WATER-COOLED STATOR WINDINGS COPPER OXIDE ISSUES

Clyde V. Maughan, President
Maughan Generator Consultants
Schenectady, NY, USA

Mathias Svoboda
SvoBaTech AG
Wuerenlingen, Switzerland
ABSTRACT

Direct water cooling of stator windings has been common since the early 1960s. In general these windings have performed well, although as would be expected in any liquid system involving many varied components, there have been problems with leaks, leaks both large and small. Equipment manufacturers working with user have developed procedure to effect necessary repairs relating to these leaks.

Perhaps less expected have been problems with copper oxide formation within the hollow copper strands which carry the water (as well as electrical current). Two types of oxide can be produced, cupric (a black compound, CuO) and cuprous (a red compound, Cu₂O).

This paper will briefly summarize some basic stator winding design, operation and monitoring considerations relating to water cooling, and will then discuss in some detail parameters relating to oxide buildup and removal.

STATOR WINDING DESIGN CONSIDERATIONS

Importance of Water Cooling

Throughout the history of the power industry, there has been a steady demand for larger and larger power generating units. By the 1950s it had become clear that in order to build the large generators needed by the power generation industry better cooling methods would be needed. Hydrogen atmosphere cooling had been initiated in the late 1930s, and this reduced windage losses to about 1/14th of air atmosphere. The hydrogen atmosphere also generally improved heat transfer. But stator winding cooling capability was now the limiting parameter.

To meet this need direct-liquid cooling of stator windings was introduced. The first stator with direct-liquid cooling was manufactured in about 1954; the initial liquid was transil oil, the oil used in transformers. However, because of viscosity and other issues, water was a more powerful coolant and transition to water came almost immediately. And with this transition came the copper oxide problem.

Application of direct liquid cooling considerably complicated the stator bar, Error! Reference source not found., the winding itself, Figure 2, and added an external liquid supply system, Figure 3 and Figure 4.

Figure 1: Typical modern bar cross section with one hollow and four solid strand arrangement.

Figure 2: Endwinding of water-cooled stator winding.

Figure 3: External pumping unit for water-cooled stator winding. GE.
Even so, because of the power of direct-liquid cooling, transition to liquid cooling of large generators almost immediately occurred.

**Effects of Restriction or Loss of Water Flow**

Water-cooled stator windings are conservatively designed with cooling water discharge temperature in the 70-85°C range. This limitation was placed on maximum water temperature to assure significant margin to boiling temperature of water. This margin is important because if water boils anywhere in the length of any bar there is the possibility that the resulting steam could effectively block water flow in that bar.

If water flow to a bar is lost, that bar will then become indirectly cooled. Copper temperature will quickly rise to the vicinity of 300-400°C. The bar will become ½ to 1” longer, depending on core length, than adjacent bars in the winding, and will fracture the groundwall insulation of the bar in the first radius of the endwinding at each end of core.

This condition should immediately trip the stator winding ground detection relay since insulation failure would be in the end arm grading paint region. With a single-ground trip there should be no consequential damage to the winding or core. However, if the condition evolved into simultaneous double grounds, damage to the generator will be severe.

**SERVICE CONSIDERATIONS**

**Monitoring, in General**

It is not possible to accurately monitor several important generator degradation mechanisms, and unfortunately liquid-cooled stator winding systems fall in this poorly monitored category. In particular copper oxide buildup within the copper strands can only be assessed indirectly. For example, if excessive oxides are collecting in the system water filters and strainers, concern must be raised on the bars themselves.

But the primary monitoring capability focuses on indirect assessment of water flow in each bar circuit. Widespread buildup of oxide blockages can be detected by monitoring pressure drop across the winding. But since buildup may not be uniform among the bars, outlet water temperature measurement is normally provided for each bar, or pair of bars. A thermocouple (TC) is normally located in each of the water discharge hoses.

But unfortunately many manufactures, e.g., GE and their licensees, typically read the mixed water flow from 2 bars in series or parallel. Thus if one of the bars is losing flow, sensitivity to that loss of flow is low. If one bar loses flow completely (in a parallel arrangement), the condition is unlikely to be observed by the TC since the TC will see normal temperature water from the unaffected bar.

