Timing for Generator Rewinds: Bridging the Gap between Statistical Methods and Condition-Based Monitoring

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ABSTRACT

Predicting the optimum timing to carry out a generator rewind can be one of the most important economic decisions faced by the manager of a hydroelectric facility. The capital expenditure of such an undertaking is significant and the warning signs (which indicate that the aging winding is due for replacement) are not always clear. Furthermore, the consequences of a winding failure can be economically disastrous to the utility if certain failure modes should occur.

The tools most commonly used to predict when the windings should be replaced are known as condition-based monitoring tools. This includes partial discharge analysis, corona discharge, ozone, stator bar vibration, Doble, and other forms of on-line and off-line monitoring techniques. Unfortunately, these methods are largely "relative" by nature and require baseline readings and trending over time to determine the sudden, or gradual, onset of insulation deterioration. These techniques typically require experienced technicians to interpret the results and do not always consider the economic consequences of an equipment failure.

Recently, statistical methods have been utilized to determine the optimum time to rewind a generator. These tools utilize industry-based failure-probability curves and take into consideration the consequences of a failure in order to quantify the risk. Unfortunately, the statistical approach does not always take into full consideration the results of condition-based monitoring tools.

In order to bridge the gap between statistical methods and condition-based monitoring, Acres International and Adwel International have been working together. This paper will present the key findings of this association on the course of establishing the ultimate tool to predict optimum timing to rewind a generator.

Introduction

Unlike most of the major components in a hydro generator, stator windings do not generally have life expectancies of greater than 50 years. This is primarily due to the considerable demands imposed on the windings by several different mechanisms. Stresses induced by electrical, thermal and mechanical factors all contribute to service conditions far more severe than for most other generator components. These factors, combined with the essential function of the windings and the consequences of a failure, have led to the introduction of numerous condition monitoring devices and tools to assist the owner in deciding when is the right time to replace or rehabilitate the windings.

In this paper, a new method is introduced which will provide owners with a means of predicting the optimum timing to replace generator windings. Unlike other approaches which have preceded it, the current method combines the statistical experience gained through thousands of machine operating years with risk assessment techniques as well as the condition indicators specific to the equipment being evaluated.

Why do Generator Windings Fail?

In order to gain a better appreciation for the method being introduced, it is important to understand the primary factors that typically cause, or contribute to, winding failures. Given the large variation in winding design, materials, manufacturing methods, installation, service and maintenance conditions, it is impossible to consider all factors leading to failure. The listing below, however, covers the problems which are most frequently experienced with windings in large hydro generators.

Design, Manufacturing and Installation

With the increase in generating unit capacities and improvements in materials technology, designers have adopted higher performance epoxy insulation systems, which have subsequently provided higher copper-to-insulation ratios. This has been achieved through enhancements to the thermal characteristics of the insulation. The increased conductor cross section of the new thermoset insulation systems results in reduced losses while the thinner winding insulation improves the heat dissipation to the core.

Several manufacturing processes have been developed over the years in the manufacture of stator windings with epoxy insulation systems. The two types most commonly in use include resin-rich insulation systems and resin-poor insulation systems. The materials, manufacturing techniques, process control and shop testing methods used for both types can have a significant influence on the life expectancy of the end product.

Unfortunately, the careful control of manufacturing processes typically in use today does not necessarily reflect the quality control and methods in use 30-50 years ago. For these older in-service windings, however, there is a wealth of knowledge which can be gained through the analysis of statistical failure data and the use of this data to predict the probability of future failures.

Service and Maintenance History

The service history for the windings plays a major role in the winding end-of-life. This includes the number of operating hours and load demand placed on the windings, for example, the absolute operating temperature of the winding. It is commonly accepted that winding operating temperature has a close correlation with remaining life. Additionally, the number of starts/stops on the machine affects the thermal cycling of the windings and the generating unit over its operating life. Thermal cycles cause expansion/contraction, loosening of wedges and therefore vibration and relative movement of the windings within the slot.

Maintenance frequencies and repair history is also a key factor affecting the remaining life of the stator winding.

Failure mechanisms

Hydro-generator stator windings may fail due to a number of different aging mechanisms and factors. These mechanisms can be classified into four causes including electrical stress, thermal stress, mechanical stress, and environmental contamination. Each cause is described below:

1. Electrical stress:

- Overvoltage stress
- Transient voltage stress
- Treeing and corona
- Insufficient space between endwindings or leads.

