KEEPING STATOR AND ROTOR WINDINGS CLEAN

Greg Stone and Earl Goodeve
Iris Power Engineering

One of the most common maintenance tasks in a hydrogenerator is cleaning the windings of a generator to remove contamination and debris from the windings. Most generator operators perform this task to some degree every 1 to 5 years. If done properly, a significant outage is necessary, and several people are needed for many days to perform the cleaning. Thus there is considerable cost. To minimize the cost, cleaning should only be performed when it is needed, and when done, the cleaning should be performed with the most effective methods and materials available. This article addresses these two issues. To put cleaning in perspective however, we first describe where contamination comes from, and the effect of this contamination on rotor and stator windings.

SOURCES OF CONTAMINATION

Contamination and debris may come from within the hydrogenerator or from outside of the machine. One of the most serious sources of contamination is from oil released from the generator bearings. In particular a leaking upper guide bearing enclosure results in oil dropping directly into the machine and eventual distribution throughout the stator and rotor by centrifugal and ventilation action creating an oily film everywhere. Combined thrust and guide bearings placed below the rotor can also contribute to contamination through the introduction of an oil vapor or “mist”. This generally occurs when differences in air pressures within the ventilation path and the bearing oil reservoir permit oil to be drawn out of the reservoir around the bearing seal area.

Another overlooked source of oil is that from a high-pressure oil lift system. While this does not generally present a problem during normal operation, since it is used only on starts and stops, the oil lift system operates at very high pressure. Pipe leaks are common and can introduce oil into the machine and eventually onto the winding.

Carbon dust is also an inevitable contaminant. In all but the very newest machines (and not even in all of them) the carbon brushes used on the generator slip rings are in the same cooling air path as the remainder of the generator. Because of this, the carbon dust that is created is actually circulated throughout the machine. In a dry machine, this dust will normally collect in stagnant air areas of the machine, usually outside of the actual stator frame. However, in the presence of oil leaks, this dust adheres to all oily surfaces and will quickly and thoroughly contaminate all components. This contamination can be quite conductive (see later).

Another significant internal source of contamination is from the operation of the brakes that are used to hasten slowing down of the rotor when shutting down the hydrogenerator. The material in the brake pads, asbestos for older machines and non-asbestos replacements in modern machines, abrades away, and is distributed over the windings by the circulation of the cooling air though the machine.

Of course another source of contamination or debris is materials left within the generator enclosure during assembly or maintenance. Such material can include rags, paper wipers, tools, insulating materials, cigarettes, etc that are inadvertently left behind. Although these objects have significant size, they tend to be ground down to a smaller size if they are picked up in the cooling air flow and are forced through confined spaces such as the air gap. (Of course a metallic object may not move due to airflow, but may move under the influence of magnetic fields.) Ironically, another source of debris is the residue left over from cornhusks, walnut shells, etc. that is used to abrasively clean the windings (see later).

There are also several sources of external contamination and debris:

- the most important is the humidity in the atmosphere, which can condense onto the windings when the generator is not running
- insects that get sucked into the machine
- other materials that may be in the plant environment such as pollen, sand, dirt, etc.

Of course these external contaminates have a greater impact on the windings if the generator is open ventilated, that is the cooling air is directly drawn in from the plant environment. Many older generators and machines smaller than a few tens of megawatts tend to be open-ventilated.

The solids from the internal and external debris tends to mix with moisture or oil to settle on the coils, as well as within narrow ventilation channels, such as the cooling ventilation ducts in the rotor and stator cores.

IMPACT OF CONTAMINATION AND DEBRIS ON WINDINGS

There are several ways that debris and contamination will affect the life of a rotor and stator winding.

Overheating

When coarse debris is present within the machine enclosure, this debris often collects in narrow passages within the stator or rotor cores. Specifically, the debris gets caught in the radial cooling ducts within the stator core. The coarse debris may also partially or completely fill the spaces between coils in the endwinding. The result of this coarse debris is that there is less cooling air moving over the stator and rotor cores, because air passages are partially or completely obstructed. The result is that the I^2R losses of the stator and rotor windings are not as effectively dissipated, raising the temperature of the windings, either in localized spots (where most of the blockages occur), or globally if passages are blocked everywhere. The higher operating temperature then 'cooks' the rotor and stator winding insulation at a faster rate. Eventually the insulation may become aged enough that it is brittle and loses electrical strength.

