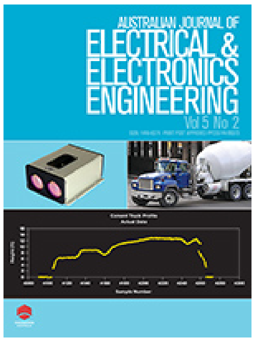

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Hydro generator high voltage stator windings: Part 2 – design for reduced copper losses and elimination of harmonics *

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SUMMARY: *Hydro generator stator winding design is one of the key factors when considering machine upgrades and uprates. The hydro generators built 30-50 years ago employed stator insulation systems with lower voltage stresses and correspondingly larger insulation allowances. Modern insulation systems use thinner, more homogenous insulations, which permit higher voltage stresses, while providing much improved thermal conductivity and better heat dissipation. There is therefore quite a scope for the high voltage (HV) stator winding designer to increase overall coil copper content by between 20-40%, which often provides copper losses at increased output not much higher than the losses produced by the existing winding at pre-uprate machine rating. In conjunction with the new insulation improved thermal dissipation, it is possible to design uprated windings with temperature rises similar to the existing ones. The main focus of the HV coil design for hydro generator upgrades and uprates is therefore reduction of copper losses, and optimisation of thermal characteristics for best dissipation of heat losses. The loads connected to the hydro generator terminals (transformers, transmission lines, switchgear, etc.) are all designed to operate with pure sinusoidal EMF (Walker, 1981). The purity limits of the generators' open circuit wave are prescribed by the standards (AEMC, 2008). Given the salient pole construction of hydro generator rotor with large variation of magnetic permeance in direct and quadrature axes, and the concentrated nature of rotor field pole windings, special measures are implemented on the geometry of rotor pole face. They include pole face shaping for sinusoidal approximation of rotor MMF, and adjustment of damper winding geometry relative to the slotted periphery of stator bore for reduction of the slot ripples (Walker, 1981). Given the relatively slow hydro generator operational speeds and necessarily large number of poles, the stator winding consists of large numbers of pole phase groups having only a few coils (typically 1 to 3). The stator winding MMF will therefore be rather coarse, and special measures must be implemented to achieve the output waveform as close to a pure sinusoid as possible. This second of four papers on hydro generator stator windings (refer to Znidarich, 2008a, Znidarich, 2009b, and Znidarich, 2009c) describes some tools at the hydro generator stator winding designer's disposal for effective reduction of harmonics and optimisation of output waveform purity. They include skewing of stator core slots, fractional (short) pitching of stator winding coils and fractional slot windings.*

1 WINDING DESIGN FOR OPTIMISED COPPER LOSSES

1.1 Reduction of hydro generator winding copper losses

Stator winding copper losses represent between 15% and 25% of overall machine losses, depending on the machine design. When considering machine uprates, reduction of copper losses is a significant consideration of the designers, to ensure that the new winding will: (i) have an acceptable level of temperature rise; and (ii) contribute to improvement of the machine efficiency at the new rating.

In addition to principal winding DC I^2R losses, which are well defined and easily calculated from winding copper physical parameters, there are also so called "extra copper losses", which are more obscure, but must be taken into account since they contribute to the winding losses and overall temperature rise.

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In any given slot, allowing the proper amount of space for insulation, the maximum copper that could be put into the slot would be a solid conductor. In fact, one of the first large machines built early last century was designed with a solid conductor. However, in operation, the machine attained only 70% of the rating before reaching operating temperature.

After a thorough and concentrated study by A. B. Fields in 1905, the cause for the extra heat and loss of output was discovered and published in his classic paper (Field, 1905). Field's study showed that in addition to the normal DC I^2R losses that exist in windings, there also exist strand (eddy current losses) and circulating current losses. Under certain circumstances, these can exceed the normal DC I^2R losses. The eddy current losses and circulating current losses are classified as part of the stray load losses of the machine. They are sometimes referred to as "extra" copper losses.

Significant research and theory development followed (Lyon, 1922; Lyons, 1930; Summers, 1927), particularly in the ways of transposing the windings for the elimination of circulating current losses. This theory is still relevant, however, new and more ingenious ways have been developed for transposition methodology.

Both strand (eddy current) and circulating current losses are caused by the leakage flux across stator slots (refer to figure 1).

1.1.1 *Design for reduced* I^2R *(DC) losses*

I^2R is the principal stator winding copper loss resulting from the power dissipated by the load current flowing through the winding of finite resistance. This is the loss that would occur if the windings were carrying a DC current of equivalent magnitude to rms AC current. Since load current cannot be reduced, I^2R loss can only be minimised by reducing winding resistance.

Stator coil resistance, usually expressed at 75 °C is given by:

$$R_{c75} = 2.0968 \times 10^{-5} \times \left(\frac{MLT_c \times T_{ca}}{A_{ct}} \right) \; [\Omega] \qquad (1)$$

where R_{c75} = resistance of stator coil at 75 °C [Ω]; MLT_c = mean length of turn for multi turn diamond coil [mm]; T_{ca} = number of turns per stator coil; and A_{ct} = cross sectional area of coil turn [mm^2].

From equation (1), it is obvious that winding resistance can only be reduced by:

- reducing winding mean length of turn by suitably altering coil geometry (shorter slot sections and/or end windings)
- increasing conductor cross sectional area.

In both cases, a satisfactory engineering compromise must be reached by maintaining an acceptable level of voltage stress in groundwall insulation, and adequate clearances between the coils in the end windings to prevent partial discharges and ensure good windability.

Since the copper losses are proportional to the square of the current, approximately a 40% decrease in winding resistance is required to permit a 20% increase in stator current.

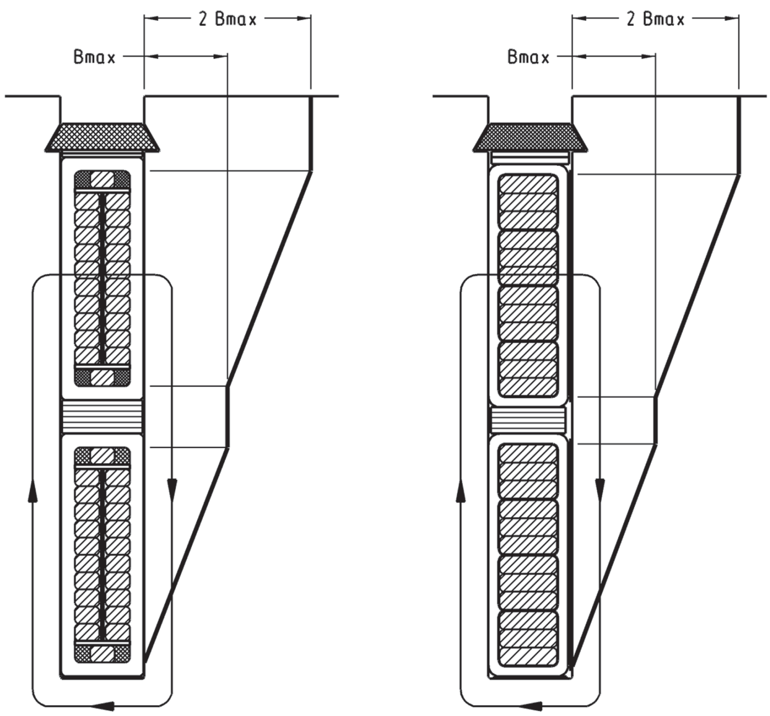

Figure 1: Cross-slot leakage flux and flux density for single turn bar and four turn coil.

1.1.2 Design for reduced extra copper losses

When load current is flowing in stator winding strands it forms the magnetic flux, which circulates around the winding conductors, in accordance with the Ampere Law. The load current creates stator MMF and corresponding flux, which opposes the field excitation flux. The stator winding current also creates a certain amount of leakage flux, which crosses the slot in a peripheral direction.

As shown in figure 1, the cross-slot flux density is zero at the slot bottom, with linear increase to a plateau in the area between the top and bottom coil sides, and then increases linearly again along the section of the upper coil side.

The AC cross-slot leakage flux produces "extra copper losses":

- strand (eddy current) losses resulting from eddy currents within each strand
- circulating current losses resulting from currents flowing between parallel paths within the coil closed by the connections between the coils.

The currents causing extra copper losses are parasitic in nature and are harmful to the electrical machine, causing unwanted losses, which increase machine temperature rise for a given load, accelerate insulation degradation, limit the machine output capacity and decrease its operating efficiency.

