Changing Stator Cooling Water Chemistry

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ABSTRACT

Large generators employ direct water cooling to remove heat losses in the stator winding. This is done by including hollow conductors in the stator bars. To prevent plugging of the hollow conductors, several regimes for stator cooling water chemistry have been established. Occasionally it can be beneficial to change from one regime to the other. However, changing regimes can introduce instability in the copper oxide layers, ultimately causing plugging of the cooling water channels.

Changing a chemical regime requires thorough planning and can involve major hardware upgrades as well as procedural changes. It is important to have contingency plans ready if conditions deviate from the expected during and after the changes to facilitate troubleshooting.

Rewinds require special attention if the current cooling water system is reused. They also present an opportunity to directly investigate problems within the stator bars and water boxes.

As recommended by different original equipment manufacturers (OEMs) it might be useful to chemically clean the entire stator cooling water system to provide a clean system for the change. After the change, the system needs increased attention for a few years until it is certain that conditions are sufficiently stable.

INTRODUCTION

Large generators remove heat losses with direct water cooling in addition to hydrogen or air cooling. Normally, copper hollow conductors are used to channel the water through the stator bars. Four different chemistry regimes are used in the industry and are recommended by original equipment manufacturers (OEMs). Deviations in the water chemistry can result in plugging of the copper hollow conductors.

Oxide plugging is a four-step process, consisting of oxidation, mobilization, migration and deposition [1]. Oxidation will always happen if oxygen is present, while mobilization can be controlled to a certain degree. Once mobilized, the oxides will migrate and deposit, ideally either in the filters or the demineralizer. However, they can also deposit at other locations, including stator bars, causing stator bar plugging.

A significant part of preventing hollow conductor plugging is minimizing mobilization by adhering to a predetermined chemistry regime for the stator cooling water, usually defined by the OEM when designing the stator cooling water system to accommodate the desired parameters (Figure 1).

It is evident that dissolved oxygen concentrations at the extreme ends of the spectrum are preferable, and indeed both strategies are widely used successfully in the industry.

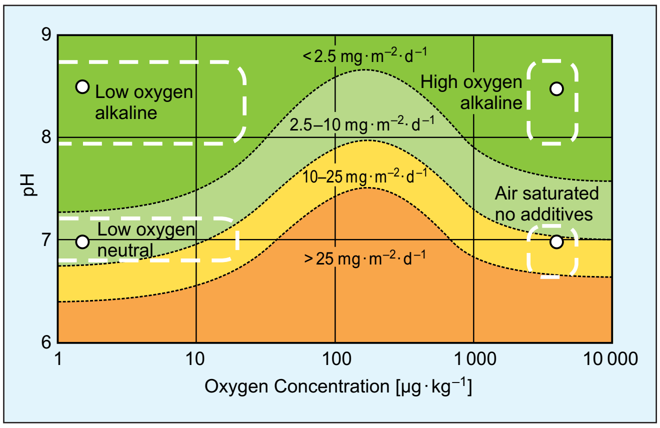

Figure 1:

Dependence of the copper release rate on oxygen concentration and pH. The copper release rate is color coded. The four established stator cooling water regimes are highlighted [1].

The pH should be kept at or above neutral to keep copper solubility low. Choosing one or the other pH regime at the design stage means deciding whether to add another subsystem (an injection system to increase pH) to the cooling water system.

On the other hand, increased pH can buffer to a certain degree problems with maintaining appropriate oxygen chemistry [2].

A special challenge is to keep up these conditions during outages, or if not practical, to dry the system to render the copper surfaces inert [3].

STABILITY OF COPPER OXIDES

Copper oxides are formed in the presence of copper, oxygen and water. Depending on several factors such as oxygen concentration, time, temperature and pH, different crystal morphologies are present. The resulting copper oxides can form a very stable and robust layer or fragile crystalline structures.

The composition of these layers is always a mix of copper oxides. Figure 2 shows that the mix is determined by several factors beyond the dissolved oxygen content.

In low-oxygen systems at neutral pH, the basic concept is to exclude oxygen from the cooling water system. Cuprous oxide (Cu_2O) is predominant and needle-like structures will form (Figure 3, left). These needles are released over time either by dissolution or by breaking apart. Small amounts of dissolved copper oxides are removed in the mixed bed; particles are removed in the filter. As long as the copper oxides are more or less continuously released and removed, plugging is limited [6].