Even in windings with one TC for each bar small changes in temperature readings may not be noticed. Complete loss of flow, particularly if sudden, may not be detected since the TC will be cooled by ventilation gas flow.

This lack of sensitivity is a major weakness as an increase of outlet water temperature of only 2 or 3°C may be very significant.

Temperature of the water is very indirectly measured by the slot resistance temperature detectors (RTDs). The reading from the RTDs is
insensitive because these devices read some aggregate of copper temperature of each of the 2 bars (through a thermal insulation blanket), the core iron temperature, and gas flow in the vicinity of the RTD. Thus a temperature rise of 2 or 3°C in one bar is unlikely to be detectable by slot RTD temperature.

Industry Experience

While copper oxide buildup in windings is rather common, actual winding failure apparently is rare. A question on the International Generator Technical Community (IGTC) web site did not produce a verifiable incident of known failure, nor did informal query of many generator service experts. Since failure vulnerability would seem significant, this is rather surprising to the authors. Explanation could be speculated: 1) the windings are designed with high temperature margin, 2) monitoring while somewhat indirect and weak does provide early indication of oxide formation, 3) flushing capability is readily available in the event of suspected oxide buildup, 4) failure mode may be similar to other causes of winding failures.

However, relating to the last point, if a bar fails due to loss of cooling, the fracture of insulation at both ends of the bar will be a large obvious tear. Careful evaluation of the bar strands will reveal plugging due to copper oxides or other obvious blockage of water flow. Thus it is difficult to believe such a failure will be mis-diagnosed by a knowledgeable engineer.

In the event multiple bars are involved, with the inevitable severe arc damage, diagnostics could be more difficult. But copper oxide buildup in the hollow strands should be widespread, heavy and prominent, leaving oxide buildup the prime suspect as root cause.

Non-copper Strands

During the last 40 years, many windings have been made with stainless steel tubes carrying the cooling water (Figure 5).

This design eliminates the possibility of copper oxide formation and has proven to be reliable providing endwinding resonances which may fracture the stainless tubes are avoided.

STATOR WATER CHEMISTRY

Water Oxygen Content

High purity water has satisfactory insulating properties. However, only minute amounts of impurities can raise conductivity considerably, which is why a demineralizer is always installed in a side-stream to the system to continuously purify the water. Furthermore, unless water is maintained at high-dissolved-oxygen or low-dissolved-oxygen conditions, oxygen in the presence of water and copper tends to be somewhat aggressive in forming copper oxides.

The General Electric designers of water-cooled stator windings chose to operate with high-oxygen cooling water chemistry by keeping an air blanket over the water in the storage tank (System is intended to be open to atmosphere). Most subsequent designers chose the low-oxygen route by either keeping a hydrogen atmosphere over the water storage tank or designing the storage tank in a dead end. (System is isolated from atmosphere.) Either approach can be satisfactory, but industry surveys tend to show a preference of high-oxygen as the more trouble-free approach.

High-oxygen systems are designed to have their water storage tanks open to atmosphere through a vent line. As long as this vent is actively communicating with the atmosphere and high
hydrogen leakage into the tank circuit does not occur, high-oxygen conditions should continue to exist. However, it has been observed that this exchange may be insufficient (diffusion alone may be ineffective) and the system can starve of oxygen. Installation of the Stator Leak Monitoring System (SLMS) or a similar system will guarantee high oxygen content at all times by continuously blowing air into the stator cooling water tank.

The higher oxidation rates tend to require higher demineralizer flow rates (10 to 20% of total stator cooling water flow) and capacity compared to low-oxygen chemistry.

With the low-oxygen systems, leakage of air into the system must be prevented. Air entry may occur, for example, due to pump shaft seal leakage or winding discharge piping leaks. Oxygen in make-up hydrogen impurities can also get into the water and oxygenated make-up water has been known to cause problems if introduced in sufficient quantities. Random problems of this type are unpreventable.

