Condition Assessment Manual

Appendix 1.09 - Guide for Generator Condition Assessment

Revision 1.0, 12/20/2011

Prepared by

MESA ASSOCIATES, INC.
Chattanooga, TN 37402

and

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Contents

1.0 General

The generator is a critical component in the powertrain of a hydropower plant. A failure of the generator stator can result in an extended outage and extensive repairs. Failure or degradation of other generator components may result in operation at reduced output or may result in catastrophic failure. While operation with a degraded condition such as aged insulation, cooler leaks or cracked structural components may continue undetected, a thorough condition assessment may avert a costly forced outage and can be used to justify upgrades and improvements. Generator reliability can decline with time while the annual cost of repairs and maintenance increases with time. Thus, rehabilitation and replacement of aging generator (or generator components) may become more economical and less risky than maintaining the original generator, especially considering the potential reliability improvements from the state-of-art generator design and from the generator material and fabrication technology advancements achieved during last decades. Yet, generator condition assessment is essential to estimate the economic lifespan and potential risk of failure, and to evaluate the benefits and cost of generator upgrading.

For any generator, the following three step analyses are necessary to arrive at a generator condition indicator:

1) What parts should be included for a generator condition assessment and which parts are more important than others (parts and their weighting factors)?

2) What metrics/parameters should be investigated for quantitative condition assessment and which ones are more important than others (condition parameters and their weighting factors)?

3) How to assign numerical scores to the turbine parts (rating criteria)?

This Appendix provides guides to answer the above questions, which can be applied to the generator and it's various subcomponents. The condition assessment is performed on individual generators in a plant, because even the originally identical generators may have experienced different Operation & Maintenance (O&M) stories and would arrive at different values of condition indicators. Due to the uniqueness of each individual generator, the guides provided in this Appendix cannot quantify all factors that affect individual generator condition. Mitigating factors not included in this Guide may trigger testing and further evaluation to determine the final score of the generator condition and to make the decision of generator replacement or rehabilitation.

This Appendix is not intended to define generator maintenance practices or describe in detail inspections, tests, or measurements. Utility-specific maintenance policies and procedures must be consulted for such information.

2.0 Constituent Parts Analysis

Generators and their constituent parts are analyzed and listed in Table 1 (references to HAP Taxonomy). Among all the generator parts, the stator is the most critical part for a generator. If any part (e.g., the common shaft being assessed with the turbine assemly) does not exist in a particular generator unit, this part will be excluded from scoring mechanism by inputting “NA” into the Table. The effect of one part exclusion is usually insignificant to the entire generator assessment, which may not justify any adjustment of the weighting factors for other parts of the generator.

3.0 Metrics for Generator Condition Assessment

For generator condition assessment, it is recognized that the physical condition cannot be properly and sufficiently evulated based on the visual inspections only while the results from some routine or available tests are more critical as indication of generator condition. Although these testing results can be catergorize into the Physical Condition, they are listed separately in adiition to the visual condition to emphazie the importances of these meterics. Thus, as listed in Table 1, the following eight condition parameters are considered for condition assessment of generator and generator parts:

- The Visual Condition
- The Age
- The Installed Technology Level
- The Operating Restrictions
- Stator Electrical Tests
- Rotor Electrical Tests
- Stator Core Tests
- The Maintenance Requirement

These eight condition parameters are scored based on the previous testing and measurements, historical O&M records, original design drawings, previous rehabilitation feasibility study reports if conducted, interviews with plant staff, and some limited inspections or previous inspections. It is noticed that there are certain level of relevance between the age and physical condition, maintenance needs, or some operating restrictions. However, as a benchmarking condition assessment without specific new testing and measurements conducted on site, these eight parameters are regarded as providing the basis for assessing the condition of generator parts and entire generator. If any type of tests or metrics are not applicable for some parts (e.g., the Stator Eletrcial Tests are only applicable to the Stator), input "NA" into the cells of irrelevant parts for this metrics.

In addition, the Data Quality Indicator, as an independent metrics, is to reflect the quality of available information and the confidence on the information used for the condition assessment. In some cases, data may be missing, out-of-date, or of questionable integrity, and any of these situations could affect the results of condition assessment. The scores of data quality are determined by the on-site evaluators for each assessed part/item to indicate the data availability, integrity and accuracy and the confidence on the given condition ratings (MWH 2010).