In low-oxygen systems with elevated pH (8.5–9.0) and temperature, the crystalline morphology changes from needle-like structures to a polyhedral layer (Figure 3, right) [5]. This layer is more stable on the surface and also the copper release rate is reduced due to the lower solubility with elevated pH. However, as the copper release rate and copper oxidation are always in equilibrium and all oxygen entering the system is still consumed, a bigger layer of copper oxide is formed on the copper surface [6].

Both low-oxygen concepts work properly as long as the oxygen concentration is kept very low AND pH is kept at design specification. Changes might result in an increase in copper oxide release, local crystallization, and subsequent plugging.

In high-oxygen systems cupric oxide (CuO) is dominant, forming a stable and compact layer of polyhedral crystals on the copper surface (Figure 4, left). Although this applies

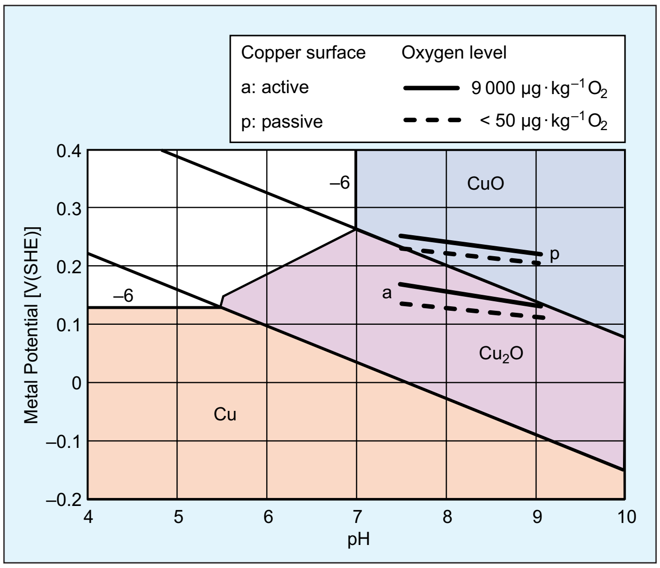

Figure 2:

Pourbaix diagram of Cu at 25 °C [4]. The domains of the various Cu-species are defined.

Included are results from laboratory tests on active (freshly pickled) and passive (oxidized) Cu specimens, in low-oxygen and in high-oxygen water [5]. It can be seen that the surface condition has a greater influence on the electrochemical potential (ECP) than the oxygen concentration in the water, and that the maturity of the oxide layer is an important factor in deciding which oxide is predominant.

It is also evident that copper oxide layers in stator cooling water systems exist close to the transition zone between CuO and Cu_2O. It becomes apparent why keeping conditions stable is so essential.

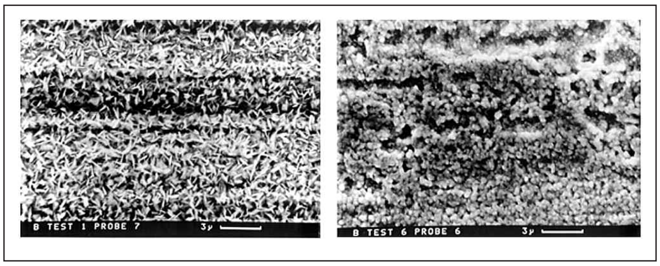

Figure 3:

Crystal structure of copper oxides formed under different environmental conditions [5].

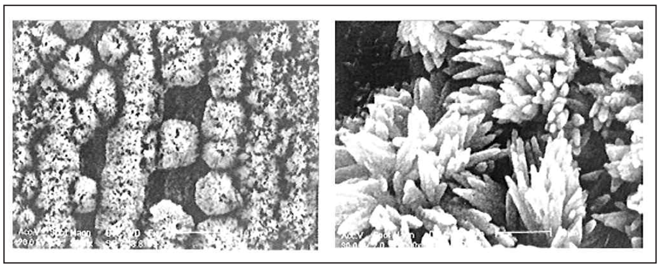

Figure 4:

Initial factory CuO layer (600 kPa O_2, 158 °C, 2 hours, left) and layer after exposure to cooling water system (200 $\mu g \cdot L^{-1}$ O_2, 60 °C, 1 000 hours, right) [6].

for neutral and elevated pH, copper release rate, and crystal shape and size are pH sensitive. Thus, changing the pH can result in a fragile system, resulting in an unstable copper oxide layer. Lowering the oxygen concentration results in two more drastic changes: an increase in the copper release rate and a change in the crystal morphology [6].

Therefore it is essential to keep the oxygen concentration saturated in high-oxygen systems as well at a constant pH (Figure 4).

As known for numerous systems (e.g. iron oxides), temperature also influences the crystalline morphology. This should be analyzed in detail in the future for the copper/water/oxygen system.

