Improving the Reliability of Stator Insulation System in Rotating Machines

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Abstract: Reliable performance of rotating machines, especially generators and primary heat transport pump motors, is critical to the efficient operation of nuclear stations. A significant number of premature machine failures have been attributed to the stator insulation problems. Ontario Hydro has attempted to assure the long term reliability of the insulation system in critical rotating machines through proper specifications and quality assurance tests for new machines and periodic on-line and off-line diagnostic tests on machines in service. The experience gained over the last twenty years is presented in this paper.

Functional specifications have been developed for the insulation system in critical rotating machines based on engineering considerations and our past experience. These specifications include insulation stress, insulation resistance and polarization index, partial discharge levels, dissipation factor and tip up, AC and DC hipot tests. Voltage endurance tests are specified for groundwall insulation system of full size production coils and bars. For machines with multi-turn coils, turn insulation strength for fast fronted surges is specified and verified through tests on all coils in the factory and on samples of finished coils in the laboratory.

Periodic on-line and off-line diagnostic tests are performed to assess the condition of the stator insulation system in machines in service. Partial discharges are measured on-line using several techniques to detect any excessive degradation of the insulation system in critical machines. Novel sensors have been developed and installed in several machines to facilitate measurements of partial discharges on operating machines. Several off-line tests are performed either to confirm the problems indicated by the on-line tests or to assess the insulation system in machines which can not be easily tested on-line. Experience with these tests, including their capabilities and limitations, are presented.

1. INTRODUCTION

Rotating machines are essential to the operation of a nuclear generating station. Premature failure of a generator or an essential motor can result in large financial losses to a utility. Also some of the machines, eg, standby generators and emergency power generators are mandatory for safe operation of nuclear stations. The present competitive utility environment makes it even more imperative to have the equipment operating reliably without any premature failures and the consequent forced outages which may severely reduce revenue. Almost a third of rotating machine failures are caused by a breakdown of stator insulation [1]. Hence taking steps to improve the reliability of the stator insulation system in all important machines in a nuclear station will pay good economic dividends. Ontario Hydro has had its share of premature failures of important machines in its nuclear stations and has taken steps to improve the reliability of stator insulation systems in important rotating machines, ie, turbine generators (TG), standby generators, and large motors rated 4.1 kV and above.

In Ontario Hydro, the process of assuring a long term reliable service life of the stator insulation system begins with the proper functional specification and continues through acceptance tests during and/or after the manufacturing and commissioning stages. Periodic diagnostic tests are also performed through the service life of the machine as discussed in the following sections. In this paper we summarize our experience in this area.

2. VENDOR QUALIFICATION

Whether purchasing the stator winding for new generators and motors or for the rewind of existing ones, the insulation designs from prospective vendors should be evaluated. This evaluation should include a review of the materials used, winding design (including voltage stresses), and manufacturing processes including sample coil testing. The vendor's capability and experience to comply with the acceptance criteria, to perform required tests (eg, voltage endurance and thermal cycling tests for groundwall, surge tests for multiturn coils etc, as described below), and to assure good quality control during the manufacturing process should be reviewed. Only manufacturers whose windings are likely to meet the specifications consistently should be asked to bid on the job.

3. FUNCTIONAL SPECIFICATION AND ACCEPTANCE TESTS

The functional specification for the machine should be based on the application and the expected performance of the machine. It should contain all the tests and the associated acceptance criteria required at various critical stages of the manufacturing process and/or after the final assembly of the stator winding. The specifications should include (along other pertinent specifications) the following important features of the stator winding insulation system design and quality assurance during manufacture:

a. Class of insulation and maximum temperature rise: Ontario Hydro often specifies class F insulation systems for class B temperature rise to ensure an adequate thermal life of critical machines.

b. Requirement (or not) for semi-conducting coating on the groundwall in the slot section & stress grading treatment at the slot to overhang transition area. Both treatments are required for machines rated higher than 4.1 kV.

c. Various type tests to be performed on coils randomly selected from the production run: By nature these tests are destructive and can not be performed on the coils or the winding to be used. These tests evaluate the adequacy of the winding design. If more than one unit of the same winding are ordered, these tests can be performed once to prove the design.

