# Hydro Generators
# Introduction to Stator Windings

François St Germain, P.Eng.
Mechanical Engineer specialized in hydro turbines and generators
**September 2019**

BBA.CA

# Disclaimer

This document is provided for informational purposes only. Anyone who uses this document is responsible for determining whether or not it applies to his or her activities. At no time will BBA or the author be held liable for any error or omission that the document may contain or that may result from its use.

The information contained in this document is the proprietary and exclusive property of BBA Inc. except as otherwise indicated. No part of this document may be reproduced, stored, transmitted, or used for design purposes without the prior written consent of BBA Inc.

The information contained in this document is subject to change without notice.

# Executive summary

A variety of stator winding types (coil, bar and concentric) can be found in our hydropower generating units. The lifespan of a winding varies depending on the use, type of insulation (asphalt, polyester, epoxy, B-stage, VPI, etc.), quality of fabrication and installation, and maintenance.

The stator winding is the part of hydropower generating equipment that has the highest operating costs due to equipment price, installation complexity, production loss and risk of unplanned breakage. With the loss of knowledge among most operators and the aging generating fleet, it is imperative to develop a maintenance strategy that incorporates specialized tests and regular inspections/assessments.

Assessing the winding is key to its sound management and extending its remaining service life, its real purpose. Once the condition of the winding is known, there are different strategies available. The complete rewinding of the stator is the most obvious strategy, and it is also the one that requires the most effort and greatest investment.

Other alternatives exist and may prove to be successful strategies for prolonging the winding's remaining service life at a lower cost and for managing acceptable risk levels. This paper covers side packing, slot wedging, coil jumping, single bar replacement or neutral and phase inversion. We explore these topics both in this publication and in future articles.

# Table of Contents

# The challenge: Operating hydropower generating equipment

Operating and maintaining hydropower plants brought many challenges at the turn of the 21st century. There's no denying that conditions are increasingly difficult.

**Equipment fleets are aging.** In fact, new medium and large power plant projects are becoming increasingly rare. In Canada, some projects (Site-C, Muskrat Falls, etc.) can still be justified, even if there are increasingly numerous obstacles (environment, social acceptability and everincreasing costs). Even after the projects have started, further work needs to be confirmed along the way because of political and economic changes. Admittedly, a hydropower project takes a long time to materialize (often close to 10 years). As such, the environment (political, economic and technical) has time to change. Also, good sites for power plants are becoming increasingly rare and remote from users. The situation in the United States is even worse because the population is denser and the sites have been harnessed for a longer time. More and more equipment is operated beyond its designed service life expectancy. Some generators are currently running with original rotors that are over 90 years old, and it is not uncommon to see cores and even stator windings that are over 60 years old. **Most North American hydropower generating equipment has exceeded, or is on its way to exceeding, its designed lifespan.**

In addition to aging equipment fleets, we are facing a loss of technical knowledge. In fact, economic constraints are forcing many operators to avoid replacing qualified employees who are retiring. In other cases, experienced staff is replaced by inexperienced staff, without support. Consequently, some organizations have a team composed of experts who are nearing retirement and young graduates, but no mid-career group to ensure knowledge transfer. The remoteness of new equipment manufacturing sites also decreases the number of local experts available to assist operators.

**Repair costs are increasing**. Inflation is being felt. Management becomes crucial, as each project has its own set of details (span, schedule, restoration, repairs or power increase,suppliers closing down, etc.). Health and safety requirements have also evolved, especially for site installation, forcing managers to improve planning.

**The change in how equipment is operated** following deregulation, and the introduction of alternative power generation, such as wind turbines, is forcing operators to consider shorter shutdowns. Additionally, stop/start frequency had to be increased to compensate for the nonconstant alternative generating capacity, which accelerated component aging.

Operators are thus faced with equipment fleets that require more and more care, in an ever more restrictive environment, with staff who have suffered a considerable loss of knowledge. New maintenance strategies must be developed in order to operate equipment optimally. It is with this in mind that we are writing this series of white papers, to help operators get the most out of their equipment. In this first article, we will focus on the stator winding. The stator winding is the part of hydropower generating equipment that has the highest maintenance costs. Not only because of expensive parts and their installation, but also due to the long production shutdown that occurs and the risks associated with stator winding operations

# The culprit: The stator winding

With stator windings in the current fleet of hydropower generators in a widely varied state (because of their age, manufacturing type, manufacturer, use, etc.), it is important to fully understand their characteristics. Unfortunately, not all stator windings are made equal and, as a general rule, they are predicted to have a lifespan of over 25 years. In reality, we hope for a useful life of 40 years or more, and there are windings that have been in operation for over 60 years. This may sound like a lot to a neophyte, in a world where everything is ephemeral. However, we must bear in mind that the power plants in which they operate are made to last over 100 years, and as long as molecular elongation problems do not arise, a long lifespan is quite feasible.

