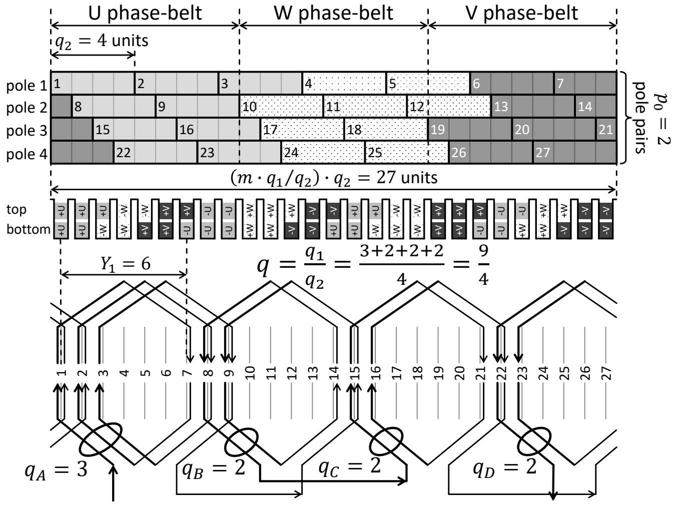

Fig. 3. Three-phase double-layer fractional slot winding and Tingley scheme, number of slots per pole and phase $q = 9/4$, winding pitch $Y_1 = 7$, number of pole-pairs of a repetitive winding section $p_0 = 2$; one phase shown only

first pole we have $q_A = 3$ and on the second, third and fourth pole $q_B = q_C = q_D = 2$. The average value is

$$q = \frac{q_1}{q_2} = \frac{q_A + q_B + q_C + q_D}{4} = \frac{9}{4} \ . \tag{2}$$

The smallest symmetrical winding unit, the repetitive section, therefore extends over $p_0 = 2$ pole-pairs. Generally the number of pole-pairs per repetitive section is [6]

$$p_0 = \begin{cases} q_2/2 & \text{if } q_2 \text{ is even} \\ q_2 & \text{otherwise} \end{cases} \tag{3}$$

The distribution of bars into the machine's winding slots is obtained with Tingley's slot diagram [3]. The slot diagram in horizontal direction extends over a single pole pitch, in vertical direction over all poles of a repetitive section. The diagram shows all slots as boxes on its correct angular position on the circumference of the machine (Fig. 3, top). The width of such a box is defined as q_2 units, therefore a phase belt (e.g. phase U) theoretically extends over $(q) \cdot q_2 = q_1$ units, and a pole-pitch needs $(mq) \cdot q_2 = mq_1$ units. In the example given here, where $q = 9/4$, the box width is 4 units, each belt zone extends over 9 and the whole pole pitch over 27 units. It can be clearly seen, that due to a fractional q the slots on adjacent poles (pole 1 versus pole 2, ...) are electrically displaced. All slot boxes are assigned to the phases, when starting within a corresponding phase belt. In our example (Fig. 3), slots are assigned to phases as

$$\begin{aligned} \text{U} &: +1, +2, +3\ , -8\ , -9\ , +15, +16, -22, -23 \\ \text{V} &: +6, +7, -13, -14, +19, +20, +21, -26, -27 \\ \text{W} &: -4, -5, +10, +11, +12, -17, -18, +24, +25 \end{aligned}$$

where a negative sign indicates reverse bar orientation.

Additional important winding parameters are the number of turns per coil N_C and the winding pitch (see Fig. 4) [21]. For bar windings the number of turns per coil is $N_C = 1$ (Fig. 4a), for multi-turn coil windings, the number of turns is $N_C > 1$ (Fig. 4b). A winding coil is formed by a half top layer and a half bottom layer coil. When the coil in circumferential direction extends over a full pole pitch it has a diametral pitch $Y_1 = Y_D = mq$; a short-pitched coil is characterized by $Y_1 < mq$.