2. Thermal stress: The stator winding operates at high temperatures for extended periods of time. The high temperatures may be caused by:

- Overloading of the generator
- Degradation of the cooling system (e.g. blockage of air passages or coolers)
- Poor design of the cooling system
- Relative motion between bar and core due to thermal cycling
- Over-heating of the stator core due to short circuits between laminations.

The stator winding insulation can be oxidized at high temperatures, resulting in embrittlement, flaking, tape separation, and delamination. Consequently, mechanical strength of the insulation is weakened and partial discharge can occur under high voltages.

3. Mechanical stress:

- 120 Hz bar vibration;
- Bar motion due to deterioration of wedges, springs and packings
- Loss of bond between strands.

Loose bars (e.g. due to loose wedges) move in the slot against the stator core, causing abrasion of semi-conductive coatings and the groundwall insulation. Damage of semi-conductive coatings results in slot discharge. A ground fault is likely to occur if approximately one third of the groundwall insulation has been abraded.

4. Environmental contamination:

External contaminants can reduce the performance of the winding insulation as well as the winding support system. Contaminants include:

- Oil from overhead bearing leakage
- Water or moisture from cooling system leakage
- Abrasive materials (e.g. dust) transported in cooling air
- Pollution of conductive materials over the endwindings, causing electrical tracking which leads to phase-to-phase or phase-to-ground faults.

Several of the above factors may be responsible for, or contribute to, a stator winding failure.

Condition Monitoring Tools

Several condition-monitoring tools are commercially available to assess stator-winding condition.

Partial Discharge Analysis (Electrical Condition)

Partial discharge (PD) is both a cause and indicator of stator winding insulation problems. On-line partial discharge testing is the most effective means to monitor insulation condition of the stator winding. A portable partial discharge analyzer (PDA) can detect partial discharges under normal machine operation to determine stator insulation condition. Partial discharge can be detected through the following mechanisms:

- Discharge from between the outer surface of the coil and stator iron (slot discharges)
- From within internal voids of the groundwall insulation
- On the end turns of the windings (Corona)
- Adjacent to coil copper (deterioration of original copper-to-insulation bond).

Noise can be eliminated by PDA to ensure that false indication is not given. Installation of an on-line partial discharge system in a hydrogenerator is shown in Fig. 1. Severe insulation deterioration can be identified by trending PD test results. If PD activity significantly increases within a relatively brief period of time, the risk of winding failure would also increase dramatically.

Figure 1: Installation of Partial Discharge Sensors in a Hydrogenerator

Temperature monitoring (Thermal Condition)

Temperature monitoring can determine if the winding insulation is being exposed to thermal deterioration. Temperature is usually measured by RTD or thermocouples embedded between the coils in stator slots to monitor thermal deterioration of the stator winding in the stator winding. However, localized hotspots distant from locations of temperature sensors may not be detected. A rotor-mounted thermal scanner [6] can detect hotspots anywhere in the stator winding.

Vibration monitoring (Mechanical Condition)

Relative movement of winding bars in the slots can cause the winding insulation to be abraded, thereby giving rise to partial discharge and, eventually, result in a phase-to-phase or a phase-to-ground winding failure. Bar vibration, which is typically the symptom of loose wedges or loss of support from insulation dry out, can be detected by using capacitive sensors to measure bar movement. Trending bar vibration level provides on-line dynamic information on the condition of the stator winding, thereby giving an indication when it is necessary to rewedge the generator.

Wedge looseness can be manually checked by an experienced operator using a hammer. Recently an automatic wedge tightness detector (WTD) equipped with an electronic hammer has been commercially available. This computer controlled instrument can give a fast and objective assessment of winding looseness conditions.

Stator Bar Wetness (Environmental Condition)

Water leakage or excessive moisture in the stator can lead to the accumulation of moisture in the windings, which may cause delamination and swelling of insulating and support materials. A new stator bar wetness detector (SBWD) has been developed to monitor such moisture within the stator bars [7]. Testing of moisture utilizes capacitance measurements which are trended over a period of time to assess stator bar wetness. Extensive field testing of the SBWD is being carried out.