4.0 Weighting Factors

There are two categories of weighting factors in Table 1. It is recognized that some condition parameters affect the generator condition to a greater or lesser degree than other parameters; also some parts are more or less important than other parts to an entire generator. These weighting factors should be pre-determined by consensus among experienced hydropower mechanical and electrical engineers and plant O&M experts. Once they are determined for each generator, they should be largely fixed from plant to plant except for special designs found in a generator where the weighting factors have to be adjusted. In this case, the adjustment of weighting factors must be conducted by HAP core process development team. The range of absolute values of weighting factors won't affect the Condition Indicator of a generator which is the weighted summation of all scores that assigned to the generator parts and eight condition parameters.

Table 1: Typical Generator Condition Assessment & Scoring

- XXX Hydropower Plant (Unit #)

Generator for Unit___	Taxonomy ID	Visual Condition Score	Age Score	Installed Technology Score	Operating Restrictions Score	Stator Electrical Tests	Rotor Electrical Tests	Stator Core Tests	Maintenance Requirement Score	Data Quality Score	Weighting Factors for Parts
Stator Windings	4.1.3.1						NA	NA			3.0
Stator Core	4.1.3.1					NA	NA				1.5
Rotor	4.1.3.2					NA		NA			2.5
Ventilation & Cooling	4.1.3.3					NA	NA	NA			2.0
Neutral Grounding	4.1.3.4					NA	NA	NA			0.5
Thrust Bearings	4.1.3.5					NA	NA	NA			1.0
Guide Bearings	4.1.3.6					NA	NA	NA			1.0
Generator Shaft	4.1.3.7					NA	NA	NA			1.5
Weighting Factors for Condition Parameters		1.0	2.0	1.0	1.0	3.0	2.5	1.0	1.5	**Data Quality -->**	*0.00*
										Generator Condition Indicator -->	***0.00***

5.0 Rating Criteria

Visual Condition - Rating Criteria for Generator Parts

Visual Condition of generator parts refers to those features that are observable or detected through visual inspections. Stator winding insulation and its condition is a significant factor in determining reliability of the unit. Previous visual inspections for loose components, evidence of corona, evidence of overheating, and fouled heat exchangers can provide valuable insight into the overall generator condition.

For HAP site assessment, it is important to review previous inspection records and interview and discuss with plant personnel to score the visual condition of the generator. The results of all related information are analyzed and applied to Chart 1 to assign the condition scores of generator parts.

Chart 1 Generator Visual Condition Rating Criteria		
Visual Condition Rating Scale		**Physical Condition Score**
Excellent	No noticeable defects. Some aging or wear may be noticeable.	**9 – 10**
Very good	Only minor deterioration or defects are evident, and function is full.	**7 – 8**
Good	Some deterioration or defects are evident, but function is not significantly affected Isolated evidence of corona, loose winding components or dirty coolers.	**5 – 6**
Fair	Moderate deterioration, function is still adequate, but the unit efficiency may be affected. Some areas exhibiting corona discharge, loose winding components or cooler fouling.	**3 – 4**
Poor	Serious deterioration in at least some portions, function is inadequate, unit efficiency or availability significantly affected. Widespread corona, greasing, loose components or hardware, fouled coolers or cooler defects. Girth cracking evident.	**2**
Very poor	Extensive deterioration. Barely functional. Loose or displaced winding components, extensive girth cracking, extensive corona, extensive greasing, mechanical damage to insulation.	**1**
Failed	No longer functions, may cause failure of a major component.	**0**

Age - Rating Criteria for Generator Parts

Age is an important factor to consider for generator reliability and upgrade potential. The most critical part, the stator, will irreversibly age and its remaining life will be a function of the original design and operating and maintenance history.   When the generator ages, the electrical insulation is more likely to develop turn to turn shorts and is more susceptible to failure from electrical transients. Heat transfer characteristics degrade as coolers and cooling passages become fouled. Raw Cooling Water (RCW) flow for coolers and bearings will degrade due to internal build-up. Meanwhile, an older generator usually has greater potential to gain efficiency and capacity by replacing and using the state-of-the-art generator design and materials.