Based on their experience and knowledge of operation, maintenance and installation information, as well as familiarity with the different types of windings (their weaknesses and strengths), experts have an idea as to the remaining service life of a stator winding. However, the age, supplier, place of manufacture, as well as the generation to which the winding belongs, must also be considered. Installing a winding (especially one that is coiled) is an art; even the best winding can be at risk if it has been improperly installed. Following the appropriate procedures and using qualified staff are imperative to get the most of each winding. The difference is often found in the details. In many instances, a proper inspection makes all the difference. What expert has not found forgotten tools in a generator? Poorly impregnated lashings? Or bolts incorrectly tightened or not tightened at all? As a guide, here is a nonexhaustive list of the types of stator windings that are still found in our hydropower units.

**Table 1: Types of stator windings in hydropower units**

| Winding type | Characteristics | Installation and parts |
|---|---|---|
| Coil | ▪ The most common in America<br>▪ 100-MW units and - | ▪ Requires more know-how to install<br>▪ Less expensive to buy |
| Bar | ▪ More common in large units 100-MW and + | ▪ Easier to install, especially in case of breakage<br>▪ More expensive to buy |
| Concentric | ▪ Less popular<br>▪ Low-power generating units manufactured before the 1970s | ▪ Very complex installation<br>▪ Few manufacturers still make them, making it difficult to find replacement parts |

Not only can the winding type vary, the generation and insulation used also play a role when it comes to understanding and assessing a stator winding. Insulation has evolved with available technology over the last 100 years. The base materials from the beginning of the last century (silk, cotton, wood, asbestos, paper, mica flakes, etc.) have been replaced by more standardized materials (glass fibre, mica dust, polyester fibre). But it is, above all, the binder that is the most important characteristic of the different generations of insulation.

Les tableaux ci-dessus montrent que plusieurs types de bobinage existent et que plusieurs variantes sont apparues au fil du temps, avec des recettes propres à chaque fabricant. Or, chaque type de bobinage a ses forces et ses faiblesses.

**Table 2: Types of stator winding insulation**

| Isolation type | Manufacture / Materials / Insulation class | Characteristics |
|---|---|---|
| Asphalt | ▪ Thermoplastic<br>▪ The standard before 1960<br>▪ Glass fibre, mica flakes, asbestos<br>▪ Class A or B | ▪ Flexible<br>▪ Installation through heating<br>▪ Forgives small core movements |
| Polyester – VPI hybrid | ▪ First thermosetting (1950)<br>▪ Mica flakes, glass fibre<br>▪ Manual taping<br>▪ VPI + polymerization under press<br>▪ Class B or F | ▪ Retains some flexibility<br>▪ Solvent evaporates with time<br>▪ Requires lateral packing |
| B-stage epoxy – Expensive | ▪ From 1960<br>▪ Mica dust, glass fibre<br>▪ Polymerization under asphaltic compound<br>▪ Class F | ▪ Very rigid, difficult to install<br>▪ Better resistance to thermal and electrical stresses |
| B-stage epoxy – Economical | ▪ From 1975<br>▪ Same materials as *B/stage epoxy – Noble*<br>▪ Class F with polymerization under press<br>▪ Variant with class B end turns | ▪ More difficult to install, fragile end turns<br>▪ Good lifespan, if properly installed |
| VPI epoxy | ▪ Tape, mica dust with or without a catalyst<br>▪ VPI and oven polymerization in forms | ▪ Similar to B-stage epoxy – Economical |

The tables above clearly show that several types of winding insulations exist and that several variants have appeared over time, with recipes specific to each manufacturer. However, each type of winding has its strengths and weaknesses.

Asphalt windings (tar derived from petroleum) were the standard before the 1960s. They were easily installed because the tar would become flexible when heated (in the oven or by electrical resistance), and the hot coil was pressed and formed permanently in the slot, moulding the shape of the core. Therefore, there was no space to be filled after its insertion. In addition, its flexibility in operation adapted well to small core movements. Its primary handicap was and remains its maximum operating temperature. Recognized as being part of class A (see table below), its maximum operating temperature is 120°C, but at this temperature, its lifespan is too short. Operating temperatures should be maintained at 100°C or less to expect a lifespan of 30 years or more. In fact, the average temperature was 80-90°C, and many of these windings are still in operation today, after more than 60 years.

