Abstract - The first installations of the new "hard" epoxy-mica or polyester-mica stator insulation systems in Reclamation generators resulted in numerous problems that were not present with the older "soft" asphalt-mica systems. One of the main attributes of asphalt-mica systems was the tendency for these materials to expand and lock themselves into the stator slots. When the asphalt becomes warm and somewhat plastic, it flows and causes the coil surface to bulge into the air passage slots. Because the binders in the "hard" systems remain rigid, the coils must be secured in the slots by other means to prevent movement.

In the early years of hard insulation system development, loose coils became the major O&M (operation and maintenance) concern. Many windings were out prematurely due to severe electrical and mechanical deterioration resulting from loosely installed coils. A factor causing looseness in the slots involves further curing of some insulation systems after installation, resulting in volumetric shrinkage of the insulation. Manufacturers have addressed this problem by developing coil-clamping systems that maintain slot pressure regardless of volumetric shrinkage.

Reclamation has developed maintenance procedures to detect loose coils and correct the situation before serious damage could occur.

Introduction

The Bureau of Reclamation (Reclamation) owns and operates over 50 hydrogenerating plants throughout the Western United States. The total installed capacity is in excess of 13,000 MW, making Reclamation the 11th largest utility (based on generating capacity) in the United States.

Reclamation's machine stator rewind program is large enough to warrant the development of several rewind and uprate "experts," thus creating a permanent database of winding case history, inspection and testing procedure, and contractor qualifications. This expertise is maintained at the Denver Office rather than at the project level. Experience with high-voltage winding insulation testing and numerous O&M problems has allowed Reclamation to formulate a successful program for new and rewound machine windings.

Approximately 20 years ago, "hard" epoxy-mica and polyester-mica insulation systems were developed.

Approximately 85 of Reclamation's 205 generators have been rewound with "hard" insulation systems. Seventeen new generators have "hard" insulation systems.

The new epoxy-mica and polyester mica insulation systems contain no bituminous or cotton materials and are rated Class "E" insulation, allowing them to operate at higher temperatures than the older low-temperature asphalt-mica insulation systems. The insulation thickness for "hard" systems is less than for "soft" systems for the same voltage withstand capability. This results in a larger cross-sectional area of copper for a coil with "hard" insulation than for a coil with "soft" insulation with identical outside dimensions. Thus, for a given size stator slot, an increase in copper cross-sectional area made possible with the hard-type insulation results in lower I2R losses. The lower loss coupled with a higher operating temperature results in a higher allowable output of a new or rewound generator.

Initial Problems

The initial problems with the new insulation systems resulted from the use of installation practices that were commonplace with asphalt-mica insulation but were incompatible with the new systems. The new insulation was hard and brittle; coils could not be deformed and forced into slots as had been done previously. Once in the slot, coils did not readily conform to irregularities. In addition, installation of side fillers was extremely difficult. These problems indicated the need for new installation practices and coils with tighter dimensional tolerances.

Some manufacturers used painted, semiconductive shielding systems for the slot portion of the coil, but these systems were very fragile and prone to damage and deterioration over time. This was compounded by the insulation on the coils undergoing volumetric shrinkage due to in situ curing of the epoxy, polyester, and/or tapes, causing the coils to become loose in the stator slot. The in-place curing resulted from thermal loading during normal operation of the generator. Once loose, additional vibration and wear occurred, often resulting in damage to the fragile, painted, semiconductive shielding system.

Damage to the shielding system allowed partial discharges to occur in the slot between the surface of the coil and the ground plane of the stator core. Slot discharges further destroyed the painted, semiconductive shielding system as well as the surface of the coil insulation.

Solutions

Reclamation found that unacceptable mechanical damage could be minimized if knowledgeable inspectors monitored the installation of new coils. To achieve this end, the Electrical and Mechanical Engineering Division of the Denver Office conducts onsite seminars prior to the installation of a winding to instruct inspectors on proper installation procedures. Specific installation procedures are beyond the scope of this paper because coils from various manufacturers require different installation procedures.

Over the years, many changes have been incorporated into the specifications for new windings to prevent the recurrence of loose and damaged coils. In addition, manufacturers have also made many improvements that have corrected first- and second-generation design deficiencies. For example, paint-type shielding systems are no longer allowed in the stator slot portion of the coils. Instead, armor tapes saturated with semiconductive paint are now required throughout the stator slot portion of the coil. The saturated armor tapes are superior in resistance to mechanical abrasion and therefore maintain a higher degree of continuity of the shielding system.