1.1.2.1 Design for reduction of strand ("eddy current") losses

When the side of the coil strand is subjected to an AC cross-slot flux directed normal to its side, then in the top of the strand a higher EMF will be induced than in the bottom of the strand due to the difference in the cross-slot flux density. This difference in induced EMF will cause eddy currents to flow in the axial core direction along the top of the conductor, and back along the bottom of the conductor between the ends of the stator core (refer to figure 2).

The major strand (eddy current) loss occurs in the straight slot sections of the stator coil located in the stator core slots, caused by stator slot cross-leakage flux. End windings experience low levels of leakage flux, and hence negligible eddy current losses.

The strand eddy current losses are directly proportional to the square of the frequency of the alternating current, and they vary in inverse proportion to the square of the strand thickness.

The ratio of the conductor width to the slot width is also an important factor. Where this ratio is lower (ie. the conductor width is smaller when compared to the slot width), the strand losses will be lower. This is due to the reduced amount of the slot cross leakage flux generated, as it has to cross a larger distance through a non-magnetic medium (slot ground insulation). With hydro generator upgrades and uprates this ratio will invariably increase, since copper conductor content is increased in conjunction with thinner contemporary ground insulations. Narrower and deeper stator core slots will have higher strand eddy current losses when compared to the wider and shallower slots.

Considering that the coil sides for fractionally pitched windings are not below north- and south-pole centres in the same instant, the instantaneous voltages generated in the coil sides of a short pitched winding will be out of phase with each other. The coil pitch must therefore be taken into account when calculating average values of strand eddy current losses.

Strand eddy current losses are analysed and quantified for each hydro generator winding design, in order to determine the optimum strand dimension,

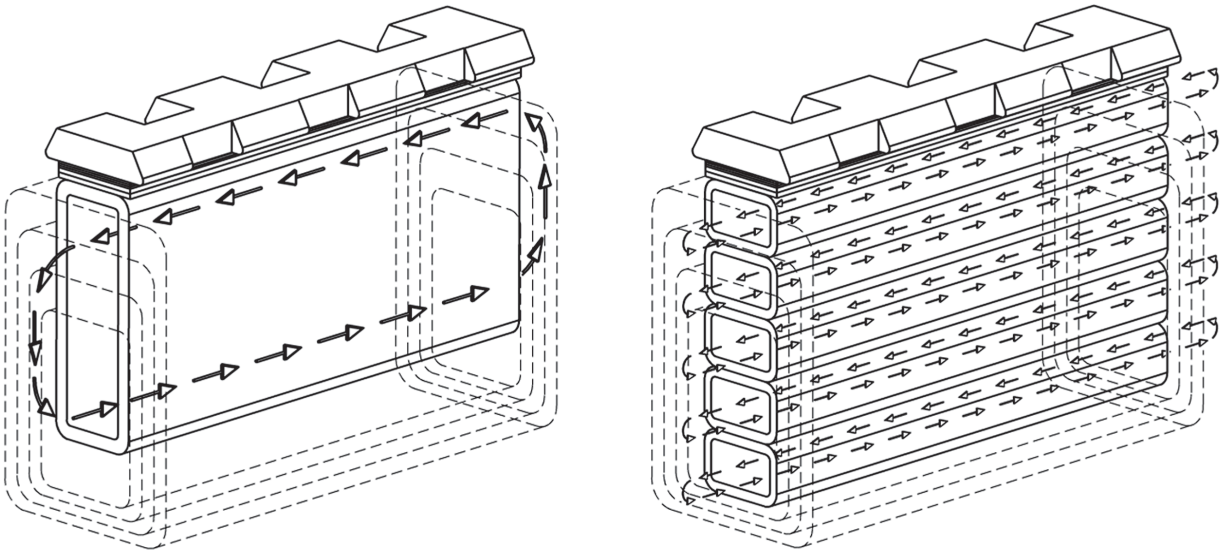

Figure 2: Axial flow of strand eddy currents, and effect of laminating the conductor.

not only from the loss stand-point, but also for the manufacturability purposes.

The generally adopted method of eliminating strand (eddy currents) is by subdividing the conductor on height, thereby increasing the number of strands above each other in the slot. The principle is similar to the laminating of the stator core, where the eddy currents are confined to much narrower higher resistance paths.

The designer must be careful not to subdivide the conductor too far. Too large a number of conductor laminations will require that excessive space is taken by the strand insulation, resulting in a reduced conductor cross sectional area, and increased DC I^2R losses. A larger number of strands is also more expensive from an economic stand-point. A balance between the two is therefore required.

The strand eddy current losses can never be reduced to a zero value.

Due to the varying density of cross-slot leakage flux along the radial depth of the stator slot, the strand eddy current losses will vary through radial slot depth, with lowest losses toward the bottom of the slot, and the highest strand losses occurring in the top coil strand nearest the machine bore.

Calculating individual strand losses through radial slot depth would be rather time consuming and impractical. It is therefore customary to calculate average eddy current losses, and to check maximum losses occurring in the top strand nearest to the machine bore. The equations for calculating the strand eddy current losses were developed in the early 20th century in Field (1905), Lyon (1922; 1927), Lyons (1930) and Summers (1927). With some small modifications, these equations are still correct for practical applications, and the author has used them successfully for many hydro generator uprate designs.

The windings for large electrical machines should, as far as practicable, be designed to limit strand eddy current levels as follows:

- strand thickness limited to 1.5-2.5 mm
- total average strand eddy current losses should be limited to less than 0.1 pu of the DC I^2R losses
- maximum strand losses in the top strand should be limited to 0.6 pu of the DC I^2R losses.

When considering single turn bars, the strands in the top bar, at the top of the slot, will have higher eddy current losses than the strands in the bottom bar. The increased eddy current loss in the top bar will produce a temperature rise difference between the top and bottom bars, with the top bar nearest to the bore being hotter. In practice, it is common to equalise these two temperature rises by reducing the thickness and increasing the number of strands in the top bar as far as possible to reduce its temperature rise, while maintaining the total copper CSA (refer to figure 3).

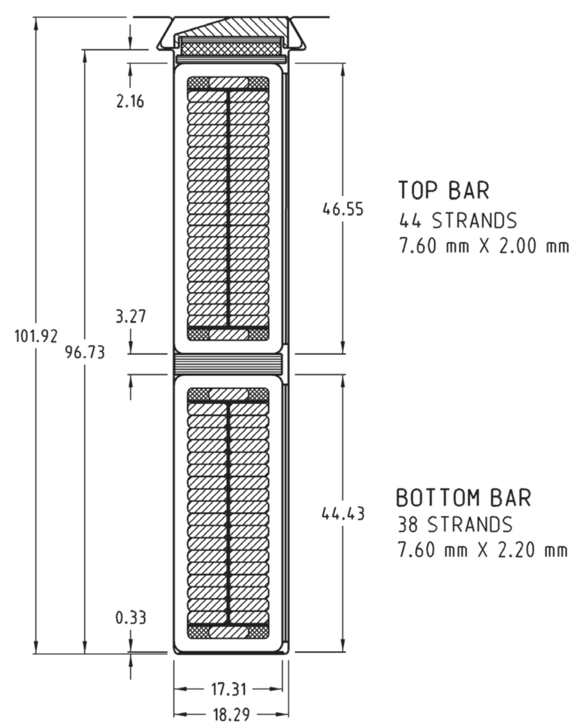

Figure 3: Top and bottom Roebel bars with different copper strand arrangements for equalisation of temperature rises.

1.1.2.2 Design for reduction of circulating current losses

When the parallel strands comprising the conductor are all connected together at the beginning and end of the coil, circulating currents will flow between strands due to the different EMF's induced in the individual strands, again, because they are exposed to different levels of cross-slot flux density. As the name implies, circulating currents are confined to the coil/bar itself, causing additional I^2R losses without any contribution to the generator output current, ie. power. Unlike the strand eddy current losses, circulating currents are not confined to the coil slot sections within the stator core, as they circulate between short-circuited ends of coil/bar, thus causing additional losses within whole length of copper turn.

Circulating current loss is proportional to the square of the number of coil/bar strands on top of each other, and can be very high for the coils with a low number of turns and high strand packs (refer to figure 4). Without specific measures to reduce circulating currents, their value can exceed the DC I^2R losses.

In order to minimise the losses, the strands are transposed. The essential principle underlying transposition theory, is to ensure that each strand in turn is exposed to the equal average leakage flux over its circuit length (Nailen, 2003). Equal average flux linkages will produce equal voltages in each copper strand on top of each other, thus eliminating or reducing per unit circulating current losses.