On the other hand, lower oxidation rates in a closed system allow relatively compact demineralizer systems that only require 2-5% of total system water flow to be diverted through their bypass loop, and no gas injection system is needed to maintain conditions.

**Alkaline Chemistry**

It was found that apart from dissolved oxygen content, pH is another major factor affecting the process of stator bar plugging with oxides (Effertz & Fichte, 1974). Accordingly, utilities and later OEMs started experimenting with increased pH in the stator cooling water. Increasing pH, alkalinization, can help stabilizing the oxide layer by lowering the solubility of copper and its oxides in water. The same effect also helps mitigating consequences of short episodes of unfavorable oxygen concentrations.

Increasing pH requires the controlled injection of an impurity into the stator cooling water system, consequently elevating its conductivity. Monitoring becomes more complex, and the additional subsystem has to be taken care of and properly maintained.

In the end, four distinct chemistry regimes have developed to control plugging (Figure 6). Each of the regimes has advantages, and each of the regimes can have its problems (CIGRE, 2011).

![Figure 6: Stator cooling water chemistry regimes. The graph represents the two most important factors influencing copper release rate (corrosion) and thus oxide plugging in the stator cooling water system.](image)

Dissolved oxygen and pH are on the x- and y-axis, while the copper release rate is indicated by colors, from green (low release rate) to red (high release rate). It is evident that intermediate dissolved oxygen levels result in increased copper release rate and thus are to be avoided, and why one major OEM and some utilities decided to use alkaline chemistry in their systems. (Svoboda & Seipp, 2004)

**Conversion Between Regimes**

Changing from one chemical regime to another, e.g., high-oxygen to low-oxygen, requires detailed planning and can involve major hardware upgrades as well as procedural changes. Also it is important to recognize that every chemistry change, be it by accident or after careful deliberation, challenges stability in the oxide layer, which can lead to rapid hollow conductor plugging.

Because of the inherent complexities, dangers and unknowns, system conversion is generally not recommended or attempted.
Plugging with Copper Oxides

Plugging of the stator hollow conductors with copper oxides can be described as a four-step process (Svoboda & Seipp, 2004). It is a gradual development from barely noticeable deposits to complete blockage of a hollow conductor. The process can take years or merely weeks, depending on conditions.

Figure 7: The plugging process with copper oxides. (Svoboda & Seipp, 2004)

The plugging process with copper oxides can be broken up into 4 phases (Figure 7):

1. **Oxidation**
   In presence of copper, water and oxygen, an evenly distributed layer of copper oxides is formed. This very thin (in the order of 1 µm) layer always consists of a mix of oxides and some amounts of metallic copper. The oxides formed by copper are the reddish cuprous oxide ($\text{Cu}_2\text{O}$) and the black Cupric oxide ($\text{CuO}$).

2. **Release**
   In contrast to the oxide layers on stainless steel or aluminum that protect their base metal below, the oxide layer on copper slowly dissolves in water and is somewhat porous. The release rate depends on several factors, most prominently the amount of dissolved oxygen and pH. Oxides can be released both as particulates and in dissolved form.

3. **Migration**
   The oxides then migrate until they are caught in the demineralizer or filters, or are trapped in depositions.

4. **Deposition**
   If conditions are favorable for crystallization in some areas, the oxides may deposit in these locations. This leads to a concentration of the before released oxides. This usually happens in zones with high turbulence and flow velocity changes, such as the hollow conductor inlets and outlets, system strainers, or sometimes the Roebel transpositions.

**MONITORING OF FLOW RESTRICTIONS**

**Oxide Formation**

The normal and expected oxidation in itself is not an issue, as the oxide layer is not much thicker than a few micro meters.

But as discussed above, changes in chemistry and the oxide layer can lead to mobilization of these oxides, so any changes or trends in the monitored parameters – physical or chemical – should be investigated and corrected.

Once the oxides migrate and re-deposit, even small amounts can start restricting flow in the hollow conductors. At that time external signals may become visible.

If signs of oxide plugging are observed, the condition is probably in an advanced state and demands immediate attention in order to avoid running into alarm. Continuing oxide buildup can eventually lead to potentially irreversible plugging of hollow conductors and possibly winding failure.