There are other useful tools to assess stator winding condition, such as, ozone monitoring, air gap monitoring, insulation resistance testing, Hipot testing, power factor testing, etc.

Applying Risk-Based Management to Windings

The Acres model, HydroVantage utilizes Risk-Based Asset Management methodologies to analyze more than 100 components, such as turbine runners, generator windings, exciters, penstocks, gates, transformers, etc, in order to establish the optimum timing to replace or rehabilitate either a specific component, a group of components or an entire power station. In order to accomplish this, the software takes into consideration a large number of factors; including the component's age, condition, operating conditions, interaction with other components, rehabilitation costs, replacement costs, O&M costs and the consequences of a failure. One of the key features of the model is the method in which the optimum cost stream is determined using the inputs listed above, historical failure data (for future risk costs) and statistical probabilities.

The recently introduced, web-based version of the Acres model, HydroVantage, offers a number of features, which were unavailable in previous versions. This includes:

- Simulation of component interdependencies and outage concurrence
- Built-in failure-probability curves, costs, benefits and failure modes
- User-defined inputs through convenient web-based architecture.

A detailed description of the operation of the model may be found in any of a number of earlier publications [Ref. 1, 4]

Failure Modes

The key to all risk assessments lies in the identification of the appropriate failure modes. This identification process requires the organization of the large number of different historical failures into a manageable number of failure modes, each of which can be quantified in a statistical fashion. For the case of the stator windings, HydroVantage can be customized to simulate the various failure modes typically experienced by windings.

The failure of generator windings is typically characterized by the loss of only one coil per failure. Of greater significance is the incidence of failures leading to severe consequential damage, such as fire or core damage, thereby requiring extensive repair and long outage times. The quantification of the latter can only be accomplished based on historical failure probabilities.

Failure Probability

Failure-probability curves are derived from survivor data accumulated from various published sources as well as Acres experience data. The data is limited to synchronous hydroelectric machines having a phase-phase voltage of 2 kV or greater and a capacity of 5 MVA or greater. A typical failure-probability curve of a component is shown in Figure 2. It is important to stress that these curves are industry average curves and do not necessarily apply to a specific component which has been subjected to conditions very different from the average.

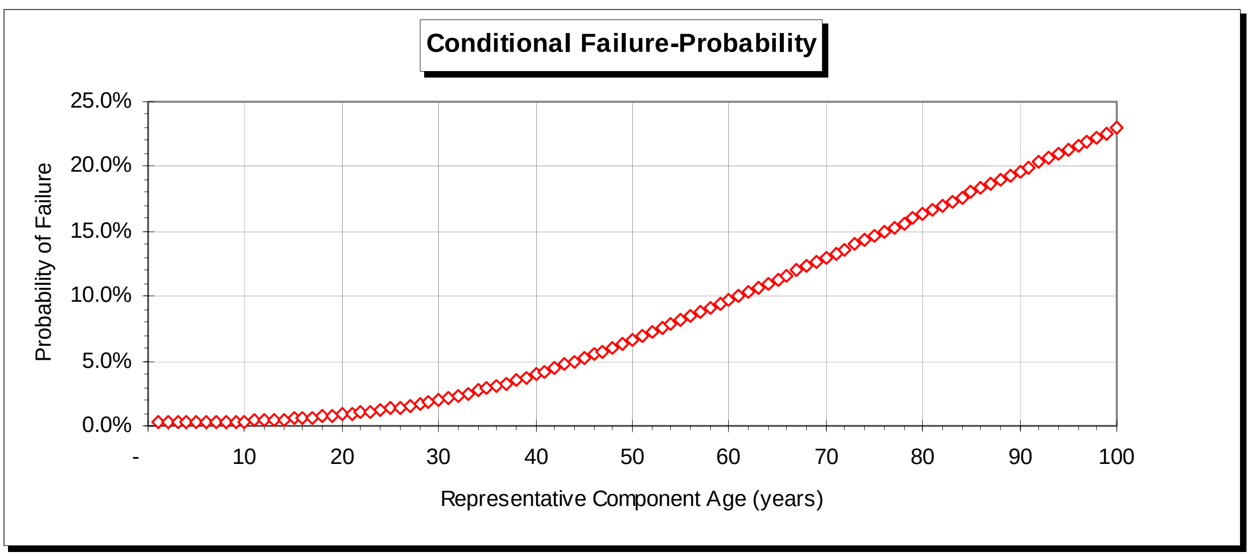

Figure 2: Failure-Probability Curve

Costs, Benefits and Consequences

In order to optimize the timing of the rewind, the model needs information for the base case "do nothing" scenario as well as the information on the planned rewind scenario. In the base case, the owner continues to operate the generator until winding failure occurs. The planned rewind is used by the model to compare the “do nothing” case. The specific information used by the model includes:

- Planned rewind costs including planned outage cost
- O&M costs before and after rewind/rehabilitation
- Consequence costs (in case of a failure)
  - repair costs
  - outage costs (i.e., lost revenue due to unit unavailability)
  - associated damage in case of a catastrophic failure
- Future benefits associated with the rewind due to improved efficiency and increased capacity.

Utilizing either default values or, if the user wishes, user-defined inputs, the model performs an automated optimization based on minimum net present value in order to determine the best timing for the planned rewind.

Bridging the Gap between Risk-Based Methods and Condition Diagnosis Results

Testing of electrical, thermal, mechanical, and environmental conditions of the stator winding is a diagnostic process. The purpose of such testing and diagnosis is to find out if the stator winding is at risk of failure. The previously described winding failure model uses experience-based failure-probability curves. This statistical method is based on machine age, previous winding failure history and experience. However, the application of a statistical model to a specific generator with severe problems has its limitations. As an analogy, it is well known that people have an average life expectancy of around seventy years. However, a 50-year old person with chronic health problems is far less likely to live to this age. To give an accurate assessment of the risk of stator winding failure, real stator winding condition must be incorporated into the winding risk assessment model.

Table 1 Generator Winding Condition Rating

	Failure Cause					Total
	Electrical (connections, system disturbances, PD, etc)	Thermal (cooling, heat transfer)	Mechanical (loose windings, poor geometry)	Defective Insulation (original manufacturing, installation)	Environmental Factors (water, oil, dust)	
Weighting Factor	38	14	29	10	10	100
Condition Factor*	0	1	2	0	-1	
Weighted Condition	0	14	58	0	-10	**62**

* Condition Legend

-1	Better than average
0	Satisfactory
1	Minor Problems
2	Consistent Problems
3	High Risk of Failure

In order to assess the probability of failure for a specific generator winding, taking into consideration its condition and history of problems, the following method has been developed. Using actual failure experience data, the five leading causes of generator winding failures were identified. Weighting factors were applied in proportion to the relative frequency associated with each failure cause. Wherever possible, the Condition Factor relates the condition of the generator winding under examination to each cause of failure, based on measurements obtained from condition based monitoring devices. Note that, a “zero” rating is considered to be “typical” relative to an industry-based standard. Thus, a winding with a score of less than zero would have a lower failure-probability than the industry and vice versa for a winding with a score greater than zero. These scores are fed into the HydroVantage model, which determines the probability of failure as it relates to the winding age and score.

As an example of a condition monitoring device, partial discharge testing can be used to provide an indication of the stator insulation condition. The best way to identify severe stator insulation problems is to trend PD activity in the stator winding over a period of time. If PD activity doubles over a six-month period, then it is likely that severe insulation deterioration has occurred. In Table 1, the Condition Factor under the “Electrical” heading would be assigned based on the measured PD level related to the industry average. Once severe insulation deterioration is detected by partial discharge testing, the winding failure-probability would be greater.

Other condition monitoring devices, including temperature monitoring and stator bar vibration are also taken into consideration in the evaluation of the Weighted Condition of the winding.

Conclusions

The prediction of the remaining life or the probability of failure for generator windings has historically been a rather unscientific process. Owners face the dilemma of either premature replacement (and major capital expenditure) or unnecessary risk of failure. The foregoing paper has presented a methodology which can be utilized to eliminate much of this guess work by considering all of the information the owner has on the specific winding as well as the industry-wide failure statistics. Furthermore, the method makes use of HydroVantage to include the consequences of a failure and all the features available therein.

The use of condition monitoring devices, such as the partial discharge analyzer, will bridge the gap which currently exists between statistical methods and the specific machine condition indicators. The quantification of these condition indicators and how they relate to the winding's probability of failure will continue to improve as statistical failure data on hydro generator windings is collected and processed.

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