Over the years many transposition schemes have been devised, with Roebel transposition for single turn bars, and inverted turn transposition for multi-turn coils being most common for contemporary winding manufacture.

Roebel transposition for single turn bars – named after its German inventor Ludwig Roebel (Nailen, 2003) – is a 360° twist of the strands within the slot area so that every strand occupies all positions, depth wise in the slot. The effect is to equalise the eddy EMF's in all laminae, and to allow the layers to be paralleled at the ends without producing circulating currents between the layers. Considerable ingenuity is shown in the design of the twist, which must be accommodated in the slot space.

The transposition can be best understood by tracking the path of a strand at one end of the straight portion of the bar and in one of two stacks. From that point, it is bent at a small angle, proceeds upwards to the middle of the straight portion, and it is then bent to a position in the other stack and from there proceeds again at a small angle to the bottom of the stack at the other end of the bar (refer to figure 5). It thus traverses all depth-wise positions in the coil side, producing equal induced voltages in every strand, and for all practical purposes, eliminates circulating current loss by 100%.

There are variations of the Roebel or 360° transposition in a single turn coil for very large machines. Some manufacturers have used the 540° transposition. This reduces some of the losses due to the leakage fluxes in the end zone. Other manufacturers use a 720° transposition in the slot, and others carry an additional 180° transposition into the end windings.

The most notable disadvantage of the Roebel transpositions for the single turn bars is the extra space occupied at the top and the bottom of the bar required for strands to cross from one to the other side of the copper stack. However, the 360° Roebel transposition is still the best solution for large hydro generators where single turn bars are commonly employed.

For *multi-turn coils*, the suppression or reduction of circulating current loss requires a different approach. In the first instance, due to the evolute in the end winding, one side of the coil is at the top of the slot and the other side at the bottom, giving a partial transposition. As a result, it can be shown that when the number of coil turns exceeds six, only very rarely will any further transposition be required. The requirements concerning thickness of the strands, as discussed for strand eddy current losses still hold here.

With deep slots and 2 or 3 turns per coil, a further transposition is necessary, and for practical reasons

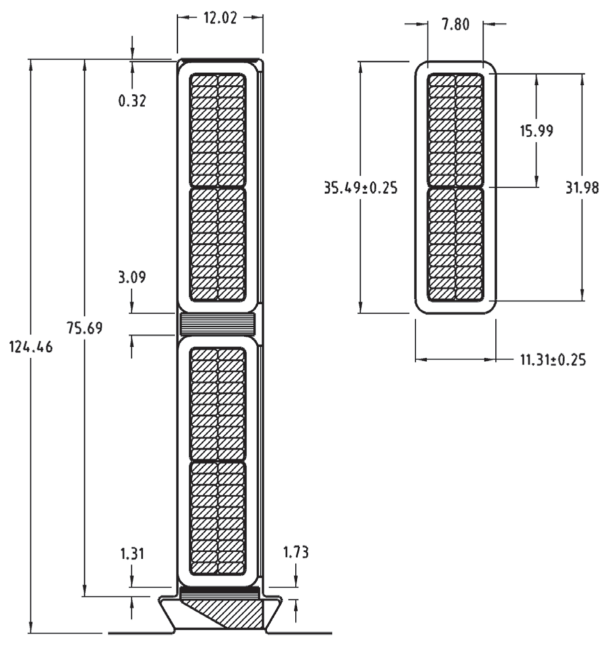

Figure 4: Typical hydro generator coil with 2 turns/coil each consisting of 20 copper strands per turn, 2 wide and 10 high. High circulating currents can be expected without transposition.

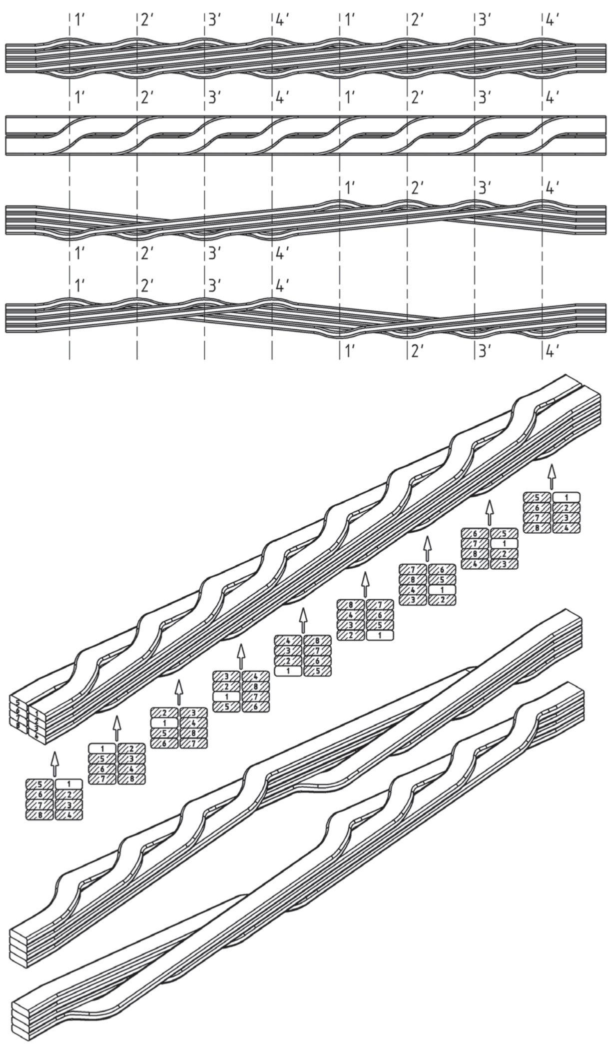

Figure 5: Roebel transposition for single turn bar.

the full (360°) Roebel transposition cannot be used. A compromise is provided by the inverted turn transposition in the form of either semi-Roebel transposition or 180° twist of the turn strands. This 180° inversion is always made outside of the slot area.

The twisted turn transposition is usually applied during the loop winding operation (refer to figure 6), whereas the semi-Roebel transposition must be applied after the loop winding operation, before coil shaping. The gain is small when making more than one 180° transposition, and for practical manufacturing purposes, only one inversion is applied in each coil. The turn inversion enables solidly connected identical coils to be manufactured practically free from circulating currents. By utilising the transpositions in the ends of a coil, a space for them is created, without sacrificing the slot room.

Design recommendations:

- Circulating current losses should be limited to less than 0.1 pu of the DC I^2R losses.
- Inverted turn transposition is only to be used for multi-turn coils with up to 6 turns (best effect is achieved for coils with 2 or 3 turns).
- The turn inversion should be located in the end winding part of the coil, and as far as practicable located in the place that will give the minimum losses.
- The number of turn inversions should be limited to one for economy of manufacturing.

The optimal locations of inverted turn transpositions and their functional locations considering practicalities of manufacturing, which still produce satisfactory reductions of circulating currents, are presented in table 1. They are derived for two possible coil lead configurations, the so-called "GE style" and "Westinghouse style" (refer to figure 7). The names were derived from the two distinctly different coil lead styles used by the two largest USA electrical machine manufacturers, which may have been influenced by patents and intellectual rights.

Table 1: Optimal locations of inverted turn transpositions and their functional locations considering practicalities of manufacturing.

Turns per coil	GE Style leads		Westinghouse Style leads	
	Best T_i	Manufacturing T_i	Best T_i	Manufacturing T_i
2	0.5	0.5	1.0	1.0
3	0.5	0.5	2.0	2.0
4	1.5	3.0	3.0	3.0
5	2.5	4.0	3.0	4.0
6	3.5	5.0	4.0	5.0