While oxidation happens uniformly across the whole copper surface, plugging affects some bars more than others. For this reason, parameters that monitor individual bars react more sensitively to flow restrictions than global parameters.
Monitoring and Assessing Oxide Buildup

Important parameters to observe and monitor include:

- **Generator history/fleet comparison**
  Comparing with sister units or commissioning data can already give a good indication if a machine’s behavior deviates from normal.

- **Visual inspections**
  If plugging is suspected, it may be necessary to inspect the inside of water boxes and Teflon hoses as this is the most reliable way to spot oxide buildups. Most oxide plugging happens inside the clips and thus is visible by borescope. These inspections are difficult and costly and can only be carried out infrequently for obvious reasons.

- **Physical parameters**
  These parameters can give an indication that the stator is plugging up. Usually the process is already at an advanced stage once plugging becomes visible through physical parameters, and action should be taken.

  - **Temperatures**
    The most useful physical parameter to monitor are temperatures. In the best case, each outlet Teflon hose and stator slot is equipped with a temperature sensor. This allows monitoring the temperature spread, which reacts more sensitively to plugging than global water temperatures.

  - **Stator cooling water flow and pressure drop**
    It is important to monitor both these parameters, and if flow decreases while pressure drop across the stator remains constant or increases, the machine should be investigated for plugging.

  - **Chemical parameters**
    While physical indicators talk of plugging that has already happened, chemical parameters can give an early warning that something is going on in the system that can lead to plugging.

  - **Copper release rate**
    Measuring and trending the amount of copper released into the stator cooling water and collected by the filters or demineralizer lets the operator know when oxides start to migrate.

  - **Dissolved oxygen (dO)**
    Oxidation as well as copper release rates are directly influenced by the amount of dissolved oxygen in the water. This parameter is one of the defining characteristics of a cooling water chemistry regime. Intermediate dO values can lead to rapid and severe plugging.

  - **Electrochemical corrosion potential (ECP)**
    This parameter indicates when chemical conditions are favorable for corrosion and plugging. It integrates several factors, including pH and dO, and is the most immediate and most targeted early warning available for copper oxide plugging.

PREVENTING COPPER OXIDE FLOW RESTRICTIONS

There are many issues that can result in copper oxide buildup at undesired locations. A few general rules listed below apply to all machines and should always be followed. However, this set of rules is not all-inclusive. Many machines develop their own peculiarities, be it by a design quirk, a defect or just aging. If these case-specific issues are addressed as well, oxide formation problems can often be mitigated before they start causing downtime.

**General Precautions**

- **Keep conditions stable and within prescribed range**
  Changes in water chemistry, but also physical stress on the oxide layer (e.g. from
rapid temperature changes or excessive flow velocity), can destabilize the oxides and cause increased copper release rates.

- **Keep conductivity low**
  In a well-designed and properly maintained closed-loop system, continuous flow through the demineralizer should assure that conductivity never becomes elevated. If conductivity is allowed to increase, numerous problems can be expected, e.g., out of range pH, excessive oxide formation, plugging of filters.

- **Minimize leaks**
  - **Gas-to-water leaks**
    Hydrogen can displace the air in the stator cooling water tank in high-oxygen systems, and air leaks can introduce undesirable oxygen in low-oxygen systems.
  - **Water leaks**
    Inside the generator casing, water leaks can lead to significant damage, up to destruction of the windings. Outside the generator casing, make-up water will have to replace the lost water.

- **Minimize make-up consumption**
  Make-up water can introduce oxygen and other impurities and should be minimized in a closed-loop system.

- **Follow proper layup procedures**
  Improper layup is one of the main causes for stator cooling water system plugging (EPRI, 2013). As soon as the cooling water is not circulating anymore, chemistry starts to deviate from its normal condition and cannot be monitored anymore. Draining a system without drying results in an air-saturated water film of acidic pH that is not compatible with the oxide layer present on the copper surfaces.