Age scoring is relatively more objective than other condition parameters. The detailed scoring criteria developed in Chart 2 allows the age score be automatically generated in the HAP

Database by the actual years of the installed part. The generator parts usually have expected lifespan of 40-45 years, highly dependent on operating conditions. Bearings and cooling component ages are based on the time since their last overhaul or replacement.

Chart 2 Age Rating Criteria for Generator Parts				
Age of the generator Stator/Insulation	**Age of the generator Rotor/Insulation**	**Age of the generator Stator Core**	**Age of Major Generator Components (Cooling, Bearings)**	**Age Score**
<5 years	<5 years	<10 years	<5 years	**10**
5-10 years	5-10 years	10-25 years	5-10 years	**9**
10-15 years	10-15 years	25-40 years	10-15 years	**8**
15-20 years	15-20 years	>40 years	15-20 years	**7**
20-25 years	20-25 years		20-25 years	**6**
25-35 years	25-35 years		25-35 years	**5**
35-40 years	35-40 years		35-40 years	**4**
40-45 years	40-45 years		40-45 years	**3**
45-50 years	45-50 years		45-50 years	**2**
> 50 years	> 50 years		> 50 years	**1**

Installed Technology Level – Rating Criteria for Generator Parts

The Installed Technology Level indicates advancement levels of designing, insulation and materials, which may effect on the generator performance. The outdated technology may bring difficulties for spare parts supply and prolonged outage when it fails.

Scoring the Installed Technology Level requires historic knowledge of generator technology advancement and familiarity with generator material advancements for electrical insulation, core steel, and heat exchangers. With the computerization of generator winding design and manufacturing (CNC), the production accuracy and overall efficiency (reduction of losses) have been improved over the original design particularly for I^2R and core losses. Generator and rotor windings with class B (NEMA class) insulation get lower scores than those with class F. The competence, professionalism and reputation of the original suppliers could also imply the installed technology levels. Compared with those from large and well-known manufacturers, the generator parts supplied by small and unnamed companies whose industry track record shows history of reliability issues due to their design would get lower scores.

Chart 3 Generator Technology Rating Criteria	
Technology Levels of the Parts/Items	**Score for Installed Technology Level**
Both stator and rotor have Class F (or greater) insulation. Core has been restacked with low hysteresis steel and / or retorqued.	**10**
Both stator and rotor have Class F (or greater) insulation. Core has not been restacked with low hysteresis steel and / or retorqued.	**9**
Either the stator or rotor have been rewound with Class F or greater insulation and the core has been restacked with low hysteresis steel.	**8**
Either the stator or rotor have been rewound with Class F or greater insulation and the core has not been restacked with low hysteresis steel.	**7**
Both the stator and the rotor have been rewound with Class B insulation system and the core has been restacked with low hysteresis steel.	**6**
Both the stator and the rotor have been rewound with Class B insulation system and the core has not been restacked with low hysteresis steel.	**5**
Either the stator or rotor have been rewound with Class B insulation and the core has been restacked with low hysteresis steel.	**4**
Either the stator or rotor have been rewound with Class B or greater insulation and the core has not been restacked with low hysteresis steel.	**3**
Stator, rotor and core are original equipment.installed prior to 1970	**0 – 3**
Add indicated points for any and each of the following installed condition monitoring devices; Partial Discharge Analyzer (PDA), Rotor Shorted Turns (Flux Probe), Rotor Air Gap Probe	**0.5**

Operating Restrictions - Rating Criteria for Generator Parts

The generator operating restrictions refer to any limitations on the output of MW or MVAR. Operational limitations play a role in determining the serviceability of generator unit: the greater the limitations, obviously the greater the generation loss.

To prevent overheating or due concerns for structural integrity due to a currently deteriorated generator physical condition (e.g., cut out coils, shorted rotor turns, degraded cooling system performance, structural (frame) concerns, hot bearings, and severe vibrations). Generator constraints do not refer to any limitation from other components in the system, e.g., if the excitation system is limiting reactive power then the excitation system rather than the generator would get lower score for the operating restrictions.

