A New Prognostic Approach for Hydro-generator Stator Windings

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ABSTRACT

Significant improvements in hydro-generator diagnostics were achieved, in the past decades, by using continuous online measurements and a number of periodic tests. In recent years, the diagnostic raw data has been converted into more useful information by way of integrated diagnostic systems that used expert knowledge. For example, an integrated methodology for hydro-generator diagnostics was developed at Hydro-Québec's research institute (IREQ) using a Web-based application. This comprehensive diagnostic system gives the degradation state of generator stator winding insulation by using a portfolio of diagnostic tools. Combining the results leads to a health index ranging from 1 (good condition) to 5 (worst condition). This system is used by Hydro-Québec's power plant managers as well as technical support and maintenance engineers in the context of condition-based maintenance (CBM). The next step of development is to add new prognostic-related features. This involves automatic identification of active failure mechanisms, root cause analysis and estimation of the stage of advancement of any active mechanism. These characteristics form the basis of predictive maintenance and support the optimization of maintenance strategies.

The approach is based on a number of causal trees (the failure mechanisms) formed by the combination of sequential physical degradation states that ultimately lead to a failure mode. Each combination of sequential physical states is unique and defines a particular failure mechanism. Failure mechanism analysis was followed by identification of all symptoms (diagnostics measurements, observations) with their respective thresholds defining each physical state.

This paper presents the development of a prognostic approach where the modeling of failure mechanisms is combined with observable symptoms from our diagnostic system for the identification of active failure mechanisms.

1. INTRODUCTION

In the case of hydro power generation plants, most of the forced outage time is due to the hydro-generator. Within the generator, the stator winding is the most critical part as it accounts for more than two thirds of the major failures as can be found in the 2003 CIGRE survey on hydro-generator failures.

For years, Hydro-Québec has adopted a maintenance strategy based on three types of maintenance: corrective, time-based and, more recently, condition-based, the last directly linked to diagnostic tests. An integrated generator diagnostic system implemented in 2008, provides information about the actual overall condition of all generators stator windings. This system ranks their condition for all Hydro-Québec power plants. The health index (I) ranges from 1 to 5, the highest being the worst condition (Hudon, Bélec, Nguyen, 2009). This information is used to prioritize the generators for maintenance. However, it does not suggest any particular maintenance action that should be performed in order to mitigate specific failure mechanisms affecting a generator stator.

In the past, a number of authors have worked on degradation state diagrams as a prognostic approach for maintenance optimization for hydro-generators and other equipment (Anders, Endrenyi, Ford & Stone, 1990; Sim & Endrenyi, 1988; Welte, 2009). Figure 1 shows an example of state diagram adapted from Endrenyi et al. (2001).

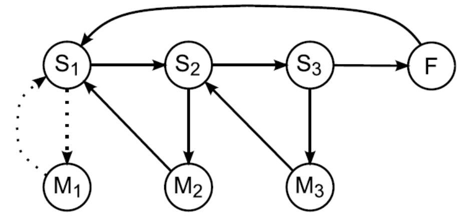

Figure 1. State diagrams including maintenance states (M1-M3) for a failure (F) following a three stages process (S1-S3). Endrenyi et al. (2001)

These state models were based on Markov or semi-Markov processes. However, they did not take into account the real physical states that can be identified by conducting a failure mechanism and symptoms analysis (FMSA) or a causal tree analysis as described in standard ISO 13379-1 on condition monitoring and diagnostics of machines (2012). They rather used health indices to characterize their degradation states as good, fair or bad for example. This type of approach does not lead to the identification of the specific maintenance action to perform within a particular physical state.

The approach taken in this work is to identify the specific failure mechanisms in play for any given hydro-generator unit in order to take the proper maintenance action. Currently, this requires that knowledgeable experts study all observable symptoms and relate them to all possible degradation mechanisms through the identification of the related physical states. Much of this tedious work could be performed by an automated prognostic tool.

In the context of existing prognostic approaches described by Byington, Roemer & Galie (2002) and shown in Figure 2, the proposed approach would fit the upper part of the prognostic approach hierarchy. It can be considered as model-based as it uses knowledge-rich information provided by a diagnostic portfolio that accounts for physical degradation states.

