Hydro Generators
Inspecting Stator Windings

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September 2019

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Executive summary

Today, maintaining hydroelectric power plants is fraught with challenges, especially because of aging equipment and fewer qualified workers. In an initial article entitled "Introduction to Stator Windings" (BBA, 2019), we established that stator windings are the part of hydroelectric generating equipment that has the highest operating and maintenance costs and carry the highest risk; the next logical step is to write an article outlining inspections and assessments.

Since stator windings in the North American fleet of generators have reached or exceeded their life expectancy, it is imperative to adopt an appropriate maintenance and management strategy. Replacing aging equipment with new equipment is an obvious and easier way to manage risk; however, this requires major investments and therefore might be delayed.

Rigorous and orderly inspection and assessment of stator windings can extend their lives by implementing effective strategies. This article simply explains the steps necessary to do this. In particular, we take an inventory of useful IEEE standards, typical tests and elements to consider when performing the visual inspection.

Assessing the remaining life of windings relies primarily on available site information combined with the results of the visual inspection and electrical tests. This information helps provide an overview of stator windings. After which, experts can develop a strategy based on experience and knowledge, as well as comparing other windings of the same type, from the same supplier or the same generation. This strategy includes a task schedule as well as the related cost estimate and risk assessment.

Table of content

Challenges to increasing the useful life of stator windings

There are many challenges to maintaining hydroelectric power plants. Of course, as mentioned in the previous article entitled "Introduction to Stator Windings", conditions are becoming increasingly difficult.

Aging equipment fleets. In Canada, the average age of hydroelectric generators is over 50 years; so, it is crucial to have an effective plan to maintain this aging fleet. It should also be stressed that there has been a **drop in experienced personnel**, which does not improve the situation.

Maintaining and extending the useful life of hydropower generating equipment must be carried out in an integrated manner. To create maximum value for operators, a **comprehensive assessment of equipment** must be performed before planning any work. When you have an overall picture of the condition of the equipment, you can target work on components that need it the most or combine tasks to shorten downtime. In fact, an investment strategy can also be established; this also falls under asset management, which goes beyond what is covered in this paper.

In the previous article, we determined that stator windings were among the most expensive hydroelectric generating equipment as regards maintenance costs, not only because of the cost of parts and their installation, but because of production shutdowns, whether planned or not. So it is natural to focus on this piece of equipment first. An assessment must be performed before considering extending the useful life of stator windings. This step provides us with a better idea of their condition and then enables us to establish proper work strategies.

The inspection and assessment stages are very important because that is when assumptions or presumptions can be confirmed or rejected. It is important to understand that generators represent a "black box" to many stakeholders; since it is a component on which work is rarely carried out, there is very little information available. Additionally, presumptions are persistent: it is very risky to compare windings from different generations, installed in different generators and functioning under their own operating conditions. For example, a 60-year-old, asphaltinsulated winding can still have several years of useful life if it has been operating at a low temperature (80–100°C) under designed operating conditions. On the other hand, a 25–30-year- old winding that has been subjected to numerous starts and stops and having withstood maximum temperatures of 120°C in a poorly assembled core is possibly ready to be retired. Every situation is unique. It is a plus to be able to compare generators with other similar generators, but only inspections and assessments will determine what happens next.

The solution: An inventory of available information, inspection and assessment

Step 1 – Inventory of available information

The first step in stator winding inspections and assessments is to collect and organize available information about the winding. This work must be performed jointly with the plant owner, and more specifically with the team responsible for operating it. The best solutions come from combining external expertise with available information. The information available at the power plant (drawings, history, etc.) must be considered.

Here is a non-exhaustive list of information to keep in mind:

- Winding age (is it younger than the generator itself?)
- The supplier's technical drawings and specifications for the current winding
- Results from routine inspections and trends
- List of work carried out on the winding since its installation
- Previous equipment reports
- Investment plans for the power plant, including the generating unit
- Problems (or incidents) encountered by this unit
- Changes made to the equipment around the winding (new wheel, original core or not, etc.)
- Presence of spare parts
- Load fluctuations (power, power factor, number of starts and stops, etc.). The analysis of the recorded PI data is a good way to know the history of the alternator's behaviour.

In order to have a proper equipment overview, an action plan can then be developed to finish acquiring data, including:

- Visual inspection
- Winding tests

After these steps are completed, the assessment can be performed. Most of the time, visual inspections and tests of windings are performed in unison: the order these steps appear in this article does not necessarily represent the sequence in a project

Step 2 – Visual inspection and standard tests

Standards

A proper inspection, supported by an adequate test plan, is the best way to assess the remaining life of stator windings. Specialized associations have produced a series of standards that can be very useful for stator winding inspections and assessments. Take advantage of the winding inspection to examine other parts around the generator such as the core, the frame and especially the rotor. The purpose of this article is not to reproduce the content of these standards, but rather to guide operators in their work.