**Examples of Case-specific Plugging**

Every machine is unique and has its unique points to address. The following four examples serve to illustrate some of these measures. All four cases required chemical cleaning to restore cooling water flow.

- **Control hydrogen purity and gas-to-water leaks**

In Plant A with a low-oxygen system, minor gas-to-water leaks allowed air from impurities in the hydrogen to enter the stator cooling water system. The resulting loss of low-oxygen conditions resulted in plugging within a few months. Correcting the leaks and bringing hydrogen purity under control, followed by a costly outage for chemical cleaning, brought conditions back to normal.

- **Ensure proper operation of stator cooling water tank and enforce aeration**
  In Plant B with a high-oxygen system, the storage tank vent line was improperly functioning. Normal hydrogen diffusing through the Teflon hoses displaced the oxygen in the expansion tank and starved the cooling water of oxygen. Installing SLMS, which also bubbles air into the expansion tank, restored high-oxygen conditions in the system.

- **Minimize water losses**
  In Plant C with low-oxygen chemistry, stator cooling water was lost through the gas vent each time the gas release valve on the gas detraining tank was opened. The gas then pushed the water column in the vent line outside to the roof. This water was consequently replaced by aerated make-up water, which allowed entry of enough oxygen into the system to plug up the machine within a year.

- **Dry stator thoroughly during outages**
  Results of improper layup during several refuel outages in a nuclear power plant with low oxygen chemistry caused oxide plugging. The stator was drained with gravity alone by opening the manifold drain valves at stator inlet and outlet. Due to stator geometry, some bars drained, while others kept the water inside. Bars that drained, slots 24 to 1, were thus exposed to air. The water films on the metal became air-saturated, and as a consequence the bars started plugging up and had higher temperature rises, Figure 8.
REMOVING COPPER OXIDE BUILDUPS

Finding and eliminating the root cause should always be the first step, as removing the symptoms is otherwise often only a temporary remedy. If the root cause cannot be found or immediately taken care of, measures to slow down or reverse the oxide buildup need to be taken if possible.

Chemical cleaning is normally a reliable method to remove copper oxides from the stator cooling water system. Some methods can even be applied while the generator is operating.

But once hollow conductors are completely plugged, chemical cleaning methods are not effective anymore. More invasive mechanical cleaning methods necessary, but even then there is a chance the plugging becomes permanent if timely corrective action is not taken.

Methods in Use

Methods to remove plugging can be divided in mechanical and chemical methods. Both have advantages and limitations.

Mechanical Cleaning. These procedures only remove part of the oxides locally, but can open completely blocked hollow conductors to make them available for chemical cleaning. The different methods require varying degrees of access to the oxide plug. This can mean anything from removing the Teflon hose to unbrazing the water box. There is a risk of damaging the stator bar in the process. They build on the fact that in most cases, oxide plugging can be found at the inlet or outlet of the stator bar.

Common mechanical cleaning methods include hot reverse flushing (flushing the stator in reverse with hot water, removing mostly particles) or simply scraping at the oxides with wires or brushes. The latter can be very effective in breaching oxide plugs at the hollow conductor ends.

Chemical Cleaning. These methods can remove all the oxides from the system as long as the chemicals have access to them; they cannot access completely plugged hollow conductors.

If done incorrectly, chemical cleaning carries considerable risk. Risks range through incomplete cleaning, instable oxide layers, release of clumps of oxide buildup, damage to system materials such as brazing joints.

This is especially true for the oldest of chemical cleaning methods applied to generators, acid cleaning. Those methods were adapted from the methods of cleaning the steel boiler components. In the stator, acid cleaning works by reducing the pH in the water, and subsequently dissolving copper oxides. Depending on the acid used, their effect is not targeted at copper oxides alone, but also affects the copper walls themselves as well as the brazes.

For this reason, the amount of acid cleaning applications for a stator bar is usually limited to one or two application during its lifetime by the OEM.

A more modern approach is to use a group of chemicals known as chelants. Their name derives from the Greek “chelè” (claw), as their molecules grab a substance like a claw. Of these, EDTA, with its exceptionally strong bond to the copper from cupric oxide (CuO), proved to be
the most useful choice. Addition of oxidizers transforms Cu₂O to CuO, making it available for removal by the chelants.