From the 1950s and1960s, organic chemistry developed resins or chemical compounds, making it possible to use higher operating temperatures. These resins, called thermosetting resins, could not be softened by heating, which greatly complicated installation. The manufacturing procedures had to be modified to ensure safe installation. The most popular resins were epoxy and polyester-based (or variants). They are part of insulation classes B and F, which are still used today. Polyester provided more flexibility, while epoxy offered better chemical and thermal resistance. Installation required a lateral gap between the winding and the side of the slot, which had to be filled after the winding was inserted. Over time, we realized the importance of the

material used to fill this gap: from asbestos at the beginning, then insulating material and finally, today, semiconducting material. This material can be wrapped around the winding, glued on or inserted as a board. For more rigidity, it can also be combined with other materials (polyester fabrics, silicone, etc.) or semiconductors. The fact remains that to install these coils, they must be deformed. As they are very rigid, cracks can form in the weak points (end turns).

**Table 3: Insulation temperature class**

| Thermal class | Associated letter | Temperature allowed | Thermal endurance | Operating temperature |
|---|---|---|---|---|
| 90 | | 90°C | >90 - 105 | |
| 105 | A | 105°C | >105 - 120 | <90°C |
| 120 | | 120°C | >120 - 130 | |
| 130 | B | 130°C | >130 - 155 | <105°C |
| 155 | F | 155°C | >155 - 180 | < 120°C |
| 180 | H | 180°C | >180 - 200 | |
| 200 | N | 200°C | >200 - 220 | |
| 220 | R | 220°C | >220 - 250 | |
| | S | 240°C | | |
| 250 | | 250°C | >250 | |

# The solution: Inspect, assess and extend the remaining service life

As mentioned above, not all windings are made equal. We also saw that installation is a determining factor for sustainability. How the generator is operated (temperature, frequent stops) also plays an important role. Each stop/start sequence creates a thermal cycle which, due to the elongation differential of various components, imposes mechanical stresses that gradually reduce the remaining service life of windings. In the most severe cases, delamination can occur inside the insulation which, combined with other factors (thermal, electrical), can lead to the demise of the winding. It is difficult to accurately "measure" the remaining service life of a winding. Different tests exist (ramp tests, partial discharge readings, etc.), and we will revisit this topic in another article.

It is imperative to perform a physical inspection of the winding. Several signs of weakness can be detected before the situation deteriorates. We look for:

- Loose slot wedges (tap test)
- Slot wedges that have moved
- Signs of partial discharge (white powder)Des signes de décharges partielles (poudre blanche);
- Foreign materials
- Dirty winding (oil, carbon dust or other)
- Poorly lashed serial or group connections
- Missing or free blocks
- Free or broken circuit or supporting ring supports
- Gaps between the core laminations
- Gaps between the winding and the side of the slot (side packing)
- Etc.

An experienced eye can detect concerning situations and possible solutions to extend the useful life of a winding. A comparison with units from the same generation and/or same manufacturer can help us gauge the seriousness of any anomaly found in the winding. Estimating the remaining service life remains a highly inexact science, but with standard tests and a proper assessment and inspection, we can get a good idea.

Depending on the condition of the winding and the level of acceptable risk, the best solution might be to order a winding set and install it at the right time. Planning the best time for replacing a winding may reduce costs, compared to an emergency rewind (for example, during peak periods), and shorten the shutdown time. This is a risk-management issue: a winding can cost millions of dollars and the energy loss can be even more expensive.

In most cases, there are immediate winding options, such as:

- Re-wedging
- Changing the side packing
- Changing the defective bars
- Shorting the defective coils off
- Neutral and phase inversion

We'll cover these options in a future paper in this series.

# Conclusion

A variety of stator winding types (coil, bar and concentric) can be found in our hydropower generating units. The lifespan of these windings varies depending on the use, type of insulation system used (asphalt, polyester, epoxy, B-Stage, VPI, etc.) and on winding maintenance. The stator winding is the part of hydropower generating equipment that has the highest maintenance costs due to material prices, installation complexity, production loss and risk of unplanned breakage. With the loss of knowledge among most operators and aging generating fleets, it is imperative to develop a maintenance strategy incorporating specialized tests and regular inspections and assessments. Assessing the stator winding is key to sound equipment management, as well as extending the remaining service life of the winding.

This publication is part of a series of articles aimed at lifting the veil on this aspect of powergenerating equipment.

# About our expert

François St-Germain, P.Eng.
Mechanical Engineer specialized in hydro turbines and generators
francois.st-germain@bba.ca

Over the course of his career, Mr. St-Germain has developed strong expertise in the field of hydro generation. He namely worked as a generator designer in GE Hydro's refurbishment group and provided on- and off-site technical assistance for the diagnosis of hydro turbine and generator failures.

Since joining BBA in 2008, he has been involved in power increase studies, hydro generator audits, development of a generator design simulation program, vibration analysis studies, and preparation of many technical specifications and installation procedures. He also participates in the start-up of hydro generator units.

BBA.CA