Here is a list of IEEE[1] standards that might be useful when assessing windings:

Table 1: List of useful IEEE standards

IEEE standards
IEEE Std 43™-2013, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery
IEEE Std 56™-2016, IEEE Guide for Insulation maintenance of Electric Machines
IEEE Std 67™-2005 (R2010), IEEE Guide for Operation and Maintenance of Turbine Generators
IEEE Std 95™-2002 (R2012), IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) with High Direct Voltage
IEEE Std 115™-2009, IEEE Guide for Test Procedures for Synchronous Machines Part I Acceptance and Performance Testing Part II Test Procedures and Parameter Determination for Dynamic Analysis
IEEE Std 492™-1999 (R2011), IEEE Guide for Operation and Maintenance of Hydro-Generators
IEEE Std 1415™-2006, IEEE Guide for Induction Machinery Maintenance Testing and Failure Analysis

[1] Institute of Electrical and Electronics Engineers

IEEE standards
IEEE Std 1434™- 2014, IEEE Trial-Use Guide to the Measurement of Partial Discharges in Rotating Machinery
IEEE Std 1665™-2009, IEEE Guide for the Rewind of Synchronous Generators, 50 Hz and 60 Hz, Rated 1 MVA and Above
IEEE Std C50.12™-2005 (R2010), IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above
IEEE Std 56™-1977, IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10,000 kVA and Larger)

Standard tests

The EPRI[2] also publishes guides that could be useful. Test results performed on each generator must be tracked to see whether or not a trend can be detected over time. Every inspection should therefore be accompanied by a series of tests to confirm winding condition.

At the very least, the following tests should be performed:

- Measuring resistance for each circuit or phase, or the series resistance of each circuit. This is to detect bad connections, faults in succession, etc. It is unacceptable to have a difference of over 0.5% between each circuit or phase.
- Measuring insulation resistance (between copper and grounding). The Megger value should be at least equal to the generator's rated voltage in kilovolts (kV) plus 1 megohm (MΩ) at 40°C, corrected for temperature. A test voltage of 500 to 5,000 is used for 1 minute.
- Measuring the polarization index (PI) on each circuit of each phase. This test compares the insulation resistance value obtained after 10 minutes to that obtained after 1 minute. The higher the index, the better the insulation. For modern thermosetting windings, the index must be 2.0 or higher (Class A insulation = 1.5 / B and F = 2.0). If the index value is lower, there could be a problem, which must be investigated. This type of result can be caused by moisture inside the insulation from prolonged shutdown of the unit during wet periods or when cleaning the winding. To eliminate this possibility, the winding can be heated (by injecting high current or heating the winding enclosure) and the space ventilated. Another option is to turn the rotor without load (speed no load); this powerful air movement is very effective in drying equipment.Once dry,

[2] Electric Power Research Institute

if the index is still too low, it could be a connection problem (poorly polymerized resin, insulation, dirt, etc.); it is therefore best to call on an expert.

- Maintenance overvoltage should be performed after repairs.

Operators might want to perform a dielectric strength test (Hipot test) to confirm the satisfactory condition of the winding, so the winding age and condition will have to be taken into account. The overvoltage should not be as high as that used in new condition (2E + 1,000). [3]Table 2 can be used as a guide; however, it must be understood that a Hipot test can be destructive. So it is up to clients to accept the value proposed by the expert, taking into account the generator age and condition as well as the desired level of risk management.

It is also a good idea to perform a DC overvoltage test; this has the advantage of being much easier to perform (equipment, safety, etc.) and much less destructive than the dielectric strength test (Hipot). Tracking the leakage current will enable technicians to stop testing if a sudden increase in leakage is observed. This method is equivalent to carrying out a ramp test. The values in Table 2 are AC; a factor of 1.7 is generally used to determine the DC test voltage.

DC value = AC value x 1.7

For a 40-year-old generator in good condition and operating at 13.8 KV, cleaned and suitably dried (to be checked using the polarization index), the value to use would therefore be:

DC value for 40-year-old equipment = 12,400 x 1.7 = 21,000 Vdc

This value represents an overvoltage of 50% for winding coils with the greatest demand (circuit head [13,500 Vdc = 13,800 Vac/√3*1.7]) and provides an acceptable level of risk management for this type of winding.

Before performing the overvoltage test, you must check the polarization index (PI).