Chemical cleaning with EDTA thus only removes copper oxides and does not attack any system materials, e.g., strand copper, braze materials or valves and piping. As its effect is not dependent on concentration, it can be so well controlled that it is possible to apply an appropriate process online while the plant is in operation. The amounts of copper removed can be calculated in real-time.

The EDTA-copper complex remains dissolved in the water and typically is removed in the existing demineralizer.

It is evident that removing copper oxide buildups from a stator cooling water system requires expert know-how and can add to the damage if not done well.

**Best Practice**

Depending on the situation and background of the blockage, a course of action can be set up. The following considerations have proven to be useful.

**Identify and eliminate the root cause:** The first step should be to eliminate the root cause, if possible. Cleaning the system of oxides removes the symptoms of a problem, but rarely the root cause itself. In most cases, plugging will reoccur if the underlying cause is still present.

**Carry out coordinated chelant cleaning:** This is the most benign and least intrusive method to remove oxides from the system. It is very effective and normally is all that is needed to return the system to design parameters. Chelant cleaning can be applied both during operation with no restriction to plant load, or as part of planned maintenance during an outage. The latter is faster and costs less; otherwise there is no difference in effectiveness since chelants are not concentration dependent.

**If completely blocked hollow conductors are present:** Chemical cleaning is generally not effective when there is no flow through a blocked hollow conductor of a bar. In some cases however, a targeted and focused chemical cleaning on an individual bar with chelants might bring success. More often, a combined approach with mechanical and chemical cleaning methods interacting is the more promising option.

There is a chance that the blockage is not accessible, for example when it is located inside the bar. In these cases, the only way to return to normal operating temperatures is a partial or complete rewind.

**A proactive approach contains and eliminates the problem:** The longer oxides have time to deposit and consolidate, the higher will be the likelihood for complete plugging that cannot be removed. If flow restriction is recognized early in the process, more time is available to identify and eliminate the root cause. Often, this is all that is needed to stop the plugging process. If the situation is deteriorating rapidly, chemical cleaning may be able to “reset” the oxide layer and gain extra time until the next major outage, or until the root cause is eliminated. After that, a final cleaning will usually be advisable.

**Preventive maintenance cleaning:** It is useful to implement a preventive maintenance schedule that includes planned chemical cleanings. Such a schedule depends on several factors:

- Age of the machine: Older machines are more likely to develop problems and need more care and maintenance. This is not only relevant for the stator winding itself, but also for the whole stator cooling water system.
- Machine history: Some machines tend to plug up more than others, some have manufacturing or system installation faults, and some machine designs need closer attention than others.
- Importance of availability: It should be taken into account what impact a forced outage or load reduction would have on the plant and the grid. Seasonal demand variations can play into this, as well as the type of plant – in a nuclear plant for instance, reducing the chances of a forced
outage is often more important than for a coal-fired power plant.

- Routine schedule: A possible approach is to clean a machine after the first 10 to 15 years of operation to determine its condition. The only way to measure the amount of copper oxides in a machine is to remove them and measure the amount removed. A well-done chemical cleaning leaves the machine with a fresh, optimal oxide layer. Depending on the results, the next preventive/diagnostic cleaning can be scheduled, typically in the range of 5-7 years later. If problems start to be noticed, the cleaning frequency can be adjusted accordingly.

CONCLUSION

Water cooling of stator windings has turned out to result in numerous operation and maintenance problems and concerns. This paper has focused on providing basic design, operation and maintenance information which may be helpful in providing overall guidance. But it is clear that power plant operations and maintenance personnel should pay close attention to the specific operating instructions provided by the OEM.

In particular, close attention to the monitoring systems output, and early corrective action taken, may prevent a minor problem from developing into a major, costly maintenance outage.

Since the scope of potential problems is so wide, and possible root causes are so varied, if problems are suspected it may usually be advisable to obtain expert technical advice from the OEM and possibly other sources.

SOURCES