RESULT OF INSTABILITY

Instability of copper oxides always occurs with deviations from design parameters. This can be either one or a combination of several factors such as pH, oxygen concentration, conductivity or electrochemical potential (ECP) [8]. It results in an instable copper oxide layer due to a change in the crystal structure as well as an increase in the copper release rate. Dissolution of oxides may also liberate embedded oxide particles.

The dissolved copper and the copper oxides migrate in the cooling water system and may redeposit locally [2]. Within the coil, typical areas are water box outlets and inlets. A direct result is reduced cooling water flow and, depending on instrumentation, may be reflected in:

- Increase in stator cooling water differential pressure
- Decrease in stator cooling water flow
- Increase in differential temperature of individual bars
- Increase in total differential temperature
- Visual inspections showing blockages

The impact on the generator can be substantial:

- Reduced cooling capacity
- Insulation lifetime is affected
- Power limitations
- Generator trip
- Forced outage
- Generator damage

Therefore, it is essential to keep the copper release rate and parameters such as oxygen concentration, pH/conductivity, and ECP at design values and stable. Also, proper monitoring during outages for lay-up is important. Chemistry regimes might be changed, resulting in instability of the copper oxide layer when taking the cooling water system back into operation.

CHANGING REGIMES

Under certain circumstances it might still be necessary and useful to change the chemical regime of the stator cooling water system. However, this is not as straightforward as it sounds. Changing the chemical regime requires expert supervision already starting with the first basic idea.

Reasons for Changing Regimes

Chemistry regimes are usually changed due to apparent chemistry-related problems in the stator cooling water system. This can be either a permanent or a temporary solution. The latter might be unintended during maintenance work or an outage. Intentional temporary change might carry a malfunctioning cooling water system to the next outage, when all necessary repairs can be performed. Reasons for permanently changing the stator cooling water chemistry might be manifold, including OEM, plant chemist or consultant recommendations.

Possible chemical parameters for changing include oxygen concentration and pH of the stator cooling water.

Changes in Oxygen Concentration

Low-oxygen systems can suffer from increased oxygen concentration in the cooling water system. Potential root causes include air being sucked into the system, impurities brought in by a hydrogen leakage, and consumption of aerated make-up water. To reduce the resulting high copper release rate, a change to a high-oxygen system could be considered. This may sound attractive, but a lot of aspects have to be considered and often more problems are caused than eliminated.

High-oxygen systems can have difficulties keeping the oxygen concentration within OEM specifications. Problems include malfunction (or absence) of an aeration system, a large hydrogen leak with hydrogen slowly replacing the oxygen in the system, or the cooling water system design is not suitable for high-oxygen operation. Redesigning a stator cooling water system to a different oxygen regime is rarely carried out as it requires complex hardware updates on the system and the conversion process is very involved. A lot of preparations as well as intense supervision of the conversion are needed. The change in oxygen concentration also introduces a change in the crystal structure of the copper oxides and can result in copper hollow conductor plugging. Prior to the change a rewind or thorough chemical cleaning is thus required.

Changes in pH

Some systems operating under neutral pH have been converted to alkaline treatment, that is, with pH 8.5–9.0. This concept is based on a decrease in the copper release. It is recommended as a standard by one OEM and has been successfully implemented in a number of plants [2]. Our experience has shown that alkaline stator cooling water systems can also suffer from copper hollow conductor plugging, mainly when the chemistry regime is not kept stable after the transition. The copper oxide morphology is changed, causing instability. This might result in a release of the copper oxides and subsequent plugging.

Therefore it is recommended by the same OEM to rewind or chemically clean the system before changing to alkaline pH [9].

PROGRAM FOR CHANGE

It is essential to have an educated and detailed plan in place before changing chemistry regimes. This should be started as early in the decision process as possible in order to avoid false expectations and getting into an unnecessarily problematic situation.

Contingency plans should be at hand and possible problems anticipated.