Perhaps the most common and widespread occurrence within any given machine is the overheating that occurs if fine (powder type) debris mixes with oil. This type of debris coats the surfaces of the coils, especially in the endwinding, and also reduces the crossectional area of ventilation passages through the cores. The extra coatings on the coil endwinding increase the thermal impedance of the groundwall insulation, and thus makes it harder for the I^2R heating from the copper in the stator endwindings to get through the combined electrical insulation and contamination layer. The result is a higher endwinding temperature, which will accelerate thermal deterioration of the insulation. In the core area, oil and dust can relatively quickly restrict airflows resulting in either a high temperature band or zone within the core iron or, if widespread, the entire core and consequently increasing the temperature of the winding within the stator.

Electrical Tracking

Oil or condensed moisture mixed with many kinds of fine debris such as ground-up salts, insects, dirt, etc will create a partly conductive film that is deposited over the endwinding. This partly conductive contamination results in tiny 60 Hz currents flowing over the surfaces of the insulation. These currents degrade the organic components of the insulation, leading to electrical track formation, and eventually fail the groundwall insulation. This problem has a greater probability of occurring in machines with high operating voltage (11 kV or higher).

The problem normally only occurs in the endwindings of stators. If the contamination has some conductivity, say less than a few tens of megohms per square, then currents can flow if a potential difference exists. Figure 1 shows the cross-section of two adjacent coils in the endwinding, together with an equivalent circuit. Assume the coils are in two different phases. The contaminated surface of the A phase coil will have a tendency to float up to the voltage of the copper within the coil, by capacitive coupling. Similarly, the B phase coil surface will tend to float up to the B phase voltage. Blocks and ties used for stiffening the endwinding structure and for electrically separating the coils bridge these surfaces. The surface of the block represents an "electrical resistance" of the contamination across the block. The equivalent circuit in Figure 1 shows the results. If the two coils are phase-end coils in two different phases, then during normal operation the full phase-to-phase voltage is applied to the equivalent circuit, and current will flow. If the contamination resistance is high compared to the capacitive impedance of the coils in the contaminated area, then the surface of the coils is almost at the same voltage as the underlying copper conductors, and nearly full phase voltage is applied across the block.

If the contamination had a very uniform resistance across the block, then little deterioration is likely to result, since the current is low (nanoamp range), and flowing uniformly across the surface. However, in reality, there are 'dry bands' where the resistance is much higher than the general resistance of the contamination. In this case, virtually the entire voltage will then appear across the small dry band, causing electrical breakdown of the adjacent air. The discharge degrades and may carbonize the underlying organic resin and tapes. This small area is eventually left very conductive. The electrical stress then transfers to another region of high resistance, where discharges ensue. The result is an electrical track, which slowly grows across the insulation (Figure 2). The track often has many branches, and appears as a carbonized, black network across the blocking. Given time, the discharges will also start boring into the groundwall. If the track is between coils in different phases, a phase-to-phase failure results, which allows extremely large fault currents to flow. Alternatively, tracks can appear between coils in the same phase, if one coil is near the phase end, and the other is near neutral. Similarly, tracking can occur along a coil between the core and further into the endwinding (Figure 3).

This mechanism is usually very slow, often taking more than 10 years from the time the winding is contaminated to when it fails. Although stator windings are most affected by this type of contamination, it is sometimes also possible for the contamination to become so conductive that turn to turn shorts or turn to ground shorts may occur in salient pole rotors with bare copper conductors on the rotor poles.