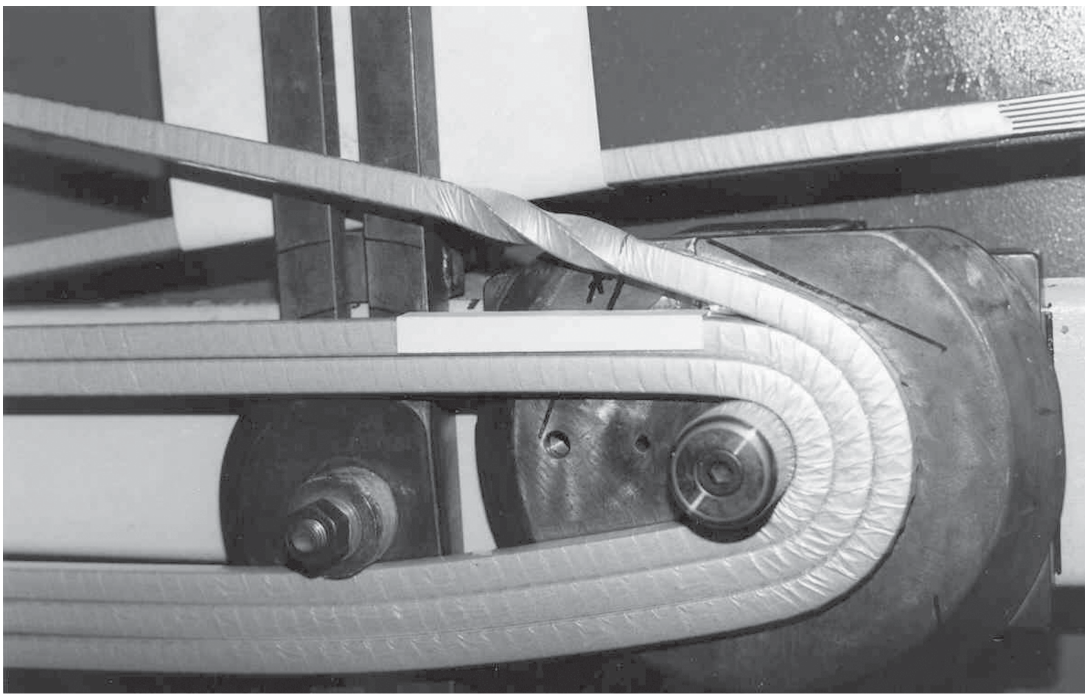

Figure 6: Inverted turn transposition applied during the coil winding process.

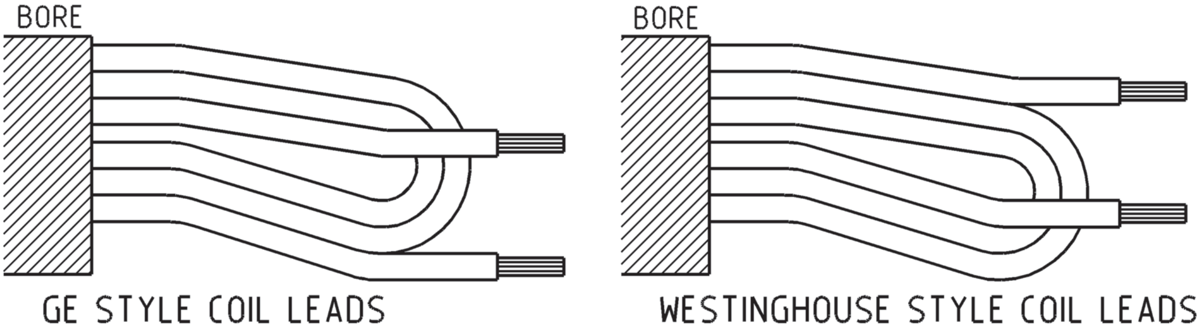

Figure 7: Stator coil lead configurations – "GE Style" (left) and "Westinghouse Style" (right).

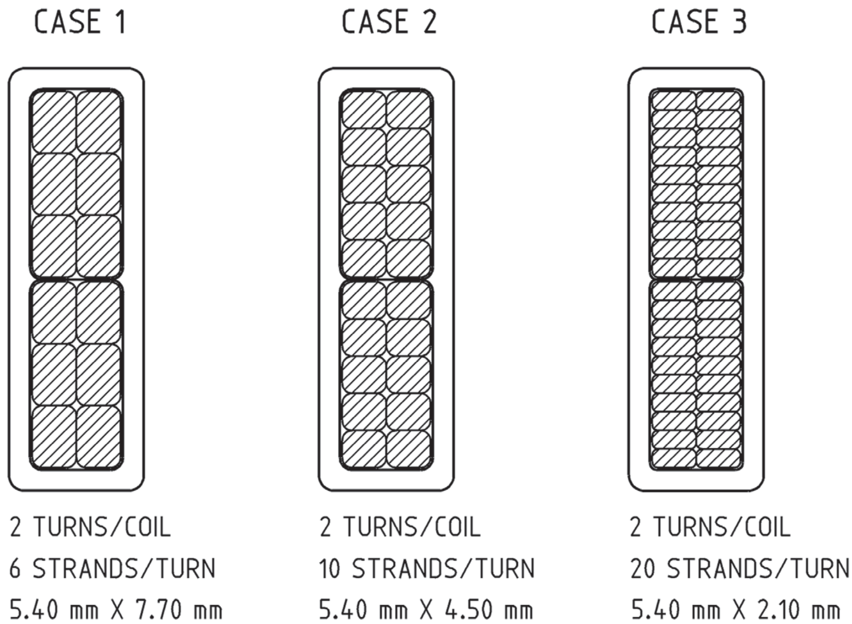

Figure 8: 50 MVA, 11 kV, 44 pole hydro generator coil with different strand sizes and arrangement.

For both styles of the coil, the number of turns after which inversion takes place T_i is counted from the inner coil lead closest to the slot centre.

1.1.3 Practical application

The theory outlined so far can best be illustrated by a practical example. Outlined in figure 8 are three different coil configurations for a 50 MVA, 11 kV, 44 pole hydro generator. The configurations of Case 1 and Case 2 are fictitious and overstated. They would never be considered for contemporary practical application, but serve to highlight the theory outlined so far. The configuration of Case 3 was actually produced by the author for 8 hydro generator windings. All three cases have the same total insulation builds (0.3 mm for the strands, 0.6 mm turn insulation, and 5.4 mm groundwall); all are fitted within the same finished slot section size of 17.40 mm wide and 54.60 mm high; and all utilise inverted turn transposition after the first half turn with GE Style coil leads configuration. The calculated copper losses for all three arrangements are summarised in table 2.

Examination of table 2 yields the following important conclusions:

- Case 1 and Case 2 are not acceptable and do not conform to previously outlined acceptance criteria since their top strand losses are much too high and would cause severe overheating of the top strand.
- Average strand eddy current losses for Case 1 and Case 2 are far above 0.1 pu of DC I^2R losses, which is above acceptable criteria.
- For all three cases, circulating currents without transposition are extremely high (79-88% of base DC I^2R loss), and for all three cases quite remarkable reduction to about 5% of base DC I^2R loss is achieved by using inverted turn transposition.
- Even though Case 3 has the highest DC I^2R losses (on account of extra space taken by the strand insulation for 20 strands), it satisfies all previously outlined design criteria and has lowest overall losses.

The importance of the correct choice and location of the inverted turn transposition cannot be overstated. The author had an experience where two 15 MVA

Table 2: Calculated copper losses for all three arrangements.

Loss designation	Case 1	Case 2	Case 3
DC I^2R loss	183.749 kW	191.520 kW	204.492 kW
Loss in top strand	5.0658 pu	1.6415 pu	0.3114 pu
Average strand eddy current loss	0.8592 pu 157.877 kW	0.2784 pu 53.319 kW	0.0528 pu 10.797 kW
Circulating current loss (without transposition)	0.8590 pu 157.840 kW	0.8801 pu 168.557 kW	0.7907 pu 161.692 kW
Circulating current loss (with transposition)	0.0537 pu 9.867 kW	0.0550 pu 10.534 kW	0.0494 pu 10.102 kW
Total loss (without transposition)	2.7182 pu 499.467 kW	2.159 pu 413.492	1.8435 pu 376.981
Total loss (with transposition)	1.9129 pu 351.493 kW	1.3334 pu 255.373 kW	1.1022 pu 225.391 kW

hydro generators rewound by the author's company were found to be running with a 35-40 °C lower full load stator winding temperature rise, when compared to an identical hydro generator in the same powerstation, which was rewound by the opposition company a few years earlier. Subsequent investigation by the author revealed that even though all machines were rewound with an almost identical copper strand arrangement, the first machine had incorrectly located inverted turn transposition. For the 2 turn coil with Westinghouse Style leads, the inversion was located after the first half turn, whereas it should have been located after first full turn. The author used GE Style leads and correctly located the inversion after the first half turn (refer to table 1).

For both cases, the calculated circulating current loss without transposition was 0.2480 pu (26.430 kW). With incorrectly located transposition the circulating current loss increased to 0.6594 pu (70.274 kW), with overall winding copper losses of 1.7028 pu (181.471 kW). In comparison, the author's winding had circulating current losses of 0.0155 pu (1.652 kW), with overall copper losses of 1.0589 pu (112.849 kW), ie. an overall reduction in copper losses of 37.81%. The first machine with incorrectly located inverted turn transposition is expected to have reduced winding life expectancy due to accelerated thermal degradation, and some effect on the overall machine efficiency.