With this nomenclature, a single phase of the winding generally has

$$N_P = qN_C \tag{4}$$

turns per pole. Then with $2p$ poles and a parallel circuits, the number of winding turns in series for voltage induction is [21]

$$N_1 = \frac{2pqN_C}{a} \ . \tag{5}$$

In general the decision between an integer and fractional slot winding is done considering stator voltage harmonics and radial forces with corresponding vibration problems [10]. As for a fractional slot winding a repetitive section extends over more than 2 poles, the winding magneto-motive force contains sub-harmonics with wave lengths greater than

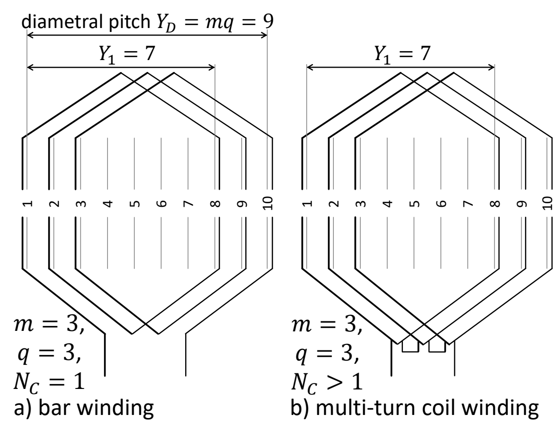

Fig. 4. a) bar winding with $N_C = 1$ turn per coil versus b) coil winding with $N_C > 1$ turns per coil; number of slots per pole and phase $q = 3$, winding pitch $Y_1 = 7$

$\lambda = 2\tau_P$. These sub-harmonics often excite radial magnetic force waves, which can create vibration problems, as long as their exciting frequencies are close to eigenfrequencies of the mechanical system.

B. Lap and Wave Windings

For lap winding types the external winding connections (pole jumpers) connecting groups of coils are clearly defined (refer to Fig. 2, resp. Fig. 5a) [3], [6]. When splitting the winding into a parallel circuits, these circuits are distributed on the circumference of the machine, which also helps to compensate unbalanced magnetic pull (ump) forces due to compensation currents.

In the case of wave windings (Fig. 5b), bars are connected from pole to pole using their end arms, resulting in wave-trains that extend over several poles [4], [7]. Therefore the sum of non-connection-end and connection-end winding pitches should be about two times the diametral pitch,

$$Y_1 + Y_2 \approx 2mq = 2Y_D \ . \tag{6}$$

For integer slot windings with q slots per pole and phase there are $2q$ short-circuited wave-trains extending over the whole circumference, q waves starting on the first and q starting on the second pole. These waves must be opened and connected: a double-layer winding with integer q and a single parallel circuit, $a = 1$, therefore only needs $2(q-1)$ short diagonal connections and one single pole jumper per phase. A corresponding lap winding needs one pole jumper per pole and phase.

Advantage of wave windings is the low number of external winding connections. On the other hand, wave windings have longer average winding pitches $(Y_1 + Y_2)/2$ and therefore bar end arms get much longer. A decision between these two winding types usually is a manufacturing and cost issue.

For fractional slot windings things get more complicated. Due to a variation of the number of coils per phase from pole to pole, the winding splits into several partial wave-trains. The connection of these partial wave-trains to a complete winding is an optimization task (section III).

C. Zone Short-Pitched Wave Windings

A zone short-pitched [4], [6] winding design helps to improve winding end connections. As discussed above, a wave winding tries to satisfy $Y_1 + Y_2 \approx 2mq$. With conventional short-pitching one of the two pitches is shortened, the other one gets stretched. This leads to a remarkable difference in the axial length of the winding overhangs on both sides of the machine. A zone short-pitched winding changes the distribution of bars into the slots in such a way, that both winding pitches get diametral,

$$Y_1 \approx Y_2 \approx Y_D \ , \tag{7}$$

the distribution of the phase bars into the slots generates the short-pitching effect. Fig. 6 illustrates the transition from a conventionally short-pitched to a zone short-pitched winding type. This example, based on $q = 3$ exchanges top and bottom layers of slots number 3, 9 and 15 in such a way, that the number of slots per pole and phase alternates between $q_A = 4$ and $q_B = 2$ from pole to pole. The mean value,

$$\overline{q} = (q_A + q_B)/2 \ , \tag{8}$$

remains $\overline{q} = 3$. The winding arrangement in the overhang zone keeps regular, winding pitches are diametral, here $Y_1 = Y_2 = m\overline{q} = 9$. Electrically, regarding the magnetic circuit performance, the conventional and the zone short-pitched winding are equivalent.