Loose Stator Windings

Windings must be kept stationary within the stator core slots. If they become loose for any reason, the huge 120 Hz magnetic forces that are acting on the stator bars and coils will tend to cause the coils to vibrate in the slot. Coil vibration will cause the coil insulation and semiconductive coating to abrade against the laminations of the stator core, resulting in ‘slot discharge’. Although this mechanism is usually associated with inadequate wedging or support in new windings, or gradual shrinkage/relaxation of the wedges and insulation in aged windings, the presence of oil contamination can accelerate the process. Oil is a lubricant, so that if the sidepacking or wedging is not completely effective, the oil will facilitate relative motion between the coil sides and the core-leading to abrasion. (This is often observed as ‘greasing’, since the fine powder released by the abrasion mixes with the oil to create a thick sludge at abrasion points within the slot and at the slot exits and visually resembles grease.) In addition, many machine manufacturers use either top or side ‘ripple springs’ to fix the coils/bars within the stator slots. The ripple springs expand as the coil insulation or wedge material shrinks/relaxes over the years, to keep the coils tight. Unfortunately, there have been reports that the ripple springs ‘lose their spring’ if they are subject to oil contamination for long periods of time. Thus oil again contributes to coil loosening and slot discharge.

Magnetic Borers

Of course large metallic objects left within the hydrogenerator, may immediately fail a rotor or stator winding if they are near the coils, and due to magnetic or moving air effects, cut through the insulation to cause a short. However, smaller bits of metallic, ferrous debris may also result in winding shorts. Such debris, for example steel filings or small curls of metal from drilling or tapping holes in the machine, tend to move to areas of high current, due to the magnetic fields. They then tend to bore through the insulation, causing a short. This can sometimes be a very slow process.

DETECTING CONTAMINATION AND DEBRIS

When a machine has been completely or partly disassembled, it is usually easy to detect that there is severe contamination which may lead to any of the above problems. That is, the cooling ducts will be partly or completely plugged, the spacing between the endwindings may be closed off, and/or there is an oily film over the endwindings. If one investigates the stator endwindings more closely, then one may also see the formation of electrical tracks (Figures 2 and 3), if they are present.

Detection of contamination or debris without disassembly would be more cost effective and less invasive. In a brief shutdown, the insulation resistance and polarization index (PI) tests can be performed. As described IEEE Standard 43-2000, a low insulation resistance or low PI suggests that there are partly conductive films over the stator endwindings or rotor windings.

Another non-invasive technique of detecting contamination, especially where debris is partly or completely blocking the cooling system, is to trend the stator winding temperature and the rotor winding temperature (where such monitoring is fitted) over time. Under the same load and ambient cooling water/air conditions, the winding temperatures should not vary more than $1^{o}C$ or so. If there is a gradual increase in temperature from the same sensor over the years, then one cause may be that the cooling is becoming less effective, possibly due to debris and contamination. (Since there are generally multiple temperature sensors, a rise is generally observed in more than one.) In the past, trending of temperature under the same load/ambient conditions was tedious. However, with the modern computer systems now used in many plants, this data is archived. A simple selective database search can often easily uncover any gradual increase in temperature.

Another powerful method to detect stator (not rotor) winding contamination/debris is on-line partial discharge (PD) detection [xx]. If the insulation overheats, the mica layers within the groundwall delaminate, creating air pockets within the insulation. Air pockets within coils connected to the phase terminals (i.e. operating at high voltage) will then electrically break down (creating small sparks) – which is called a partial discharge. Thus PD is a symptom of thermal deterioration, and hence the contamination which accelerates thermal deterioration. Similarly, if the contamination causes electrical tracking, by definition, the tracking process creates PD. Finally, where oil contamination accelerates the loose winding failure process, the abrasion will gradually wear away the black semiconductive coating in the slot and the insulation. Once an air gap appears between the coil surface and the stator core, PD (also known as slot discharge in this circumstance) occurs. The most well known method to measure the PD activity in an operating hydrogenerator is the PDA test [xx].

CLEANING METHODS

A variety of cleaning methods are available for rotor and stator windings, with varying degrees of effectiveness.

The most thorough and rapid cleaning method might be called particulate blasting. This is where materials such as ground-up corncobs, walnut shells or dry ice (frozen CO_2) are 'blasted' at the winding surfaces at high velocity using special equipment. In essence it is the electrical equivalent of sandblasting. The idea is to remove the bulk of any debris and surface contamination by the force of the propelled material. Skilled personnel are required for the blasting method since if the nozzle that is blasting particulate is held over the insulation for too long, the coil coating and even the groundwall insulation can be rapidly abraded, creating a weakness in the coil. Usually, the stator or rotor winding must be encapsulated in a temporary tent to contain the particulates and debris, and personnel must use breathing apparatus. After particulate blasting is completed, a significant effort is needed to vacuum up the blasting material and removed contaminants, and for inspections to make sure any remaining material does not block ventilation gaps in the rotor or stator cores. For hydrogenerator applications, many users believe that the most effective blasting particulates for removing both debris and oil are corncobs or walnuts shells. Dry ice blasting has the advantage that the particulates do not have to be vacuumed up. However, dry ice does not seem to be as effective at removing oily contamination.