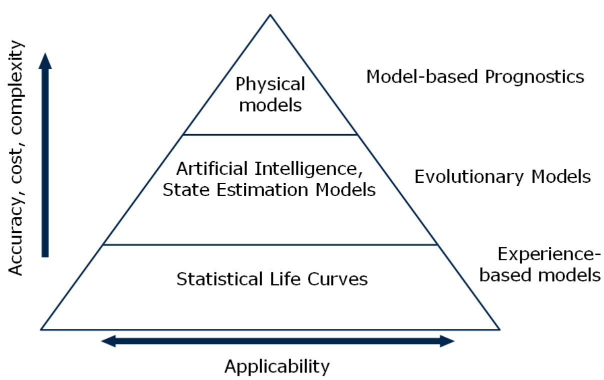

Figure 2. Hierarchy of prognostic approaches. Adapted from Byington et al. (2002).

Figure 3 illustrates how different maintenance strategies can coexist depending on the condition of components and subcomponents and information available about them. Since maintenance can be optimized through a predictive failure mechanism and symptoms analysis, the present work systematizes this approach. It is based on an analysis of the possible failure mechanisms for hydro-generator stator windings that was carried out by Nguyen & Yelle (2001). These failure mechanisms lead to one of the seven failure modes listed in Table 1. A failure mode is defined as the final stage of a failure mechanism, after which the equipment can no longer perform its function.

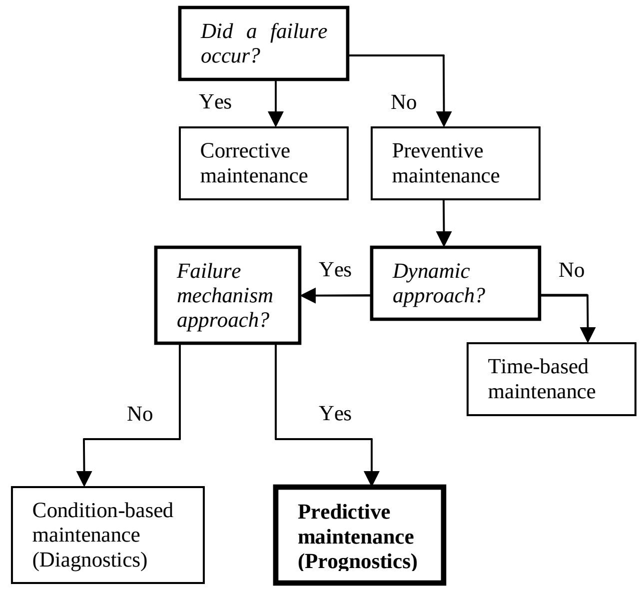

Figure 3. Existing maintenance strategies and their interrelations.

Table 1. Hydro-generator failure modes

f1	Phase-to-phase breakdown
f2	Phase-to-ground breakdown in the slot
f3	Phase-to-ground breakdown outside the magnetic core
f4	Excessive rotor vibration
f5	Loss of magnetic field
f6	Melting of damper bar
f7	Stator electrical connection failure

2. FAILURE MECHANISMS ANS SYMPTOMS ANALYSIS

A failure mechanism is any physical, chemical or other process that leads to failure. For generators, it originates from one or a combination of four stresses: Thermal, Electrical, Ambient and Mechanical (TEAM). As illustrated in figure 4, under these stresses, root causes are responsible for initiating the failure mechanisms in the same way as in a causal tree such as described in standard ISO 13379-1 (2012). Failure mechanisms result in a sequence of events leading from one physical state to the next. In this model, each physical state is labeled according to its stress category (for example e3 is an electrical process). Each sequence in Fig. 2 leads to a potential failure mode (f1…f6). Several mechanisms may sometimes be active at the same time, but only one will lead to failure. Each potential failure mechanism is defined by a unique sequence of physical states. For example, figure 4 shows three possible failure mechanisms given the available symptoms: (T1,t1,…,t4,f1), (T1,t5,…,e3,f3) and (A3,a6,..,e3,f3).