For fractional slot windings, the determination of the distribution of phase bars into slots is again based in Tingley's slot diagram [3]. With two alternating numbers of slots per pole and phase, q_A and q_B, where the average of both is q, the widths of the phase zones alternate in the following way:

$$(+U)_\mathrm{A}\ (-W)_\mathrm{B}\ (+V)_\mathrm{A}\ (-U)_\mathrm{B}\ (+W)_\mathrm{A}\ (-V)_\mathrm{B}$$

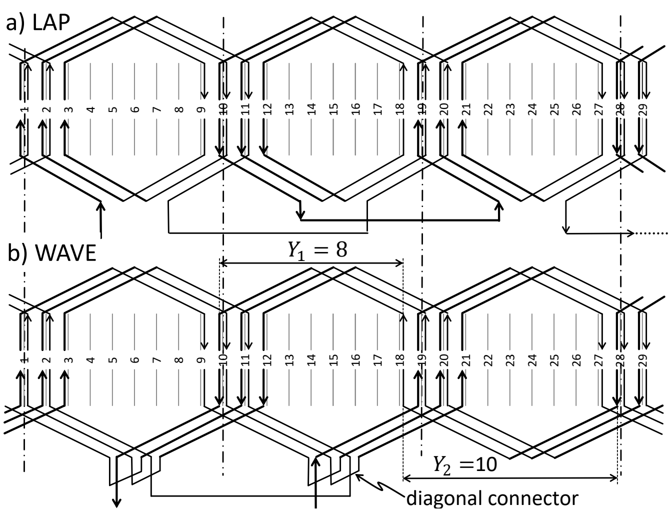

Fig. 5. a) Lap winding versus b) wave winding, three-phase double-layer windings with $q = 3$, $Y_1 = 8$; one single phase shown only

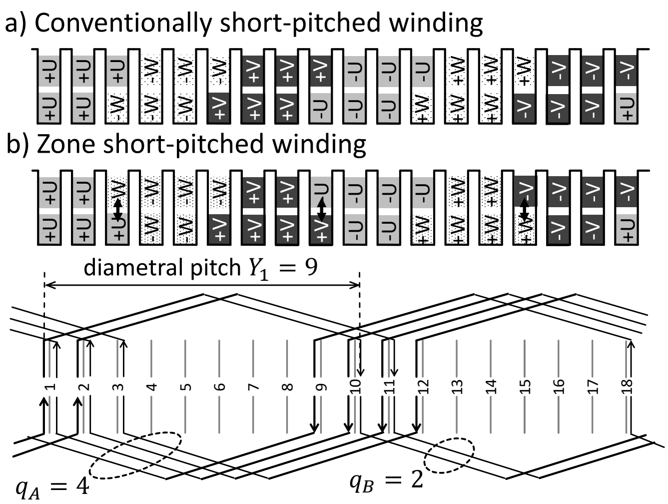

Fig. 6. Zone short-pitching with $q = 3$, $q_A = 4$, $q_B = 2$ and $Y_1 = 9$, exchanging top and bottom layers in slots 3, 9 and 15

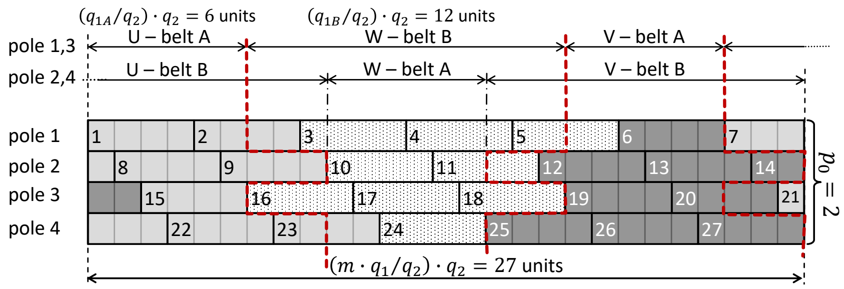

Fig. 7. Tingley's slot diagram for a three-phase double-layer zone short-pitched fractional slot winding with $q = 9/4$, $q_A = 6/4$, $q_B = 12/4$

Fig. 7 shows how the bar distribution is obtained from the slot diagram using alternating zone widths for $q = 9/4$, $q_A = 6/4$, $q_B = 12/4$.