1.2 Hydro generator high voltage coil insulation design

Hydro generator high voltage (HV) coil insulation consists of strand-to-strand insulation, turn–to-turn insulation, and ground insulation. The iterative design process must balance conflicting requirements between dielectric strength requirements and heat dissipation properties.

The allowances must also be provided for the space required by corona protection system layers, conductive radial slot packing, and conductive slot side packing.

1.2.1 Strand-to-strand insulation selection

Strand-to-strand insulation is required to insulate individual strands within a turn pack from each other, so that strand eddy currents are confined to each individual strand and thus minimised, and to keep strands in each height-wise tier insulated from each other, so that effective schemes for reduction of circulating current losses can be incorporated into coil design. Dielectric stresses on strand-to-strand insulation are low, since it only has to cater for rather low strand-to-strand voltages induced by cross-slot leakage fluxes.

The commonly used materials for strand-to-strand insulation are fused dacron glass yarns (cheaper, low dielectric strength, often porous), or resin rich mica tapes (more expensive, excellent dielectric strength, dense and void-free).

For HV hydro generator coils, the author has mostly used resin rich mica tapes, partially because of better dielectric properties, which then contribute to the better turn-to-turn voltage capability. The main reason is the resulting void-free homogenous structure, which operates with a reduced amount of internal partial discharges, and thus provides better longevity of service.

The typical overall resin rich mica strand-to-strand insulation allowances are 0.2-0.3 mm.

1.2.2 Turn-to-turn insulation selection

The turns of the HV stator coil are the wires in parallel that are carried around the loop in series before the coil is formed. For larger machines, there may be four or six in parallel, and for large machines such as hydro-generators there may be 10 to 20 wires in parallel. The actual insulation applied between the turns depends on the turn–to-turn voltage, expected transient over voltages and the physical size of the coil.

In addition to normal turn-to-turn operational voltages (10-250 V/turn), insulation between turns in HV stator coils must be able to withstand transient surge voltages, which may be as high as 5 pu with a voltage rise time ranging from 0.1-1.2 μs. Numerous stator winding failures and potential hazards caused by transient over-voltages highlighted the need to specify extra dielectric strength for turn-to-turn insulation, to withstand the over-voltages and the need for acceptable standards and testing requirements (IEEE, 1992).

A turn-to-turn fault generally results in localised overheating due to the very high current developed within the shorted turn. Eventually, the melting of copper destroys the ground insulation, resulting in a phase-to-phase or phase-to-ground fault. There is no way to clear a turn-to-turn fault until it goes to ground. However, it can be detected by neutral current protection, but this system is usually only used on larger HV machines.

Until recently no generally accepted approach to the selection of the turn-to-turn test voltage had existed. Many different machine design parameters had been used to determine the turn-to-turn test voltage, such as the size and weight of the coil, length of the turn, arrangements of turns within the coil, operating voltage per turn or per coil, system voltage, and the inter-turn and turn-to-ground capacitance.

Modern trends in turn-to-turn insulation design and testing are based on maximum expected transient over-voltages. The turn-to-turn insulation is always manufactured from resin rich mica tapes. Depending on the coil configuration it may be applied during or after the loop winding process. Turn-to-turn insulation in the slot section area is always consolidated in the hot presses before ground insulation is applied. This provides homogenous void-free structure of very close dimensional tolerances, to ensure correct thickness of ground insulation can be applied.

The recommended impulse test withstand voltages (IEEE, 1992) and resin rich mica tape insulation builds for commonly encountered system voltages are presented in table 3.

1.2.3 Ground insulation design and selection

The copper to ground insulation ratio is designed for the best heat dissipation and optimal voltage stresses. Thicker insulation provides a more effective and more durable dielectric barrier, but impedes heat dissipation from the coil, causing the increased winding temperature rise and accelerated thermal degradation.

Quite often the client's specification defines the maximum permissible design voltage stress to be used, but ultimately the manufacturer must select ground insulation that will provide the necessary heat dissipation to comply with the required winding temperature rise, and the reliable long-term operation from the dielectric and thermal degradation view point.

In the author's Australian experience, the present compromise between a desire to maximise the uprating and a sensible trade off with the insulation allowances is to design the ground insulations with the voltage stresses between 2000 and 2600 V/mm. For lower voltages such as 6.6 kV, the insulation thickness giving about 2000 to 2200 V/mm stress is common, as the mechanical strength of the insulation during winding insertion must also be considered. For voltages of 11 kV and above, voltage stresses between 2200 and 2600 V/mm are generally employed.

The turn-to-turn insulation allowance is included together with ground insulation for calculation of voltage stresses in ground insulation.

All modern hydro generator stator windings are manufactured with insulation materials rated to thermal Class F (155 °C). Often, even for the upgraded and uprated generators, the end users specify Class F materials with winding temperatures limited to Class B (130 °C) to minimise thermal degradation of insulation and prolong winding life.

Table 3: Recommended impulse test withstand voltages (IEEE, 1992) and resin rich mica tape insulation builds for commonly encountered system voltages.

System voltage [kV rms]	Impulse test voltage [kV peak]	Number of impulses [0.1-0.2 μs]	Turn insulation thickness [mm]
3.3	9.43	5	0.3-0.4
6.6	18.86	5	0.4-0.6
11.0	31.44	5	0.6-1.0
13.2	37.72	5	0.8-1.2
13.8	39.44	5	0.8-1.2

In addition to reliable operation in service, HV ground insulation must be capable of passing dielectric strength testing, and in modern times accelerated ageing testing.

In recent years, tests have been developed for accelerated aging of insulation's such as voltage endurance and thermal cycling tests (IEEE, 1996a; 1996b; 2002). If these tests are required, the slight engineering compromise is to err on the insulation dielectric properties (thicker insulation), while sacrificing some thermal dissipation, to ensure passing of the voltage endurance test. Voltage endurance, and in some cases thermal cycling tests, are presently almost always included as a part of the new hydro generator winding specification. Accelerated ageing testing will be covered in more detail in the fourth paper of this series (Znidarich, 2009c).

2 WINDING DESIGN FOR ELIMINATION OF HARMONICS

2.1 Winding waveform and harmonics

Under ideal conditions, the generator output voltage waveform would be a pure sinusoid of the form:

$$e(t) = E_m \sin \omega t \quad [\text{V}] \tag{2}$$

where $e(t)$ = instantaneous voltage [V]; E_m = voltage peak value [V]; ω = angular velocity ($2\pi f$) [rad/s]; and t = time [s].

To achieve a purely sinusoidal output voltage waveform, the MMF's of both rotor field excitation and armature winding would also need to be of the pure sinusoidal form, ie. the requirement is of sinusoidal rotor field winding waveform, and armature core and winding assembly that will not distort the induced voltage waveform (Ames, 1990). In practice this is not possible given the engineering design compromises when considering the geometry of the machine magnetic circuit and armature windings, and variable loads that a generator must cater for. The sinusoidal field excitation MMF is in practical design approximated by the non-uniform air gap shape of the rotor pole shoe. Even if this shape could produce perfectly sinusoidal MMF at a particular load, the effects of the flux pulling (Ames, 1990) at other loads will cause the excitation MMF to digress from the pure sinusoidal shape. The stator core and stator winding assembly will further distort the wave shape of the induced voltage, due to the winding phase belts consisting of individual coils being placed in the slotted armature core. As the rotor field poles pass over the discontinuous slotted stator bore surface, the ripples will be induced in the flux wave, thus further distorting the wave shape of the induced voltage.

If the MMF and voltage waveforms differ from pure sinusoidal shape, they are termed complex periodic waveforms. It can be shown by Fourier waveform analysis (Bell, 1984), that any complex periodic waveform can be represented by or decomposed to a number of pure sinusoids having frequencies that are integral multiples of the fundamental frequency of the waveform. These waveform components are termed harmonics (refer to figure 9).

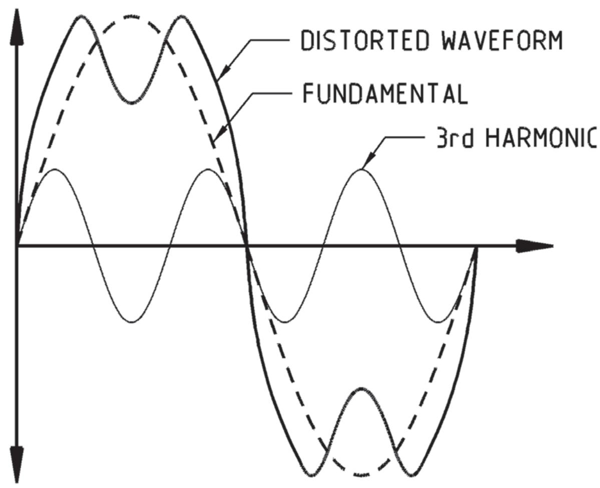

Figure 9: Sine waveform distortion by high 3rd harmonic.