Chart 4 describes the ratings of generator operating restrictions.

Chart 4 Generator Operating Restrictions Rating Criteria	
Operating Restrictions or Off-Design Conditions	**Score for Operating Restrictions**
The design standard has no changes, and the original generator design has no constraints on the required operation.	**8 – 10**
Minimal restraints: Temperature resistrictions, vibration issues, cooler leaks	**5 – 7**
Moderate restraints: Cut out stator coils, shorted rotor turns, grounded rotor, structural defects	**3 – 4**
Severe limitations: The generator is undesirable to operate anymore; the original design has significantly degraded and limited the performance and reliability if it operates under current requirement.	**0 – 2**

Stator Electrical Tests

In conjunction with a thorough visual inspection electrical testing will reveal the most information about the health of the winding. Basic tests include the insulation resistance (IR) test, polarization index (PI) test, and a bridge test for winding resistance. Hi potential test, either AC or DC or very low frequency AC test may be performed. The hi potential test may be performed as a proof type test where the objective is simply that the winding withstand the imposed test voltage or a stepped or ramped voltage test offering some insight into winding condition. Partial discharge analysis (PDA), if available, offers on-line diagnostic ability to assess winding insulation condition. Engineering judgement will be required to assign a score based on available test data and weighing of comparative test results.

Chart 5 Stator Electrical Tests Scoring	
Test Results	**Score for Electrical Condition**
Insulation resistance (IR) > 100megohms, polarization index (PI) >2.0, withstood AC/DC or VLF hipot, low partial discharge levels (or no significant increase from previous) all as indicated by most recent test, stator winding resistance within 5% of design value and balanced. All of these 5 criteria met.	**10**
Insulation resistance (IR) > 100megohms, polarization index (PI) >2.0, withstood AC/DC or VLF hipot, low partial discharge levels (or no significant increase from previous) all as indicated by most recent test, stator winding resistance within 5% of design value and balanced. 4 of 5 criteria met.	**8 - 9**
Insulation resistance (IR) > 100megohms, polarization index (PI) >2.0, withstood AC/DC or VLF hipot, low partial discharge levels (or no significant increase from previous) all as indicated by most recent test, stator winding resistance within 5% of design value and balanced. 3 of 5 criteria met.	**5 - 7**
Insulation resistance (IR) > 100megohms, polarization index (PI) >2.0, withstood AC/DC or VLF hipot, low partial discharge levels (or no significant increase from previous) all as indicated by most recent test, stator winding resistance within 5% of design value and balanced. 2 of 5 criteria met	**2 - 4**
Insulation resistance (IR) > 100megohms, polarization index (PI) >2.0, withstood AC/DC or VLF hipot, low partial discharge levels (or no significant increase from previous) all as indicated by most recent test, stator winding resistance within 5% of design value and balanced. 1 of 5 criteria met.	**1**
None of the above criteria met	**0**

Rotor Electrical Tests

IR, PI, bridge resistance and an electrical test for pole shorted turns usually provide adequate indication of the electrical health of the rotor windings. Hi potential test for the rotor are not usually performed as a routine test. With rotor electrical tests some engineering judgement will be required to assign scores based on available data.

Chart 6 Rotor Electrical Tests Scoring	
Test Results	**Score for Electrical Condition**
No rotor turn faults (shorts), insulation resistance > 100megohms,, polarization index (PI) >2.0, all as indicated by most recent test, rotor winding resistance within 5% of design value.	**10**
No rotor turn faults (shorts) indicated, insulation resistance > 100 megohms,, polarization index (PI) >2.0, all as indicated by most recent test, rotor winding resistance within 5% of design value. (i.e. 1 of 4 criteria not met)	**8 - 9**
No rotor turn faults (shorts) indicated, insulation resistance > 100 megohms,, polarization index (PI) >2.0, all as indicated by most recent test, rotor winding resistance within 5% of design value. (i.e. 2 of 4 criteria not met)	**5 - 7**
No rotor turn faults (shorts) indicated, insulation resistance > 100 megohms,, polarization index (PI) >2.0, all as indicated by most recent test, rotor winding resistance within 5% of design value. (i.e. 3 of 4 criteria not met)	**2 - 4**
No rotor turn faults (shorts) indicated, insulation resistance > 100 megohms,, polarization index (PI) >2.0, all as indicated by most recent test, rotor winding resistance within 5% of design value. (i.e. 4 of 4 criteria not met)	**1**
Rotor not serviceable due to ground faults, shorted turns or high resistance connections	**0**