Table 1 sums up the stages of such a program. It is evident that the actual change itself is the shortest part in

Before the change	Define a clear reason for the change
	Carry out a check-up
	Collect unit history
	Document condition before change
	Ask for industry experience
Planning the change	Define target parameters
	Define procedural and hardware changes to achieve these values
	Clarify usefulness or necessity of chemical cleaning
	Conduct risk analysis
	Prepare transition procedures
	Define hold points and inspection points
	Update drawings and draw changes
	Update procedures and manuals
	Train personnel for the transition and to operate the new system
	Involve stakeholders early and keep them in the loop
	Profit from experience
	Prepare contingency plans
During the change	Carry out mechanical changes
	Carry out chemical cleaning
	Run monitoring program during the change
	Troubleshoot
Special case: Rewind	Carry out additional examinations
	Remove copper oxides in the rest of the system
	Investigate if the source of the problem is outside the generator
	Inspect and overhaul cooling water system if reusing
	→ Change whole cooling water system if possible
After the change	Document situation after change
	Compare with target situation
	Troubleshoot if necessary
	Implement long-term monitoring program
	Give increased attention for 1–2 years
	Maintain know-how gained during the process

Table 1:
Main steps in the program for changing operating regimes in a stator cooling water system.

the following discussion. It is often relatively trouble-free if carefully planned.

Before the Change

Changing water chemistry safely is not trivial; it should be certain that there is a benefit in doing so. Clearly defining the problem to be averted helps in determining whether the planned changes make sense, and if the chances for success are sufficiently high.

The opportunity to check the whole system for problems presents itself at this point, with special consideration of the planned regime change. All available data from the unit's history should be collected: inspections, special events, modifications, leak repairs, and other data. This will be used later to create a baseline ("fingerprint") or to help with troubleshooting.

The condition before the change needs to be well documented and understood to add to the baseline. It is important not to do a spot check but to obtain data representative of the system over some time. Parameters to record include chemical parameters (conductivity, ECP, dissolved oxygen, copper release rate, copper concentration), physical parameters (flow, pressure differential, Doppler flow tests, etc.), and also visual inspections to investigate system cleanliness.

Find out if others have gone through the same changes and ask about their experience. If no one has done it before, find out why and reconsider pioneering an unproven technology.

Planning the Change

After defining the reason for the change and which operating regime to convert to, a clearly defined set of target parameters has to be outlined.

Once the desired parameters are set, the tools to achieve this goal can be delineated, a quality plan put in place, hold points and inspection points set, etc. This includes defining instrumentation and sampling system upgrades, and new operating parameters. Examples of such parameters include demineralizer flow, pH, or dissolved oxygen content. This is an important point that leads to questions such as whether to use an injection pump or a dual-bed resin system to achieve an alkaline environment, whether a new expansion tank has to be built, or whether other potentially major hardware upgrades are necessary (Table 2).

Often it is a good idea to start from a clean condition, which usually involves chemically removing all copper oxides from the system, and build up a fresh oxide layer suited to the new conditions. In many cases it is a necessity, as mentioned above. Proper execution requires expert know-how and experience.

A comprehensive risk analysis covering machine and personnel, both during and after the change, should be carried out. Risks posed by the new operating regime itself, but also risks resulting from necessary operations during and after the change, should be covered. Use the results from the risk analysis when preparing procedures for the transition. Include mechanical changes and a monitoring program during the change period, as well as other operations.

During the planning process, it is helpful if the system drawings align with reality. If that is not the case, now is the best opportunity to update them. Then the planned upgrades can be added. Updates for all pertinent procedures and manuals should be ready well before the change. During the change there will most likely be no time as planned changes in stator cooling water system regimes typically happen during an outage.

Desired Change	Hardware Changes	Operating Parameter Changes
Low to high oxygen	Forced aeration system Larger mixed bed size and flow Larger expansion tank Installation of oxygen monitoring Finer filter mesh size	High dissolved oxygen content Slightly higher conductivity
High to low oxygen	Leak-proofing of entire system Inert gas blanket in expansion tank	Low dissolved oxygen content Reduced demineralizer flow
Neutral to alkaline	Installation of sodium injection system	Higher conductivity Regular sodium sampling Reduced demineralizer flow
Alkaline to neutral	—	Low conductivity

Table 2:
Examples of possible hardware and operating parameter updates required for a change in operating regimes.

The whole new operating regime can be upset if not all personnel is trained and ready. An obvious example is an injection system for an alkaline cooling water system. Personnel should be trained before the change, not only for the new regime, but also for the transition. Everyone involved in and affected by the change should be informed and consulted early in the process to cover all angles. Finally, consider engaging external consultants with experience in the field to avoid reinventing the wheel or running into avoidable issues.

All other issues should be covered by contingency plans.

During the Change

This is the time to implement the plan. A major part is often of mechanical nature: adding new filters or changing filters to different models, updating the expansion tank, installing injection devices and tying them into the existing plant instrumentation, or installing updated instrumentation. Another major mechanical change which directly affects the stator cooling water system would be a rewind.