Regarding the hydro generator stator windings:

- The three phase winding star connection eliminates all triplen harmonics from the generator lines (3rd, 6th, 9th, 12th, etc.).
- With generator voltage, current and MMF waveforms being symmetrical about the horizontal axis, only odd harmonics will be present (5th, 7th, 11th, 13th, etc.).

The hydro generator stator winding design therefore concentrates on elimination of odd harmonics, and in particular the harmonics of lowest order (5th and 7th), which have highest amplitudes.

The following section will explain the most common methodology available to the winding designer for suppression of unwanted harmonics.

2.2 Skewed stator winding slots

Inevitable ripple in the induced voltage waveform results from stator core slotting discontinuity. This is caused by the different air gap permeance due to the slotting. As the rotor pole shoe passes the stator core teeth and slots, the flux density will be highest between the rotor pole shoe and the core tooth, and somewhat lower between the rotor pole shoe and open stator slot, due to the varying permeance. Another possible problem is the vibration caused by the higher magnetic pull between the rotor and stator teeth, and between the rotor and open slot areas. To avoid this problem, the stator core slots or the rotor poles may be skewed, ie. rather than being parallel with the axis of the machine they are manufactured at a slight angle to each other. If, for instance, the stator core is skewed and the rotor poles are parallel with the machine axis, the rotor flux will not suddenly change between stator slots and teeth, but will pass the stator slot and tooth gradually, starting at one end, and finishing at the other. The stepped ripples in the waveform resulting from the parallel arrangement will thus be smoothed, producing the waveform closer to the sinusoidal shape with a lower harmonic content (Ames, 1990).

Since the stator slots are running at the periphery of a cylinder, stator slot skewing will produce stator slot twist. That was not much of a problem with the earlier generation of thermoplastic windings based on bitumen impregnation, since stator coil slot sections could be twisted during insertion into the slots, and would conform to the slot shape. The problem arises with the modern resin rich “hard slot cells”, which do not have enough flexibility to conform to the slot section if they are moulded straight. For that reason, the modern stator core designs avoid slot skewing. The problem still exists with the older machines with skewed stator slots, which originally employed thermoplastic windings. The author has successfully manufactured resin rich windings for those machines (up to 65 MVA size), by 3D machining of the hydraulic press platens to approximate the slot section twist. This was done for both consolidation and final pressing of the groundwall insulations.

The most commonly employed slot skew is equivalent to one slot pitch angle (refer to figure 10).

2.3 Fractionally pitched stator windings

The hydro generator windings are always pitched shorter than the 180 °el pole pitch. These windings are known as fractional pitch windings. Advantages of fractional pitching include reduced copper losses for shortened winding mean length of turn (MLT), better spacing of end windings for voltage clearances and cooling, and quite importantly, reduction of harmonics. By appropriately pitching of stator winding coils, some harmonics can be totally eliminated, and compromises can be reached in the reduction of others.

Referring to figure 11, it is obvious that if the coil is shortened by $1/n$ of the pole pitch, the n^{th} harmonic will be fully eliminated (Puchstein et al, 1954).

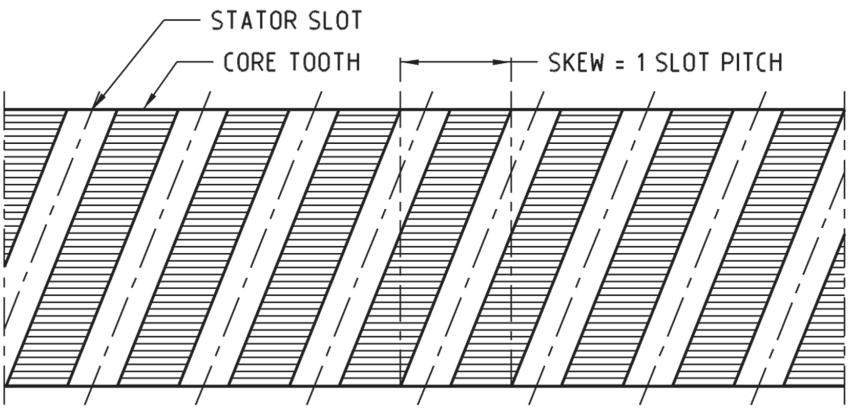

Figure 10: Stator core slots skewed by one slot pitch.

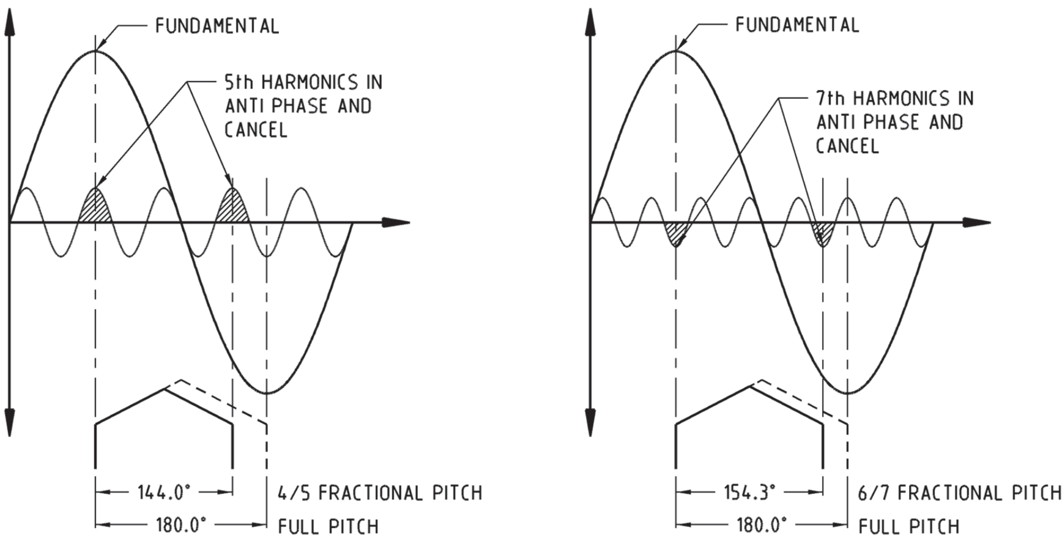

Figure 11: Elimination of 5th and 7th harmonics by fractional pitching of stator winding.

Considering that the coil sides are not below north- and south-pole centres in the same instant, the voltages generated in the coil sides of a short pitched winding will be out of phase with each other, and instead of being summed algebraically must be added vectorially. The pitch factor k_p shows pu reduction in coil generated voltage between the short and full pitched coil.

The winding pitch factor for any harmonic is given by:

$$k_{p(n)} = \sin n\left(\frac{\alpha}{2}\right) \quad [\text{pu}] \tag{3}$$

where $k_{p(n)}$ = pitch factor for stator winding for any harmonic [pu]; n = order of harmonic (for fundamental n = 1); and α = pitch angle [°el].

Equation (3) is utilised to arrive on some fundamental and harmonic pitch factors presented in table 4.

Examination of table 4 yields the following important conclusions:

- Full pitched stator windings contribute nothing to the reduction of harmonics, and all harmonics are present with their maximum magnitudes.
- As previously stated, if the coil is shortened by $1/n$ of the pole pitch, the n^{th} harmonic will be fully eliminated, ie. 2/3 coil pitch fully eliminates 3rd harmonic, 4/5 coil pitch fully eliminates 5th harmonic, 6/7 coil pitch fully eliminates 7th harmonic, etc.
- Disregarding the 3rd harmonic, which is eliminated by the star connection, the best coil pitch for reduction of low order harmonics is found to be 5/6, (or 150 °el, or 0.833 pu). It reduces the fundamental by only 3.4%, and 5th and 7th harmonics to 0.259 pu and –0.259 pu, respectively. This is indeed the winding designer's coil pitch of choice, if the number of the stator slots permits it. Quite often it will be found that the number of slots for a hydro generator is designed to permit the winding with the 0.833 pu coil pitch or close to it (eg. 10 pole hydro generator stator winding having 132 slots).