Stator Core Tests

The stator core health is critical to operation of the unit. Core assessment tools are primarily visual. However, two tests, which both require a unit outage usually with the rotor removed, have been developed to aid in locating of core faults (shorted laminations). Both tests produce a flux in the core. The rated flux method, "loop" test or "ring flux" test uses thermal imaging to detect overheating defects. The low flux method, the Electromagnetic Core Imperfection Detection (El-Cid) test utilizes a low (3-4% rated) flux and a "Chattock Coil" to detect a voltage signal proportional to the eddy current flowing between laminations. These are not routine tests and are most likely performed in conjunction with a rewind or when core damage suspected. In the case there is no data for review this parameter will be automatically excluded from scoring mechanism by inputting "NA".

Chart 7 Stator Core Tests Scoring	
Test Results	**Score for Condition**
Previous electrical core test, i.e. ElCid (low flux) or Loop Test (rated flux) showed no anomolies	**10**
Previous electrical core test, i.e. ElCid (low flux) or Loop Test (rated flux) showed minor suspect areas, repaired	**5 - 9**
Previous electrical core test, i.e. ElCid (low flux) or Loop Test (rated flux) showed minor suspect areas ,not repaired	**1 - 4**
Operating with known major defects	**0**

Maintenance Requirement – Rating Criteria for Generator Parts

The amount of corrective maintenance that either has been or must be performed is an indication that how the generator condition is. No corrective maintenance is an indication that the generator is in good shape. Frequent and extensive corrective maintenance or stator failures typically requires a major outage and is indicative of severe duty and/or aging.

Other factors to consider for maintenance scoring include:

- The need of maintenance is increasing with time or problems are reoccurring;
- Deteriorating trend in insulation integrity test results;
- Previous failures related to the generator parts;

- Industry experience with failures and problems with generators of similar design.

The results of generator maintenance history (including routine maintenance and corrective maintenance) and trended test results are analyzed and applied to Chart 8 to score the generator.

Chart 8 Generator Maintenance Requirement Rating Criteria	
Amounts of Corrective Maintenance	**Maintenance Requirement Score**
Minimum level (normal condition): A small amount of routine preventive maintenance, cleaning and routine testing is required and performed at the recommended frequency.	**9 – 10**
Low level: Small amounts of corrective maintenance (e.g., less than 3 staff days per unit per year). Repairs that could be completed during a unit preventive maintenance outage that is scheduled on a periodic basis (e.g., cooler tube cleaning, cooler system maintenance).	**7 – 8**
Moderate level: Some corrective maintenance that causes extensions of unit preventative maintenance outages (e.g., coil replacement, stator rewedge).	**5 – 6**
Significant/Extensive level: Significant additional and corrective maintenance is required; forced outage occurs and outages are extended due to maintenance problems (e.g., bearing oil leaks, cooler leaks, overheating electrical connections).	**3 – 4**
Severe level: Severe corrective maintenance that requires scheduled or forced outages. Repeated forced outages, frequent repairs, abnormal wear to components, and/or labor-intensive maintenance is required.	**0 – 2**

Data Quality – Rating Criteria for Generator Parts

The Data quality scores reflect the quality of the inspection, test, and measurement results to evaluate the condition of generator parts. The more current and complete inspection, the more consistent the testing and trending, the higher the Data Quality scores. The frequency of normal testing is as recommended by the manufacturer, industry standards or dictated by operating organization's experience.

Reasonable efforts should be made to perform visual inspections and data collection (measurements, tests, operation logs, maintenance records, design drawings, previous assessment reports and etc.). However, when data is unavailable to score a condition parameter properly, it may be assumed that the condition is “Good” or numerically equal to some mid-range number 3-7. Meanwhile, the Data Quality score is graded low to recognize the poor or missing data.