[3] E = rated generator voltage

Table 2: Overvoltage tests for stator windings

Rated generator voltage (E)	New winding	Warranty period			
		0-5 years	5-20 years	20-35 years	35 years or more
	2E + 1,000	.85 (2E + 1,000)	.65 (2E + 1,000)	E	.90 E
2,400	5,800	4,930	3,750	2,400	2,150
4,160	9,320	7,900	6,050	4,160	3,750
6,600	14,200	12,100	9,250	6,600	5,950
11,000	23,000	19,550	14,900	11,000	9,900
12,000	25,000	21,250	16,250	12,000	10,800
13,200	27,400	23,300	17,800	13,200	11,800
13,800	28,600	24,300	18,600	13,800	12,400
16,000	33,000	28,050	21,450	16,000	14,400

In addition to this series of electrical tests (Megger, PI and Hipot), it is a good idea to check partial discharge values (if the generator is equipped with couplers). This test can be performed on the entire winding when the unit is online. As a general rule, at least two capacitive couplers are installed per phase to eliminate indications from outside the winding. Partial discharges (PD) can also be measured on a portion of the winding (e.g., TVA/Corona probe). Interpreting the PD values is more complex than for the polarization index (PI); it requires more knowledge and experience. The PD values must be compared with those of other similar coils to follow their trend. An investigation is required if the value increases by 30% or more in six-month intervals for three or more consecutive readings; a problem might develop inside the stator.

There can be multiple PD causes: bad lateral wedging of bars or windings in the slot, destruction of the semi-conducting or gradient paint, vacuum inside the insulation, vacuum between the copper and insulation, casting between connections, etc. A visual inspection could help determine causes. It has become more common in recent years to use partial discharge measurements. It usually takes at least three sets of results before they can be used. Measuring PDs under different operating conditions (power, operating temperature) can help determine the type of discharge involved.

Other electrical tests can be performed: TVA/Corona probe, dissipation PF, AC overvoltage, etc. These tests are valid and can be performed in addition to the tests mentioned above. However, it is best to standardize tests for comparison purposes and to perform other types of tests in case of specific issues.

Visual inspection

Visual inspections are a must. Experts use their experience to identify elements that need to be observed during the inspection because they understand what the weak points are for various winding types and generations. They can prepare a checklist and photos to take, and document the evolution of the winding's general condition. Using this information, experts can differentiate between normal aging and a situation that requires work; as such, they can suggest strategies to extend useful short- and medium-term life. By considering the visual inspection, test results, the age of the winding and its past maintenance, as well as the type of operation, experts get an overall idea of the winding's condition. Again, risk management and financial aspects remain key in assessing the general situation.

This is a list of elements to observe when performing the visual inspection:

- Loose slot wedges (tap test)
- Slot wedges that have moved
- Signs of partial discharge (white powder)
- Signs of fretting
- Foreign bodies
- Dirty winding (oil, carbon dust, etc.)
- Poorly lashed serial or group connections
- Missing or free spacing blocks
- Free or broken circuit or supporting ring supports
- Gaps between core laminations
- Gaps between the winding and the side of the slot
- Etc.

Step 3 – The assessment

The assessment is crucial: this is when expertise is the most essential. Existing information as well as test and visual inspection results must be balanced to produce a useful document for operators. This report must reflect available information, provide a statement about equipment condition and propose a work strategy. This strategy must take into account the technical assessment, associated risk assessment, production requirements and the financial impact of various proposed options.

Complex situations should not lead to fuzzy strategies. Rather, options must be clearly shown and the impacts of the actions described in detail. Even if the assessment of the winding condition is somewhat uncertain, the conclusions and assumptions used must be clearly defined.

Continual monitoring is very important when it comes to equipment that can survive past a generation of experts. It is therefore vital to present work already performed and include new information and knowledge in the assessment report. The report must include the sequence of work to perform on the equipment in the short-, medium- and long-term. It is also best to use standard inspection sheets to ensure no important points have been overlooked.

Conclusion

Most stator windings in North American hydroelectric power plants have reached or exceeded their life expectancy, so it is imperative to adopt a proper maintenance and management strategy. Replacing aging equipment with new equipment is an obvious and easier way to manage risk, but it also requires the most investment and therefore might be delayed.

Rigorous and orderly inspection and assessment of stator windings can extend their life by implementing effective strategies. At this stage, the IEEE or EPRI standards can be very useful. Additionally, it is important to use the same methodology to compare results from different generators, or to compare the results of the same generator over time. This comparison must be based on a series of dielectric tests and standardized visual inspections.

This article is the second in a series aimed at lifting the veil on stator windings. The next article will focus more specifically on repairing stator windings.

About our expert

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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.

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