For standard windings the bottom layer bar/coil distribution corresponds to the top layer distribution, only shifted by the non-connection end winding pitch Y_1 with reverse current flow. For wave winding types a common practice is the application of a zone displacement [4] on the bottom layer. As shown in Fig. 8b, the phase belts of U, V, and W are diplaced by $\Delta z \in -(q_2 - 1)\dots(q_2 - 1)$, thus leading to a different phase belt pattern. The consequence of a different pattern on bottom layer is that natural wave trains are also interupted on non-connection end, therefore we might have to apply external connections (pole jumpers) on both axial ends of the machine. Both techniques, the zone short-pitching and the bottom layer zone displacement are applied in chapter III in order to optimize wave winding connections.

III. Optimizing Wave Winding External Connections

This section presents a novel method for optimizing external connections (pole jumpers) for three-phase wave winding types based on a computer algorithm. Due to manufacturing reasons wave windings are typically applied for bar winding types only, therefore we postulate $N_C = 1$. For given number of slots per pole and phase q, number of parallel circuits a

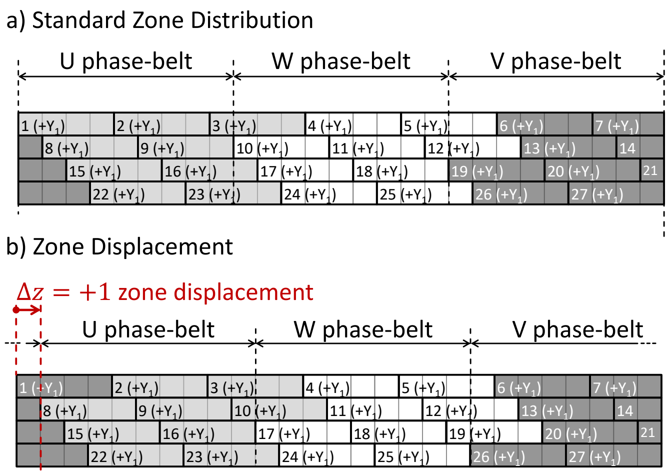

Fig. 8. a) Standard winding distribution from Fig. 3, b) application of a zone displacement $\Delta z = +1$; the bottom layer offset $(+Y_1)$ indicates, that the displacement is applied on bottom layer only

and diametral winding pitch, $Y_1 \approx Y_1 \approx mq$, where Y_1 and Y_2 are integer, the algorithm varies

- the zone-short-pitching by variation of $q_A = q_{A1}/q_2$ and $q_B = q_{B1}/q_2 = 2q - q_A$,
- the zone displacement Δz in the typical range ($\Delta z \in -(q_2 - 1)\dots(q_2 - 1)$).

For the whole variant space $\mathcal{V}_i(q_A, \Delta z)$, $i \in 1\dots n$, a company-internal search algorithm generates wave trains for all parallel circuits a and all phases U, V, W considering the following strategies:

- avoiding (if possible) opening natural wave train connections;
- avoiding long pole jumpers (e.g. over more than 2 poles);
- generate a circuit- and phase-balanced winding;

On a modern computer using parallelization such a search creates n different winding diagrams and evaluates them by a company-internal evaluation criteria considering

- the operational harmonic winding factor ξ,
- the actual effective winding pitch ratio $Y_1/(3q)$ (e.g. impact on pole face losses),
- the number of pole jumpers and short diagonal connectors N,
- the total length of connections L.

Table I shows part of the result of such an optimization run based on a three-phase winding with $2p = 16$ poles, $q = 27/8$ slots per pole and phase, $a = 1$ parallel circuits and winding pitches $Y_1 = Y_2 = 10$. The first column indicates the evaluation factor, the best variant has a factor of 1.00. Fig. 9 displays the optimized winding diagram. The optimization algorithm internally generated more than

TABLE I
Result of wave winding optimization, example machine with $2p = 16$, $q = 27/8$, $a = 1$, $Y_1 = Y_2 = 10$ (only part of the best out of more than 300 variants shown)

Eval.	q_{A1}	q_{B1}	Δz	ξ	$Y_1/(3q)$	N	L, in m
1.00	43	11	2	0.904	0.79	5	33
1.12	17	37	0	0.940	0.89	5	37
1.21	43	11	0	0.904	0.79	4	39
1.27	41	13	0	0.915	0.81	4	41
1.36	19	35	0	0.946	0.91	5	45
1.48	11	43	2	0.915	0.81	5	49
1.69	11	43	0	0.915	0.81	4	55
1.87	21	33	0	0.951	0.94	5	62
1.88	21	33	2	0.951	0.94	6	62
1.91	13	41	2	0.925	0.84	6	63