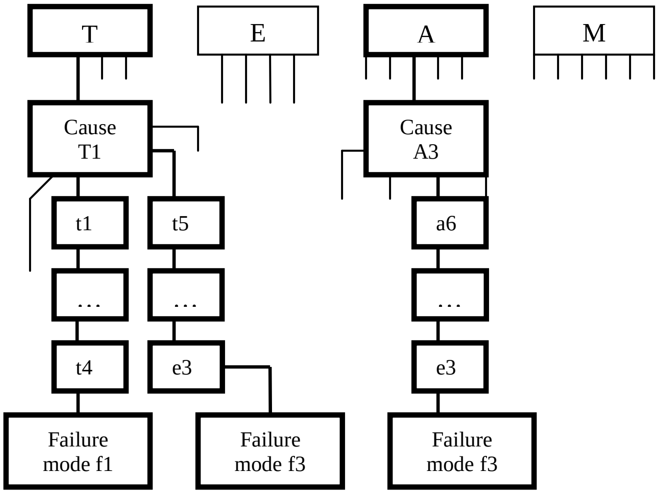

Figure 4. Three active failure mechanisms. Causes are in upper case and physical states are in lower case.

Table 2 shows, by category of stress, all root causes for each of the 111 failure mechanisms that were identified. Of these failure mechanisms, 8 are initiated by root causes related to thermal stress, 8 to electrical stress, 35 to ambient stress and 60 to mechanical stress. The number of intermediate physical states in these failure mechanisms is given in Table 3 for each type of stress category.

3. PROGNOSTIC MODEL

The prognostic model is based on automatic identification of the physical states from available symptoms. One specific set of symptoms, with their respective thresholds to comply with, defines one single physical state. Each characteristic symptom comes from the results of diagnostic tool measurements or visual inspections logged into our integrated diagnostic system for generators.

The health index of the generator is computed by combining individual diagnostic results but each diagnostic tool also provides detailed information (symptoms) that can be used to identify the generator's physical state at a given time. For instance, a generator's condition could come from combining partial discharge (PD) measurements, visual inspection input, and polarization/depolarization current. In addition to this overall index, it is possible to mine data to the level of symptoms and determine whether gap discharges, say, are accompanied by visual signs of powder between end arms and, if so, the number of such sites. These symptoms are the key to identifying active physical states. Table 4 overviews the actual diagnostic tools logged in the database and the number of detailed symptoms that each can provide. Note that the scope of such an analysis is currently being expanded to include other characteristics logged in other monitoring system, such as air gap measurement, temperature and vibration analysis.

Table 2. Root causes for failure mechanisms

Root causes per stress category	**Number of failure mechanisms**
***THERMAL STRESS* (T)**	**8**
T1 Thermal aging (normal operation)	3
T2 Accelerated aging (operation above specified rated temperatures)	3
T3 Aging due to thermal cycling (frequent start/stop operation)	2
***ELECTRICAL STRESS* (E)**	**8**
E1 Improper manufacturing or design of bars	2
E2 Poor semiconducting coating on the straight part of the bars (slot discharges)	1
E3 Poor design or manufacturing of end winding stress grading material (corona discharges)	1
E4 Insufficient spacing between end windings (gap discharges)	1
E5 Overvoltage transients	3
***AMBIENT STRESS* (A)**	**35**
A1 Conducting contamination (carbon, steel or copper dust)	6
A2 Non-conductive contamination (construction dust or oil)	9
A3 Moisture in ambient air	7
A4 Abrasive material attack	3
A5 Water leakage (cooling system failure, fire protection and spills)	10
***MECHANICAL STRESS* (M)**	**60**
M1 Loose windings	17
M2 Bad connection	6
M3 Presence of external objects or loose parts	5
M4 Mechanical shocks	4
M5 Projectiles	4
M6 Rotor and/or stator deformation	24

Table 3. Number of physical states per process

Types of process	**Number of physical states**
Thermal (t)	9
Electrical (e)	22
Ambient (a)	14
Mechanical (m)	35

Table 4. Diagnostic tools and detailed symptoms.