2.4 Distributed stator windings

The hydro generator winding pole phase groups consist of a number of single coils, which are distributed into the number of successive stator slots, rather than being concentrated as one coil.

2.4.1 Distributed integral slot stator windings

The induced voltages in each coil will be out of time phase with each other, because there is a definite time required for the rotating excitation field to move from one coil to another. The voltages induced in individual successive coils of each phase group must therefore be added vectorially, rather than algebraically. The total voltage in the distributed pole phase group will be lower when compared with the voltage that would be induced if the pole phase group was concentrated, ie. consisted of only one coil. This ratio of voltage induced in distributed winding over the voltage induced in concentrated winding is defined as the distribution factor k_d.

The distribution factor for integral slot winding is given by:

$$k_{d(n)} = \frac{\sin n\left(\frac{\theta_{PB}}{2}\right)}{q_{spp}\sin n\left(\frac{1}{2}\right)\left(\frac{\theta_{PB}}{q_{spp}}\right)} \quad [\text{pu}] \tag{4}$$

where $k_{d(n)}$ = distribution factor for stator winding for any harmonic [pu]; n = order of harmonic (for fundamental n = 1); θ_{PB} = phase belt angular spread [°el]; and q_{spp} = number of slots per pole per phase.

From examination of figure 12, it is obvious that the distributed pole phase group having six coils per pole phase group, will produce a smoother induced voltage waveform when compared to the pole phase group containing only two coils. Therefore, waveforms produced by distributed pole phase groups comprising a larger number of coils contains less harmonics, and that is demonstrated by the values of the distribution factors presented in table 5.

Table 4: Fundamental and harmonic pitch factors.

Coil pitch [Fraction]	Coil pitch [°el]	Coil pitch [pu]	Fundamental [pu]	3rd harmonic [pu]	5th harmonic [pu]	7th harmonic [pu]
1	180.00°	1.000	1.000	1.000	1.000	1.000
8/9	160.00°	0.889	0.985	–0.866	0.643	–0.342
7/8	157.50°	0.875	0.981	–0.832	0.556	–0.195
6/7	154.29°	0.857	0.975	–0.782	0.434	0.000
5/6	150.00°	0.833	0.966	–0.707	0.259	0.259
4/5	144.00°	0.800	0.951	–0.588	0.000	0.588
3/4	135.00°	0.750	0.924	–0.383	–0.383	0.924
2/3	120.00°	0.667	0.866	0.000	–0.866	0.866

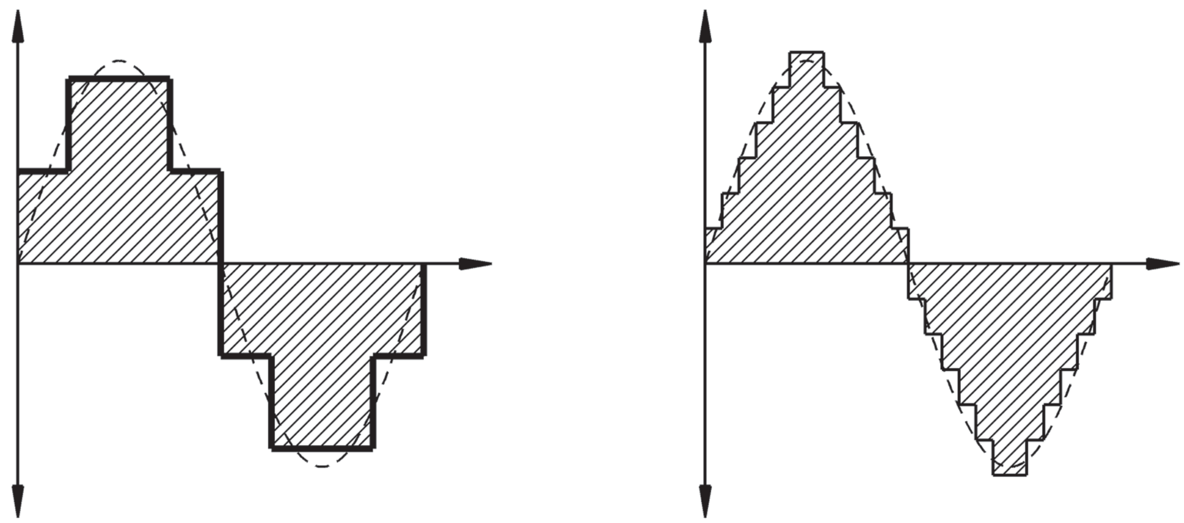

Figure 12: Induced voltage waveforms for pole phase groups containing two and six coils.

Table 5: Distribution factors.

Number of coils/ppg	Fundamental [pu]	3rd harmonic [pu]	5th harmonic [pu]	7th harmonic [pu]	11th harmonic [pu]	13th harmonic [pu]
1	1.000	1.000	1.000	1.000	1.000	1.000
2	0.966	0.707	0.259	–0.259	–0.966	–0.966
3	0.960	0.667	0.218	–0.177	–0.177	0.218
4	0.958	0.653	0.205	–0.158	–0.126	0.126
5	0.957	0.647	0.200	–0.149	–0.110	0.102
6	0.956	0.644	0.197	–0.145	–0.102	0.092
7	0.956	0.642	0.195	–0.143	–0.097	0.086
8	0.956	0.641	0.194	–0.141	–0.095	0.083
9	0.955	0.640	0.194	–0.140	–0.093	0.081
10	0.955	0.639	0.193	–0.140	–0.092	0.079
∞	0.955	0.637	0.191	–0.137	–0.087	0.074

Examination of table 5 yields the following important conclusions:

- The stator windings with one coil per ppg, ie. concentrated winding contribute nothing to the reduction of harmonics, and all harmonics are present with their maximum magnitudes.
- The fundamental is not affected (reduced) much even with infinite number of coils per ppg.
- With the exception of the 11th and 13th harmonics for two coils per ppg, all other harmonics are drastically reduced with three coils per ppg and above.

2.4.2 Balanced symmetrical fractional slot stator windings

The theory outlined so far refers to the integral slot windings, where the number of coils per pole phase group is an integer, ie. 2, 3, 4, etc.

As already outlined, hydro generators for medium and low heads operate at low speeds, and have a larger numbers of poles. For example, 360 slot, 60 pole machine will have only 2 coils per pole phase group resulting in a higher harmonic distortion of the waveform. Trying to fit larger number of slots would necessarily increase machine diameter size and cost, as proportional content of insulation to stator core and winding copper would increase.

The problem is ingeniously solved using a fractional slot windings, which are employed for almost all hydro generators encountered today.

As the name implies, for fractional slot windings the number of coils per pole phase group is a fraction. Contradictory to this statement, the number of coils per pole phase group cannot physically be a fraction, as we cannot fit a fraction of a coil. It follows that individual pole phase groups will consist of different