One very small hydrogenerators, it may be practical and possible to steam clean them in a manner similar to that used on motors. However, this is not a common practice and is seldom applied due to difficulties in heating the stator core sufficiently high to prevent excessive condensation within the stator and hence re-depositing or positioning of the contaminant.

A more labor-intensive process is to manually clean the stator endwindings and rotor windings. This involves equipping staff with rags and either a solvent or a water-based detergent, and cleaning with 'elbow-grease'. In the past solvents such as **trichlorethylene** were very effective in removing grease and oil contamination. Such materials constitute a health hazard, and are no longer permissible. Today, citrus-based solvents or just detergent and water are more common. With this approach, many areas of the winding cannot be effectively cleaned because they are essentially inaccessible. Care must be taken to ensure the solvent or detergent/water mixture does not degrade the insulation. In addition, cleaning with liquids or solvents can "transport" contamination, especially brush carbon and brake dust into areas where it is inaccessible and can cause future problems. Usually most modern insulation systems such as epoxy mica and polyester mica are essentially impervious to common cleaning liquids.

If the windings have been contaminated by moisture alone, then the windings can be dried either by blowing hot air over the windings, or by circulating a current through them with a welding machine. It may take days to dry a winding. The length of time for applying heat or hot air can be determined by when the insulation resistance increases to the acceptable minimum (100 Megohms for modern windings) or a polarization index >2, according to IEEE 43-2000.

PREVENTIVE ACTION

The most effective means of preventing the ill effects of contamination is to ensure it does not occur in the first place. When maintenance is being done, many utilities find it prudent to restrict access to the machine, and ensure that all items (and especially metallic objects) that are not required for work within the machine are excluded from entering a well-defined perimeter. Furthermore, all tools should be logged on entering the generator perimeter, and again when leaving the perimeter. Finally, a thorough cleaning and visual inspection of the machine is conducted before it is returned to service. The purpose of all this is to make sure that both large and small objects are not left within the machine and become a hazard to the windings.

Other preventive measures include:

- Keeping the oil out. As mentioned above, oil is a contaminant that can cause several problems. The most likely source of oil is the upper guide bearing (where present) since any loss here, even in a pipe, will drip into the machine Good maintenance procedures and strictly following the manufactures guidelines will minimize the likelihood of oil from this bearing dripping onto the rotor. The same applies to the main thrust and guide bearing. Persistent leaks here (as well as the upper bearing) are often the result of a low air pressure area immediately outside of the bearing housing actually drawing oil up past the shaft seal area. Oil vapor extraction system modifications and/or adjustments may correct this problem. Also, most machines use baffles (often a circular ring of thin steel around the shaft and fastened to the machine brakes) to control cooling airflows over and under the rotor. Some minor adjustment of these may be all that is needed to stop a seal leak. However, adjusting these directly impacts cooling of the unit and should not be done indiscriminantly or without consultation with the machine manufacturer.

- Maintain the piping system for the oil lift system.

- Plant operators should be trained to minimize the use of brakes, and when used, to use them properly to minimize the amount of debris that is created when applying the brakes.

- Of course, for enclosed generators, the filters used to keep debris outside of the generator enclosure must be fitted, and cleaned regularly.

References

1. J.F. Lyles, T.E. Goodeve, G.C. Stone, "Using Diagnostic Technology for Identifying Generator Winding Maintenance Needs", Hydro Review, June 1993, pp 58-67.

Figure 1 (see 8-7 in Visio file): Cross section of two adjacent stator coils that are the phase end coils in two different phases, with electrical equivalent circuit.

Figure 2: Electrical tracking (the carbonized, lightening-like lines) over an insulating block between two phases caused by electrical currents flowing in surface contamination.

Figure 3: Photo of phase to ground electrical tracing over the noises of several stator coils.