Diagnostic tool		Number of detailed symptoms
(1)	PD analysis (intensity, number) – PDAH	3-4
(2)	Phase-resolved PD – PRPD	6
(3)	Visual inspection	70
(4)	Polarization/depolarization currents (stator)	4
(5)	Ramped voltage current measurements	5
(6)	Semiconducting coating integrity measurement	2
(7)	Ozone concentration measurements	2
(8)	Dissection (postmortem)	23

Once problematic generators have been identified in our integrated generator diagnostic system (I=5), the prognostic tool analyzes the database for each of them to identify the most probable active failure mechanisms. In order to do so, a prognostic database was built including all potential failure mechanisms (sequences of physical states) and the set of symptoms with their threshold values associated with each physical state. Figure 5 shows an example of failure mechanism with the corresponding symptoms and thresholds defining the physical states.

Active failure mechanisms are identified automatically using the available symptoms obtained from diagnostic tools. A search engine was developed to retrieve the symptoms from the integrated generator diagnostic system and compare them to the defined symptoms with thresholds for each physical state in the prognostic database. The active failure mechanisms proposed by the system are then displayed. The list of active failure mechanisms clearly depends on the data available. When many diagnostic symptoms are available, the search engine usually displays fewer possible failure mechanisms with higher confidence. When only a few symptoms are available for the generator, more possible failure mechanisms are displayed with lower confidence. Work is currently underway on confidence levels to develop a feature that would automatically propose the best test to minimize the uncertainty of failure mechanism identification. Pinpointing this one mechanism is therefore the issue to address first.

4. FUTURE WORK

The main objective of using such a prognostic approach is to improve maintenance strategies. The key is to include in the database all maintenance actions for each physical state in the failure mechanisms. Figure 6 shows the two step process: available symptoms identify the active physical state and for each physical state a maintenance action is defined.

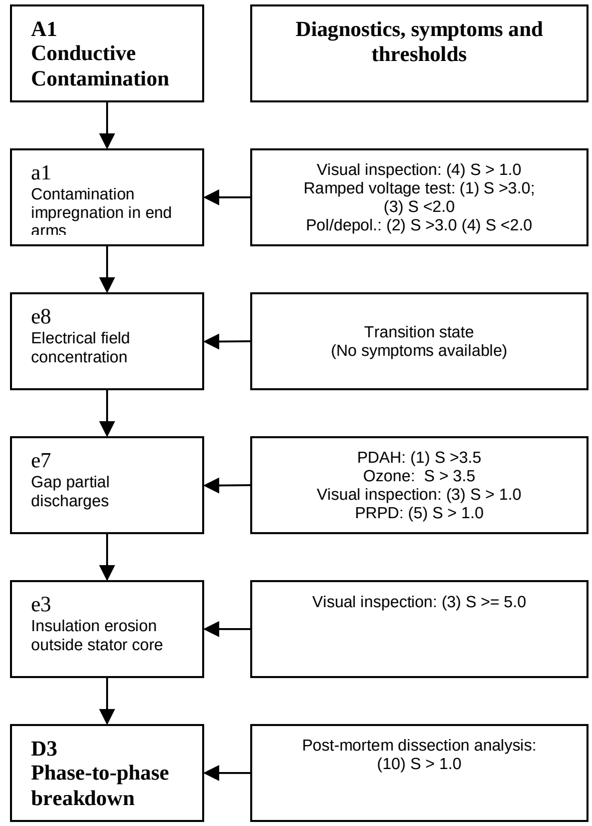

Figure 5. Failure mechanism with symptoms and thresholds defining physical states. Between parenthesis are symptoms pertaining to the diagnostics. S is the severity ranging from 1 to 5.

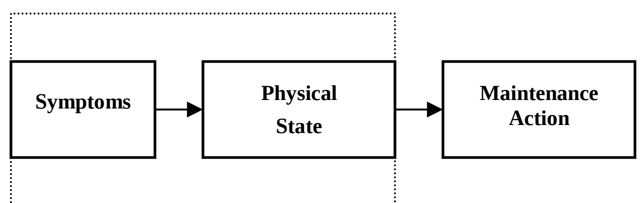

Figure 6. Symptoms identify the active physical state for which maintenance actions are defined.

The doted area shows what has been accomplished yet. Future work will consist in the identification of maintenance actions for each physical state in the prognostic database. This will enable the predictive maintenance strategy.

When an active mechanism is identified as the most critical, the system would thus propose customized maintenance action to solve the specific problem. Every maintenance action for a specific physical state would either completely restore the condition of the generator (“as good as new”) or just restore one of its previous physical state (“as bad as old"). The effect of every maintenance action for each state/mechanism must also be included in the database.