Qualified personnel should make a subjective determination for the Data Quality scores, considering as many factors as possible. The suggested criteria for scoring the Data Quality of turbine parts are developed in Chart 9.

Chart 9 Generator Data Quality Rating Criteria

Data Availability, Integrity and Accuracy	Data Quality Score
High – The generator maintenance policies and procedures were followed by the plant and the routine inspections, tests and measurements were performed within normal frequency in the plant. The required data and information are available to the assessment team through all means of site visits, possible visual inspections and interviews with experienced plant staff.	**8 – 10**
Medium – One or more of routine inspections, tests and measurements were completed 6-24 months past the normal frequency, or small portion of required data, information and documents are not available to the assessment team.	**5 – 7**
Low – One or more of routine inspections, tests and measurements were completed 24-36 months past the normal frequency, or some of results are not available.	**3 – 4**
Very Low – One or more of required inspections, tests and measurements were completed >36 months past the normal frequency, or significant portion of results are not available.	**0 – 2**

6.0 Generator Condition and Data Quality Indicators

In Table 1 final condition score of the generator, i.e., the Condition Indicator, *CI*, can be calculated as follows:

$$CI = \frac{\sum_{K=1,M}^{J=1,8} S_C(K,J) \times F(K) \times F(J)}{\sum_{K=1,M}^{J=1,8} F(K) \times F(J)} \qquad (1)$$

The generator Data Quality Indicator, *DI*, will be the weighted summation of all Data Quality scores received for its associated parts/items:

$$DI = \frac{\sum_{K=1,M} S_D(K) \times F(K)}{\sum_{K=1,M} F(K)} \qquad (2)$$

Here M = the total number of parts/items associated with a generator; K = the identification No. of generator Parts (from 1 to M); J = the identification No. of condition parameters (from 1 to 8, respectively for physical condition, age,…); $S_C(K, J)$ = the condition score of a generator part for one of 5 condition parameters; $S_D(K)$ = the data quality score for a part; $F(J)$ = the weighting factor for a condition parameter; $F(K)$ = the weighting factor for a generator part.

The calculated Condition Indicator from equation (1) may be adjusted by the results of internal inspections and specific testing results that would be performed, since the specific generator testing, such as the hi pot and megger testing would more directly reveal the condition of generator.

7.0 Reference

EPRI (2001), Hydro Life Extension Modernization Guide: Volume 3: Electromechanical Equipment, Palo Alto, CA: August 2001. TR-112350-V3.

MWH (2010). Final Report of Hydropower Modernization Initiative Asset Investment Planning Program, MWH prepared for U.S. Army Corps of Engineers Northwest Division, Hydroelectric Design center, October 21, 2010.

USACE (2001). Major Rehabilitation Evaluation Report, Center Hill Power Plant, prepared by U.S. Army Corps of Engineers, March 2001.

HAP Team (2011a). HAP Best Practice Category of Hydropower Unit and Plant Efficiency Improvement, prepared by Mesa, HPPi and ORNL.

HAP Team (2011b). HAP Condition Assessment Manual, prepared by ORNL and Mesa.

TVA (2010). Enterprise Asset Management (EAM) Asset database Modification and Unique Identification of Structures, Systems, and Components.

March (2011). “Best Practice” Guidelines for Hydro Performance Processes, by Patrick March, Charles Almquist and Paul Wolff, Hydro Vision Conference July 2011. USACE (1985). Engineer Manual, No. 1110-2-1701. Engineering and Design – HYDROPOWER, US Army Corps of Engineers.

HydroAMP(2006)- Hydropower Asset Management-Using Condition Assessments and Risk-Based Economic Analyses. Appendix E- Equipment Condition Assessment Guides.

For overall questions
please contact:

Brennan T. Smith, Ph.D., P.E.
Water Power Program Manager
Oak Ridge National Laboratory
865-241-5160
smithbt@ornl.gov

or

Qin Fen (Katherine) Zhang, Ph. D., P.E.
Hydropower Engineer
Oak Ridge National Laboratory
865-576-2921
zhangq1@ornl.gov