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Various manufacturers are presently using three distinct restraint systems to prevent the coils from becoming loose in the slot. One company employs alternating layers of conductive and nonconductive RTV (room temperature vulcanizing) silicone rubber on the sides of the insulation to provide an interference fit between the coil and the stator slot. These coils must be pressed into the slot. The press fit eliminates preload on the coil and maintains it in good physical and electrical contact with the slot, even after volumetric shrinkage. Another company coats the surface of the coil with conductive epoxy and paper just prior to insertion into the slot. Upon insertion, the epoxy is force fit into the shape of the slot, including the air passages, locking the coil into the slot when the epoxy cures. This company and other companies use compressible filler materials called ripple springs to maintain pressure in the radial direction. Some side filler is still required to prevent movement in the tangential direction if conductive epoxy and paper are not used to lock the coil into the slot.

Experience with slot wedging systems using ripple springs has led to the following installation and monitoring procedures:

- The wedge holes must be spaced to allow for depth measurements to high and low points of the ripple spring.
- Wedge holes must be protected during the painting process to prevent paint from blocking the holes.
- Depth gauge measurements indicate the amount of compression of the ripple spring. In one case, the majority of ripple springs in an entire winding were found to be completely relaxed after 1 year of operation, causing the coils to become loose in the slots. The problem was confirmed from corona probe measurements taken with a hand-held radio-frequency-type detector, which indicated moderate partial discharge activity in the slots. Partial discharge activity for a 1-year-old tight-fitting winding should be very low.

Reclamation winding specifications now require three inspections of a new winding prior to the end of the 5-year warranty period. Experience has shown that the first inspection, which is done after 6 months to 1 year of operation, is the most important. Ordinarily, most of the shrinkage occurs in the first 6 months of operation and is found during the first inspection. The rotor is removed for each of the three inspections. This permits wedge tightness to be checked and each coil inspected for signs of movement. Any looseness is corrected prior to reassembly of the generator. Removal of the rotor also makes it easier to perform partial discharge measurements with a hand-held corona probe. Partial discharge levels are monitored to determine if coil movement has damaged the semiconductive shielding system on the surface of the coil. The hand-held probe is an excellent device for determining the exact position of the discharges. The probe is tuned to monitor RF energy in the 5-MHz range. We have found that the RF signal strength at this frequency attenuates very quickly in a generator winding, allowing the source of the discharge to be isolated to a specific section of coil in the stator slot.

Repairs to the painted semiconductive shielding system of coils in the stator slots have been attempted with various degrees of success. In some cases, complete reestablishment of contact between the coil and the stator slot ground plane has been achieved, and in other cases no measurable improvement could be determined. In either case, the problem area was detected with the corona probe and either fixed or earmarked to be monitored until a complete repair could be achieved.

The second inspection is performed 2 1/2 to 3 years into the warranty period, and once again wedge tightness, coil movement, and partial discharge activity, if necessary, are monitored. Any tightening performed on the second inspection usually occurs in areas not loose enough to warrant concern or remedial action on the first inspection.

The final inspection is performed just prior to the end of the 5-year warranty period. Once again, wedge tightness and coil movement are checked. Partial discharge activity is monitored if there is reason to suspect that something has caused a change. Since this is the last in-depth inspection of the winding prior to the normal maintenance program, the inspection is taken to ensure that the winding installation fully meets all of the specification requirements. Engineers from the Electrical and Mechanical Engineering Division in the Denver Office normally assist with the final inspection. Reclamation encourages the winding manufacturer to have a representative present during these inspections in order to expedite the manufacturer's recommendations and suggestions on repair procedures.

Conclusions

The advent of the new hard mica insulation systems initiated several problems requiring special attention to the installation and inspection of new stator windings. Reclamation's experience with the hard insulation systems indicates that in the early years these systems were prone to allow coils to become loose in the stator slots. Once loose, the coils would sustain mechanical wear which lead to increased partial discharge activity. This focused our attention on the need for improved installation practices with particular emphasis on mechanical binding in the slot, followed with frequent physical inspections during the first years of service. The high percentage of loose coils in newly installed windings implied that the first inspection should occur within the first year of operation. This inspection usually indicated that extensive addition of filler material was required behind the slot wedge. Subsequent inspections after up to 5 years of operation have shown that most, but not all, of the loose coils were discovered in the first inspection.

Newer hard insulation systems embody coils with an interference fit in the stator slot. The use of compressible filler materials (ripple springs) has virtually eliminated loose wedges and coil movement problems. However, the inspection program still uncovers a sufficient number of problems in other areas to warrant its continued use. This program has effectively eliminated partial discharge problems in the slot portion of the coils. Problems still exist in the end turn and connection areas. A detailed physical inspection is an effective means of locating these problems.

Reclamation winding installation and inspection programs have evolved over the years and have greatly improved the service life and reliability of our generators. All major problems associated with the
new hard-type insulation systems have essentially been eliminated since the present approach has been formulated and adopted.

A partial listing of Reclamation case histories involving the new hard winding insulation systems is included.