   Voltage endurance tests, as described in IEEE Standard 1043 [2] are conducted on at least two coils. The coils are expected to survive 250 hours at 110 C and 2.5 pu voltage (eg, 35 kV for 13.8 kV coils). For machines to be used in cycling duty, thermal cycling tests [3] are specified. For machines with multi-turn coils, the turn insulation strength should be determined for complete coils, and it should exceed 3.5 pu for surges with rise times in 0.1 to 0.2 μs range [4]. Although not accepted yet as a standard, a recently described endurance test for turn insulation [5] should be specified for multiturn coils of critical machines.

   In some cases, Ontario Hydro has specified the maximum acceptable void sizes in the insulation system. The voids can be measured in the coils dissected after the type tests above.

d. Insulation resistance (IR) and polarization index (PI) for the coils and/or complete winding: Acceptable values and the voltage to be used for test should be specified. IEEE Standard 43 [6] provides the required guidance. However, the IR values in this standard should be treated as bare minimum values; modern insulation systems have much higher values. This is being addressed in the next revision of IEEE Standard 43.

e. Dissipation factor at low voltage (10 % of the rated line to ground voltage) and tip up (difference in dissipation factor at 10 % and full rated line to ground voltage) for the winding [7]. For stator windings with modern insulation systems, the acceptable values are 1 to 2 % for the low voltage dissipation factor and less than 1 % for the tip up.

f. Hipot tests for the winding: The voltage levels and the type of voltages used to hipot the complete winding should be specified [8]. One minute ac test at (2E+1) kV is normally specified for the new windings, where E is the rated line-to-line voltage of the machine in kV. Whether equivalent DC hipot tests [9] or equivalent lightning surges can be used as an alternative should also be specified.

g. Partial discharges: Partial discharge (pd) activity is an important parameter for judging the quality of an insulation system. It detects the imperfections like voids, contamination etc. However, measuring pd levels quantitatively in a stator winding is not a simple task. The measured results for a winding at a specified voltage depend on the size and type of defects, the location of pd sites, characteristics of the measuring system, and the connections of the winding for the measurement. There is no standard at present for partial discharges in rotating machines. Working groups are active in IEEE, CIGRE, and IEC in this area. Based on extensive experience with measurements done on large number of new and old machines, Ontario Hydro specifies pd levels for new machines at the rated line to ground voltage as measured with its own wide band pd measurement system. PD measurements are made on individual phases of a winding, with the other two phases connected to ground. For good machines with modern insulation systems, the pd levels are 100 mV or less. Another utility, Electricite de France, also specifies pd acceptance limits.

New techniques for on-line pd measurements have been recently developed [10]. However, for such measurements the pd sensors have to be built into the winding. Therefore specifications should include installation of any sensors (with necessary details) required for later on-line measurements.

h. Quality assurance tests during manufacture: There are some tests which can and should be performed at various stages of manufacturing process. For example hipot tests, turn insulation tests, partial discharge measurements, hipot tests may be specified for each coil to weed out coils with defects before insertion in the stator core. This is easily specified for coils with vacuum pressure impregnated (VPI) or resin rich insulation systems; in this process the coils are effectively finished before insertion in the stator core. However, for the global VPI insulation system, the coils are not impregnated before installation in the slots. The hipot test levels (including surge levels for the turn insulation in multiturn coils) for this type of green coils should be lower, typically 2/3 of those for the finished coils or the complete winding.

i. Acceptance tests for the complete winding: Insulation resistance, polarization index, hipot tests, dissipation factor, and partial discharges are specified for the whole winding and, if possible, for individual phases. Also tests should be carried out to check the tightness of wedges in all TGs and SGs before the rotor is installed.

4. POST COMMISSIONING TESTS

Once the new or rewound stator is installed at site, some baseline test data should be obtained to allow monitoring of the winding for evidence of continued "good health", or degradation while in service. As the windings may settle during the first few months of operation, these tests should preferably be performed about a year after commissioning and should include the following.

a. IR and PI tests
b. Off-line PD and capacitance/dissipation factor tests
c. On-line PD tests (for machines fitted with PD sensors)

5. IN-SERVICE DIAGNOSTIC TESTS

Once the stator winding is in service, tests should be performed to trend the insulation condition and to detect any significant degradation. The goal is to detect a degraded condition before it leads to an unexpected premature failure and to either correct the situation or to remove the machine from service before a costly forced outage. Some researchers have reported methods to estimate the remaining life of machines [11-13]. However, their results have not been confirmed in other studies. A large EPRI study [14-16] concluded that (a) estimation of the remaining life was impossible at present; (b) no single parameter gave consistent results on the condition of stator insulation systems, and (c) an assessment of the insulation condition can be made by measuring multiple parameters and trending the results for the same machine over time or comparing the results for similar machines.