A corollary to the effect of maintenance is to determine the transition time between successive physical states as degradation evolves. This feature will allow us to know the proper timeframe for maintenance as well as the impact of performing the job before a failure occurs. Automatic analysis will also be extended to rotor degradation mechanisms and, most importantly, incorporate all economic considerations, e.g., the cost and duration of each maintenance action, and the loss of revenue in the event of a forced outage.

5. Conclusion

The development of a prognostic model was initiated in order to optimize future maintenance of hydro-generators. At this stage, the model consists of a database of potential failure mechanisms combined with automatic recognition of active mechanisms from symptoms that define physical states. Embedded in the database are all the criteria used to define the physical states. This may be viewed as a means of capturing expert knowledge. A search engine can already be used to data mine the integrated diagnostic system Web application, and automatically identify and sort failure mechanisms from the data available for each generator.

Many desirable features are not yet implemented, such as relating maintenance actions to physical states and estimating transition times between states, to name but two. Future work will address these features and also broaden the scope to the rotor. The prognostic engine will continue to evolve in the years to come and will be validated by case studies.

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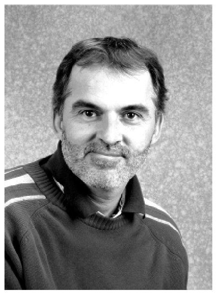
Biographies

Normand Amyot was born in Sorengo Switzerland in 1964. He received the M.Sc.A. degree in physics engineering from École Polytechnique de Montréal in 1990. He has worked one year at the Université des Sciences et Techniques (USTM) de Masuku in Gabon, after which he joined the Research Institute of Hydro-Québec (IREQ), where he is now employed as a senior research scientist. His field of expertise includes electrical insulation aging and characterization, diagnostic techniques, condition based maintenance and more recently prognostics. He is an active member of CIGRÉ working groups and member of IEEE DEIS. He is the author or co-author of more than 40 scientific papers.

Claude Hudon was born in Montreal, Québec, Canada on 21 December 1963. He received the Ph.D. degree in engineering physics from École Polytechnique de Montréal in 1993. He worked for two years at the Corporate Research and Development center of General Electric, after which he joined Hydro-Québec's Research Institute, IREQ, where he is now employed as a senior researcher. His fields of interest are generator and motor diagnostics, the development of diagnostic tools and the measurement and analysis of partial discharges. He is the author of more than 45 scientific papers.

Mélanie Lévesque was born in Chicoutimi, Québec, Canada on 24 November 1980. She received the PhD degree in electrical engineering from the École de Technologie Supérieure (ÉTS) of Montréal in 2012. Her PhD's degree was done in collaboration with the Research Institute of Hydro-Québec (IREQ). She is currently working as a researcher at IREQ on generator diagnostics.



Mario Bélec was born in Ste-Anne-du-Lac, Québec, Canada on 20 March 1962. He has received the B.Ing. degree in electrical engineering from École Polytechnique de Montréal in 1987. He joined the Research Institute of Hydro-Québec (IREQ) in 1987 as a researcher. As a generator diagnostic specialist, he has been involved in partial discharge recognition activity, and development of new diagnostic tools and correction methods for high voltage rotating machines. He is also working on a condition-based maintenance diagnostics methodology of generators. During the recent years, he is also working on development of partial discharge monitoring system for gas-insulated system (GIS). He is active member of IEC and CIGRE working groups. He is the author of more than 50 scientific papers.

France Brabant was born in St-Jerome, Quebec, Canada . She received a Bachelor degree in Computer Sciences from the University of Sherbrooke in 1988. Upon graduation she was hired by Hydro-Quebec for Field Testing, particularly in the opening of Post Radisson for the James Bay project. She joined IREQ in 2002 and has done software development for many innovation projects. Her specialities include object technology such as Java, UML, etc., human-machine interfaces, data processing, and programming in a Matlab environment .

François-Xavier Frenette was born in Montreal, Canada in 1991. He will receive, in December 2013, a Bachelor degree in computer science from the Université de Sherbrooke. During his studies, he did two internships at the Research Institute of Hydro-Québec (IREQ), where he mainly worked on developing web interfaces for two projects related to diagnostic tools.