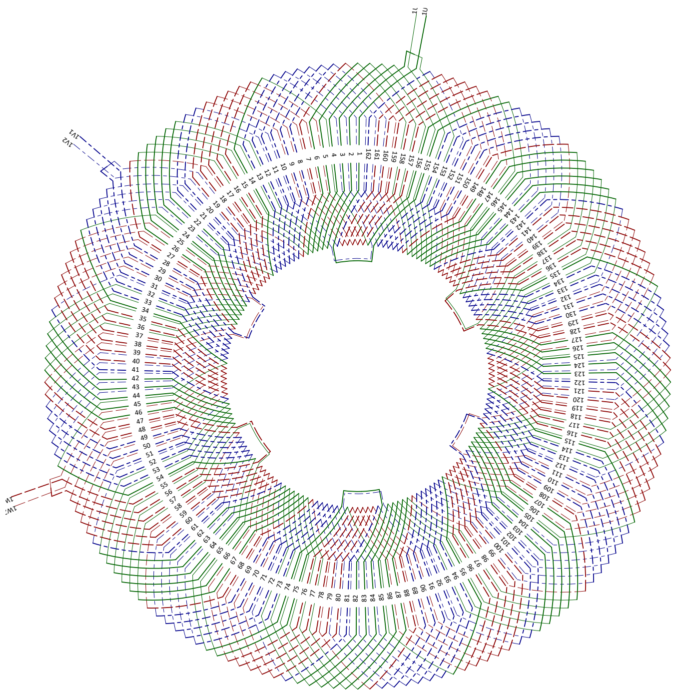

Fig. 9. Optimized wave winding variant, presented 3-phase winding example with $2p = 16$, $q = 27/8$, $q_A = 43/8$, $q_B = 11/8$, $Y_1 = 10$, $Y_2 = 10$, $a = 1$, $\Delta z = 2$: winding diagram including external connections

300 winding diagrams within a calculation time of less than 500 ms.

IV. Circuit Unbalance due to Bypassed Coils

In the case of a winding failure, e.g. an earth fault on a single winding coil, it is possible to bypass the bad coil in order to do a quick repair and keep the machine's down time short [22], [23]. Usually such a bypass requires a down-rating of the machine, because due to missing coils the magnetic flux will increase and the rotor field winding gets overloaded. The bypass of bad coils can be done in the following ways:

- removal of the bad coils and equivalent coils in each parallel circuit of **each** phase; this solution needs the highest effort but results in a balanced winding;
- removal of the bad coils and equivalent coils in each parallel circuit of **a single** phase only; this solution needs less site works and results in a phase unbalance;
- removal of the bad coils only; this solution needs lowest effort but results in circuit and phase unbalance;

Note that all of these variants have been actually done. Fig. 10 shows such a coil bypass, the bad coil from slot number 29 to slot 26 is disconnected, grounded and bypassed. If such a repair leads to a circuit unbalance, circulating current must be at least estimated. It is quite common to disconnect a coil for bar windings, $N_C = 1$, because this means loss of a single turn only. For multi-turn coil windings, such a bypass leads in many cases to non-acceptable circulating currents.

An estimation of circulating currents between the parallel circuits of a phase (as proposed in [22]) helps as a evaluation critiera. The calculation here is derived for a circuit unbalance of a single parallel circuit, as it is the case when a single coil in a circuit is bypassed. As a worst case assumption, only the winding leakage inductance x_σ is used in the circuit's paths [22]. Fig. 11 shows the equivalent circuit arrangement. Due to coil bypass, circuit one has a differential voltage,

$$\Delta \underline{u} = \underline{u} \cdot \frac{\Delta N_1}{N_1} , \tag{9}$$

where $\underline{u}$ is the nominal per-unit voltage (e.g. 1 pu) and ΔN_1 the number of bypassed winding turns, out of N_1 turns per circuit. Note that the phase angle between coils is neglected in such a simplified consideration. The per-unit leakage reactance x_σ of the whole phase gets $a x_\sigma$ on each circuit, except the bypassed circuit, where the leakage reactance is reduced to

$$x'_\sigma = x_\sigma \cdot \frac{N_1 - \Delta N_1}{N_1} . \tag{10}$$

The per-unit circular current, referenced to the nominal phase current I_N therefore gets

$$|\underline{i}_c| = \frac{I_C}{I_N} = \frac{|\underline{u}|}{a x_\sigma \cdot \left[\frac{N_1}{\Delta N_1} \cdot \frac{a}{a-1} - 1\right]} . \tag{11}$$