Ontario Hydro uses both off-line and on-line tests to assess the condition of stator insulation systems. On large turbine generators, partial discharges are measured on line periodically. If a large deleterious change is noticed, the machine is subjected to off-line tests and visual inspection. On other critical machines, like standby generators, off-line measurements are made every five years or so. If a problem is observed, the measurements are repeated at shorter intervals to assess the rate of degradation.

Off-line measurements include IR and PI, capacitance and dissipation factor, and partial discharges. The measurements are made on individual phase windings as it provides an opportunity to compare three phases. Further, energizing one phase, with the other two phases grounded, produces an electric stress in the endwindings. This stress permits probing for problems in these areas due to contamination or incorrect design of interphase clearances. The hipot tests are potentially destructive and not applied every time but only in case of suspected weaknesses to assure survivability in operation. Performance of a hipot test requires that the utility is prepared for the consequences of a failure. In our tests on many machines, no single test provided consistent assessment of the insulation condition. However, examination of all the parameters, comparison of their values for the same machines at different times, and a comparison between similar machines or different phases of the same machine were used to assess the insulation condition. The results for a number of standby generators and emergency power generators were reported in earlier papers [17-18].

The IR values are a measure of moisture, contamination, or cracks in the stator insulation and tell little about the insulation aging or degradation. PI values less than 2 are often indicative of aged insulation. However, for the modern insulation systems with IR values in several GΩ range, the values of PI are not very relevant. Also for such high IR values, the measurement of PI is difficult. Most often the IR values are used only to decide whether high voltage can be applied or not and not to assess the insulation condition.

The measured values for modern insulation systems (epoxy resin systems) in good condition are 1 to 2 % for the dissipation factor and less than 1 % for the tip up. However, the measured values are affected by the stress grading coatings applied in the machine. Hence the comparison with earlier measurements or baseline measurements is more useful than the absolute values of the parameters. Also for some of the older machines with softer insulation systems, the values can be substantially higher. A negative tip up can be an indicator of serious degradation of the insulation system [19].

Partial discharge measurements are made both off-line and on-line. On good stators, using the Ontario Hydro wide-band detector, measured pd magnitudes can be expected to be 100 mV or less. Magnitudes above 400 mV indicate serious problem. In off-line measurements, discharge inception voltages (DIV) and discharge extinction voltages (DEV) are also measured. A low DEV value indicates poor condition of the insulation system. Some machines may have high pd levels from the beginning which may not increase significantly with time. Again, a significant increase in pd over time is a better indicator of degradation than the absolute value of pd magnitudes. On-line pd measurements are used to examine if any deleterious change has taken place. In cases where such measurements indicate a problem, further investigations using off-line tests and inspections are warranted

Hipot tests are performed on machines in service to assure their serviceability. They should not be used as routine tests as they are potentially destructive in nature. The voltage used is (1.5E+1) ac or equivalent DC level. The relationship between the ac and dc test levels is not completely understood [20] and Ontario Hydro prefers the ac test. The ac and dc hipot tests stress the groundwall insulation only and not the turn insulation in multi-turn machines. For multiturn machines in service, Ontario Hydro does not use or recommend turn insulation tests using fast rise time surges on complete windings as the detection of a turn insulation fault is quite difficult.

6. VISUAL INSPECTION AND MAINTENANCE

If a problem is indicated by diagnostic tests, a visual inspection of the winding is necessary. Normally one looks for damage by overheating or discharges, looseness of the coils in the slots, general contamination or cracks in the winding, signs of damage to semiconductive coating in the slot section and the stress grading coating, and any softness or puffiness in the insulation. Wedge tap tests are performed on large machines to examine the tightness of wedges. In recent years Ontario Hydro has been evaluating the effectiveness of robotic equipment to perform tests and inspections in turbine generators without removing the rotor. These devices can move along the air gap to perform wedge tap tests, core insulation tests, and visual inspection with a video camera. Some of the problems can not be corrected by maintenance and a rewind of the stator is then required. In some cases maintenance actions, like cleaning and/or drying the winding, tightening the wedges, and touching up the stress grading coating, may make the machine serviceable with little cost.

7. CONCLUSIONS

The reliability of stator insulation systems in large rotating machines can be assured and improved by proper specifications for the winding, quality assurance during the manufacturing process, acceptance tests in the factory, proper application of machine, periodic on-line or off-line tests, and necessary maintenance.

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