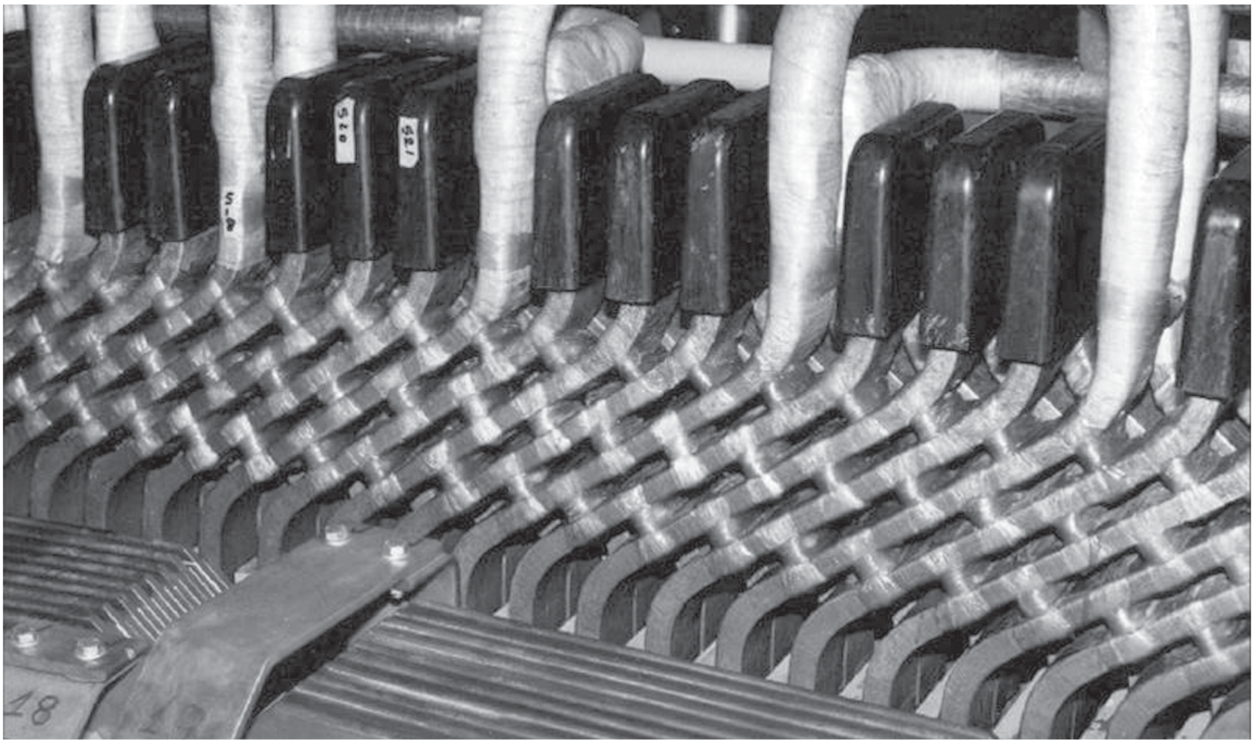

Figure 13: Hydro generator winding employing fractional slot principles – one pole phase group on the left contains 3 coils and the other three on the right contain 4 coils.

numbers of coils, which is also known as “odd coil grouping”. The simplest example is 3.5 coils per pole phase group, where each repeatable pole phase group sequence will consist of one pole phase group with 4 coils, and one pole phase group with 3 coils. It is important to note that each phase winding will consist of a number of identical repeatable winding parts, and each repeatable winding part will consist of an identical sequence of odd pole phase groups. Even with pole phase groups consisting of a different number of coils, the winding must be arranged to achieve complete electrical and magnetic balance, with phase EMF’s being spaced exactly 120° from each other (Say, 1984).

Some general rules will be stated and illustrated by a simple example:

$$q_{spp} = \frac{Z_s}{m \cdot p} = I + \frac{n_{um}}{d_{en}} = \frac{N_{um}}{d_{en}} \tag{5}$$

where q_{spp} = number of slots per pole per phase; Z_s = number of stator core slots; m = number of phases; p = number of poles; I = integral part of the mixed number; n_{um} = numerator of the mixed number proper fraction; d_{en} = denominator of mixed number proper fraction and of improper fraction; and N_{um} = numerator of improper fraction expressed to its lowest terms.

Referring to equation (5), the following rules apply to the fractional slot winding:

- Number of pole phase groups in one repeatable winding part = d_{en}.
- Number of slots per phase (ie. coils) in each repeatable winding part = $N_{um} = q_{spp} \times d_{en}$.
- In each phase winding, the number of repeatable winding parts, and highest number of possible parallel winding paths = p/d_{en}.
- In each repeatable winding part there will be:
  (a) $(d_{en} - n_{um})$ pole phase groups consisting of I coils.
  (b) n_{um} pole phase groups consisting of $(I + 1)$ coils.

The conditions of balance for fractional slot winding are:

$$p/d_{en} = \text{an integer} \tag{6}$$

$$d_{en}/m \neq \text{an integer} \tag{7}$$

$$Z_s/m = \text{an integer} \tag{8}$$

The above rules can best be explained by a simple example illustrated by figure 14.

The simple fractional slot winding example illustrated by figure 14 is a 10 pole winding having 48 stator slots. Following the rules set out above we will have equation (5), and therefore:

$$q_{spp} = \frac{48}{3 \times 10} = 1\frac{3}{5} = \frac{8}{5}$$

From the above, $I = 1$, $n_{um} = 3$, $d_{en} = 5$ and $N_{um} = 8$.

- Number of pole phase groups in one repeatable winding part = $d_{en} = 5$.
- Number of coils in each repeatable winding part = $N_{um} = 8$.

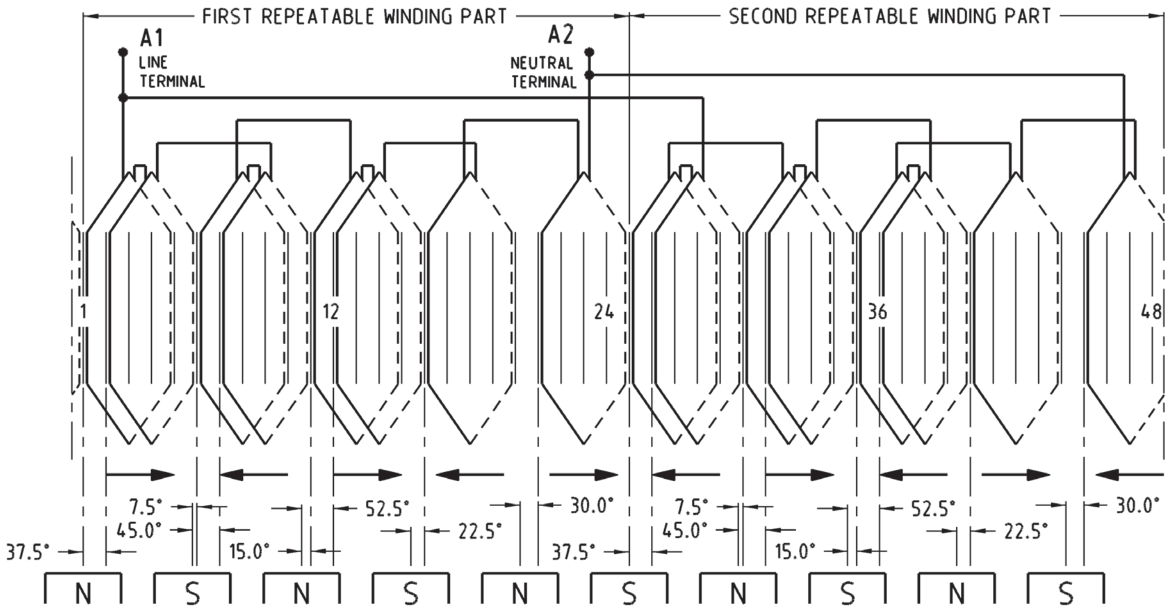

Figure 14: A simple fractional slot winding example.

- Number of repeatable winding parts per phase = p/d_{en} = 10/5 = 2.
- In each repeatable winding part there will be:
  - (a) $(d_{en} - n_{um})$ = 5 – 3 = 2 pole phase groups consisting of (I) = 1 coils.
  - (b) n_{um} = 3 pole phase groups consisting of $(I + 1)$ = 1 + 1 = 2 coils.

The conditions for balanced fractional slot winding are:

p/d_{en} = an integer = 10/5 = 2

$d_{en}/m \neq$ an integer = 5/3 = 1 + 2/3

Z_s/m = an integer = 48/3 = 16

All above values and conditions for winding balance are satisfied.

Given 48 slots and 10 poles, the full winding pitch is: 48/10 = 4.8 slot pitches.

With the actual fractional winding pitch of 4.0 (coil spanning between slots 1 and 5), the per unit coil pitch will be: 4.0/4.8 = 0.833 pu, which will attenuate all lower order harmonics (5th and 7th in particular).

The most important point to note in figure 14 is the cyclic shift of 7.5 °el of each coil in each repeatable coil part with respect to their excitation pole axes, which are positioned symmetrically 180 °el (36° mechanical) apart from each other around the rotor periphery. This cyclic shift results in each pole phase group behaving as if it has N_{um} coils per pole phase group. In the above example, the pole phase groups consist of two and one coils, and with fractional slotting, each pole phase group will behave as if it consists of eight distributed coils, ie. approaching an infinite distribution. As outlined previously, larger numbers of coils per pole phase group will attenuate harmonics and produce a smoother waveform, without greatly affecting the magnitude of the fundamental. Given hydro generator low speeds and high number of poles, only small number of coils per pole phase group are possible, and fractional slot windings are almost always employed as a means of obtaining satisfactory output voltage waveforms. One example is the 420 slot, 44 pole hydro generator winding, where q_{spp} is 3 + 2/11, and N_{um} is 35/11. Although physically distributed coil groups consist of only three and four coils, for elimination of harmonics they will behave as if they contain 35 coils per pole phase group.

The fractional slot windings cannot be fully pitched as their full pitch calculated values are also a fraction. Therefore, they will always be short pitched around 0.833 pu. The equations for calculating the fractional slot winding pitch factor are exactly the same as pitch factor equations for integral slot windings.

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