If a chemical cleaning was found to be necessary or useful during the planning phase, this can be carried out during other work if done correctly. If no cleaning was planned, be prepared for an emergency chemical cleaning after the unit is back in service as part of the contingency plans.

Carefully follow the monitoring program during the change of regime. This can give a good indication of whether things are going as planned or if adjustments are needed. Use the contingency plans if things deviate from the expected.

Special Case: Rewind

A rewind is a significant intervention in the cooling water system and has a few peculiarities in addition to the challenges posed by the rewind itself.

Often the root cause for plugging or other troubles in generator cooling water systems is found outside the generator itself, be it an air leak, contaminated make-up water or other outside influences. In this case even a new stator coil can foul within a short time.

Coolers and dead ends can contain large amounts of oxides. These deposits can be mobilized and plug up the new stator. Obviously, they should be removed beforehand. Chemical cleanings of the stator cooling water system can be carried out with the stator bypassed, in parallel to the rewind operation.

The best solution is to replace the whole stator cooling water system along with the coil. Often though, the additional cost may outweigh the risk of reoccurrence of the problems. In this case, inspecting the whole system in-depth and overhauling all components of influence on the stator cooling water chemistry, such as flanges, pumps, valves, coolers etc., can help minimize the risk.

If a rewind is carried out, secure representative or interesting bar samples from the old coil, including water boxes. Investigate their condition for indications of problems. If known problems prompted the rewind, use this opportunity to thoroughly inspect replaced bars to help find the root cause.

After the Change

Carefully document the situation after the change in the same way as before and during the change. This should be the new fingerprint to be used as a baseline for future reference. Be careful to recognize outlier measurements. Check if the new operating parameters are in line with the desired values defined in the planning phase.

If the current situation deviates from the desired situation, contingency plans spring into action. If troubleshooting is not successful, assess the situation. If it is stable and likely to remain stable, and is compatible with a healthy stator cooling water system, a modification of the target parameters can be considered. A change in operating regime, coupled with hardware upgrades, presents itself as an opportunity to renew interest in the system and to put a sustainable, robust monitoring program in place. This is especially important for the first few years with the new regime, as early detection of problems is often the key to solving them before they become serious [10].

Changing the stator cooling water operating regime will create a lot of know-how around the system. Many stakeholders are intimately involved in the system for weeks. This know-how should be maintained within the team and handed over to future generations.

CHEMICAL CLEANING OF THE COOLING WATER SYSTEM

As discussed previously, it might be essential to clean the entire system before changing the chemical regime of the generator cooling water system. Different types of mechanical and chemical cleanings have been described in [11].

Mechanical cleaning methods are only applied locally and thus incompletely prepare the system for a regime change.

Acid cleaning methods involve difficult and dangerous chemicals and waste handling. Different kinds of system materials – the bare copper itself, braze and cooler materials – are also attacked and removed. In previous studies, super glue and epoxy-type adhesives used for repairs lost their bond to the copper when exposed to acid cleaning reagents [12].

If carried out carefully and with expert supervision, chelating agent based cleaning methods remove copper oxides from the entire system and are safe for system materials. Only copper oxides are removed; all other system materials including braze and resin repairs remain unaffected [11,12].

The chelant based chemical cleaning removes the unsuitable copper oxide layer in the system and prepares the unit for the new chemical regime. Especially in high-oxygen systems it is important to grow the preferred crystal structure after a chemical cleaning. One further aspect to be considered is that it can also be applied online at any given generator load and does not require any disassembly of the cooling water system.

Therefore, chelant based chemical cleaning is the preferred method for preparing the generator cooling water system for a change in the chemistry regime.

CONCLUSIONS

In order to prevent stator plugging, four regimes for stator cooling water chemistry have been established. Occasionally it can be beneficial to change from one regime to the other. However, changing regimes can introduce instability in the copper oxide layers, ultimately causing plugging of the cooling water channels.

Consequently, a change in the operating regime has to be carefully considered and a well thought-out plan put in place.

The current condition and the reason for changing regimes have to be clear before the planning phase. They define all the following steps, starting with the target parameters. Changing a chemical regime can involve major hardware upgrades as well as procedural changes. It is important to have contingency plans ready if conditions deviate from the expected during and after the changes to facilitate troubleshooting.

Rewinds require special attention if the current cooling water system is reused. A rewind also presents an opportunity to directly investigate problems within the stator bars and water boxes.

In many cases it is prudent or even necessary to chemically clean a stator cooling water system before a change in chemistry regime in order to avoid instability within the oxide layers.

After the change, the system needs increased attention for a few years until conditions are certain to be sufficiently stable.

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