Based on the nominal current per parallel circuit $I_{Na} = I_N / a$, the per-unit current overload of the bypassed circuit then follows to

$$\frac{I_C}{I_{Na}} = \frac{|\underline{u}|}{x_\sigma \cdot \left[\frac{N_1}{\Delta N_1} \cdot \frac{a}{a-1} - 1\right]} . \tag{12}$$

Fig. 12 shows the per-unit circular current of the bypassed coil for an example with $x_\sigma = 0.17$ pu and $a = 2, 3, 4$ circuits as function of the relative number of reduced turns $\Delta N_1 / N_1$. A reduction of 10 % of the turns leads to an over-current of about $15 \ldots 30$ %, thermally overloading circuit one. Generally a

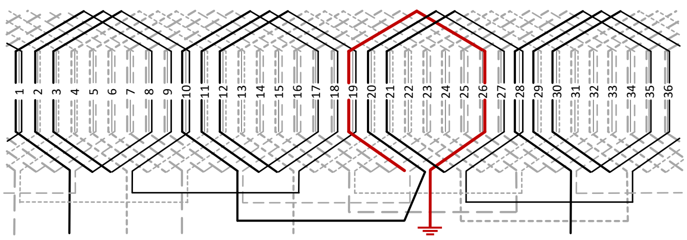

Fig. 10. Disconnection, earthing and bypass of a bad coil (slot 29–26) in one phase of a three-phase winding for a quick repair

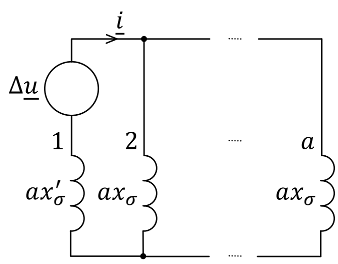

Fig. 11. Equivalent circuit for computing circular current with unbalance of one single parallel circuit of the stator winding (circuit 1 of a circuits)

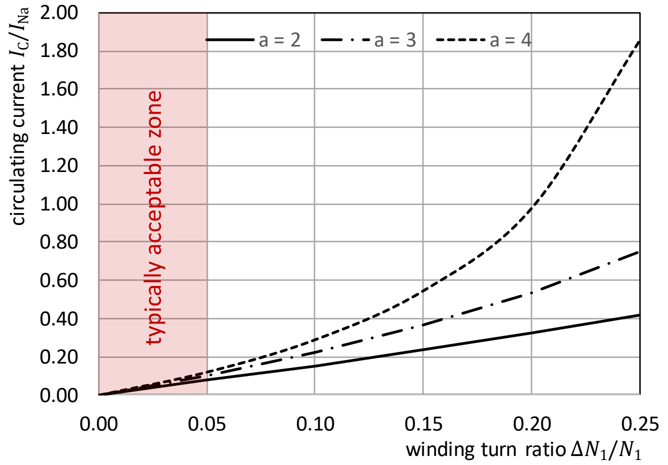

Fig. 12. Circulating current in a single parallel circuit I_C/I_{Na}, referenced to the nominal current per circuit $I_{Na} = I_N/a$ as function of the relative number of removed winding turns $\Delta N_1/N_1$; machine with $x_\sigma = 0.17$ pu and $a = 2, 3, 4$

thermal calculation of the machine [24] determines the limit of such a repair measure, nevertheless a downrating of the machine often avoids local thermal overheating. Typically feasible bypasses remove less than 5% of the winding bars.

V. Conclusion

This paper discusses various aspects of three-phase stator windings in large salient-pole synchronous machines for hydro power application. As the winding design has big impact of the machine's performance, special attention must be laid on design optimization considering

- Integer of fractional slot windings;
- Lap or wave winding application;
- Conventional short-pitching or zone short-pitching with bottom layer zone displacement;

A novel wave winding optimization algorithm is presented with uses zone short-pitching in combination with bottom layer zone displacement for reducing the number of external winding connections (pole jumpers) for cost and manufacturing optimization.

An important issue is service and maintenance, therefore repair issues like coil bypassing and estimation of circulating currents due to the resulting unbalance was covered, too.

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Biographies

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