Partial Listing of Generator Hard-Type Stator Winding

Yellowtail Powerplant - four generators - 65.78 MVA at 0.95 power factor, 13.8 kV, 225 r/min, in service 11/85.

The stator winding in unit 3 suffered a phase-to-ground fault in November 1980. Dissection and analysis of the failed coil revealed that elevated levels of internal partial discharge activity had deteriorated the epoxy binder. Vibration of the copper strands resulted in strand-to-strand faults and eventual failure of the groundwall insulation. Partial discharge tests were then performed on the entire winding and revealed very high levels of internal partial discharge on two coils and moderately high readings on six coils. These coils were not in the immediate area of the fault. The two coil fronts with very high readings were removed via half-coil splits. Dissection of these coils revealed an advanced state of internal deterioration that was present in the failed coil. Partial discharge surveys of the other three generators indicated they all had the same problem. The final conclusion was that the problem originated from a coil manufacturing process that left voids in the insulation next to the surface of the conductors. This situation initiated the Reclamation procedure of research engineers dissecting and inspecting coil samples of a manufacturer's coils prior to award of a new winding contract. In one case, these dissections led to one manufacturer changing part of the coil manufacturing process. All four generators at Yellowtail Powerplant have since been rewound without any other inservice failures being encountered.

Palisades Powerplant - four generators - rewound for 30 MVA at 0.95 power factor, 11.5 kV, 163.6 r/min, in service 2/85.

The stator windings in units 2 and 3 have always had a history of high ozone production. High-voltage ramped d-c absorption tests were conducted on unit 2 in 1981. The absorption tests revealed that the grading paint was not satisfactory. The rotor was removed and a detailed physical inspection revealed that residue from partial discharges was present in the coil end turn area, in the slots, and in areas where the coils were secured to the surge rings. There was evidence of partial discharge activity at the junction of the semiconductive slot paint and the grading paint. Corona probe tests confirmed the findings of the physical inspection. Visible discharges were also detected during blackout (total darkness) tests in areas where the residue was located. An attempt was made to eliminate the partial discharge activity by application of semiconductive paint, conductive silicone rubber, and conductive side filler in the stator slots where discharge activity was prevalent. Results of the repairs were marginal since the ozone level inside the generator air housing returned to the prerewind concentration during operation. The repairs are presently scheduled for uprating and rewinding.

Spring Creek Powerplant - two generators, rewound for 100 MVA at 0.90 power factor, 13.8 kV, 225 r/min, in service 7/81.

Installation of the original bar windings in unit 2 resulted in very high levels of partial discharge activity between the end turn areas of the bars. The coil design had insufficient clearance between bars in the end turn area, causing excessive voltage stress. The top bars in the slots had to be replaced with new bars designed to provide additional clearance between end turns. The new bars were coated with conductive epoxy and paper in the slot area just before installation and were held in place with compressible filler materials (ripple springs). Partial discharge in the slot is not a problem on these windings.

Hoover Powerplant - Unit 8 rewind, 115 MVA at 0.95 power factor, 16.5 kV, 180 r/min, in service 4/82.

The new winding provided a painted, semiconductive shielding system in the slot portion of the coil and was secured in the slot with compressible filler material (ripple springs). Inspection after 2 years of operation revealed moderately high levels of partial discharge activity and small damaged areas of semiconductive paint in the slot portion of the coil. No side filler had been used to hold the winding firmly in the slots. Approximately 70 percent of the wedges were loose. Measurements of ripple spring tension indicated almost complete relaxation of the spring compression. Most of the winding had become extremely loose in the slots. The unit was rewound after the addition of side filler and sufficient edge filler to compress the ripple springs.

Mt. Elbert Pumped-Storage Powerplant - Unit 1 - 105 MVA at 0.95 power factor, 11.5 kV, 180 r/min, in service 7/82.

Inspection of the motor/generator after 1 year of operation revealed loose wedges but low levels of partial discharge activity in the slots. Ripple springs were not used to secure the winding in the slots. Slippage of side filler was evident. Repairs included adding side and edge fillers, and then rewinding.

Mt. Elbert Pumped-Storage Powerplant - Unit 2 - 105 MVA at 0.95 power factor, 11.5 kV, 180 r/min, in service 2/84.

Inspection after 1 year of operation revealed loose wedges but low levels of partial discharge activity in the slots. Evidently, the wedges loosened but the coils did not lose contact with the stator iron ground plane. Loose wedges were tightened.

Grand Coulee Pumping Plant - Unit P/G-9 - 53.9 MVA, 13.8 kV, 200 r/min, in service 4/84.

This unit is also a pumped-storage-type unit, but it is used almost exclusively as a pump. Inspection revealed 75 percent of the wedges were loose, but measured partial discharge levels were low. The unit was rewound with redesigned wedges to accommodate ripple springs.