Corrosion and Deposits in Water-Cooled Generator Stator Windings: Part 4: Operating Experience with Flow Restrictions in Stator Cooling Water Systems

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ABSTRACT

A common problem with water-cooled generator stator windings is plugging of the hollow conductors that act as cooling channels. The causes are sometimes difficult to identify, but some common factors can be found. Insufficient layup during outages is a common one. The importance of good monitoring and maintenance practices is highlighted throughout the discussed examples.

The stator is the main concern, because of its vulnerability to oxide deposits in the hollow conductors and the fact that if it fails, the whole power plant has to be shut down. Strainers and filters can also plug up and act as early warning devices for stator plugging. If replacing them is not an option, chemical cleaning can help, but it usually only removes the symptoms.

Proactive treatment of these problems should be a priority, as damages can go into the millions. Even when cleaning is still possible, persistent deposits can often only be removed by more invasive treatments.

INTRODUCTION

Since water cooling was introduced in generator stator windings in the 1950s, an estimated 20 % of machines have run into problems with copper oxide plugging of the hollow conductor cooling channels during their lifetime. As fleets age, these problems are expected to increase. It is often hard to pinpoint the exact root cause, and this is exacerbated by the fact that several issues can conspire to create conditions that facilitate plugging.

Tight chemistry control and a good monitoring regime to maintain stator cooling water system (SCWS) parameters within their specifications is important. An adverse condition that is caught at an early stage is almost always easier to remedy than dealing with severe plugging later. It is a recurring theme in the authors' experience that these problems went unnoticed for extended periods until late in the process.

To prevent problems from the get-go, well-written and adhered-to procedures, particularly during outages, are just as important. Improper layup has caused many plants to run into flow restrictions after the system went back into service.

However, even with the best procedures and a tight chemistry regime in place, problems cannot be completely eliminated. Other factors, such as hollow conductor dimensions or fabrication errors can reduce the margin for trouble-free operation so much that plugging may still occur over time.

The goal of this paper is to present examples that illustrate typical problems that can occur with SCWS plugging, and to explain how to prevent them.

This is the final part in a series of five papers to appear in this journal on corrosion and deposits in water-cooled generator windings [1–5].

CASE STUDIES

Insufficient Layup during Outages Creates Cumulative Problems: Plant T1

Plant T is a two-unit nuclear facility with two large turbo generators whose cooling water systems have run with low dissolved oxygen regimes since 1988. Cooling water chemistry is tightly monitored during operation and no major excursions have been observed.

However, no special provisions were taken during outages, when the system was drained and left open to atmosphere, unless a dry winding was required, for example for DC high-potential (Hipot) testing. This only happened every six to ten years, which left the majority of outages without proper layup applied to the machines.

This did not affect any parameters negatively at first, until an extended outage in 2003 left Unit One in intermittent operation without chemical control for six months.

When the unit was taken back into service, water samples showed somewhat higher copper concentrations than before (near 20 µg · kg^{-1} compared to below 10 µg · kg^{-1} for the first 15 years of operation) [6].

Six years later, after another outage, five consecutive sets of filters plugged up and had to be replaced within one fuel cycle of 18 months, and copper concentrations of up to 240 µg · kg^{-1} were measured. In a stator cooling water system with nominally neutral pH, the highest possible concentration of dissolved copper is around 20 µg · kg^{-1} [7]. This means that large amounts of copper oxide particles had been mobilized.

Initially, no adverse effects on the stator were observed. This may be because the cooling water pumps are controlled to keep stator inlet pressure constant and coolant flow to the stator is not measured. With pressure-controlled valves, flow will be reduced with increasing plugging, until it is eventually reflected in stator bar temperatures. Another reason for the plugging going undetected at first is that alarms were tied to the temperature difference between the coldest and hottest bar, and the temperature increase across the winding was merely logged.

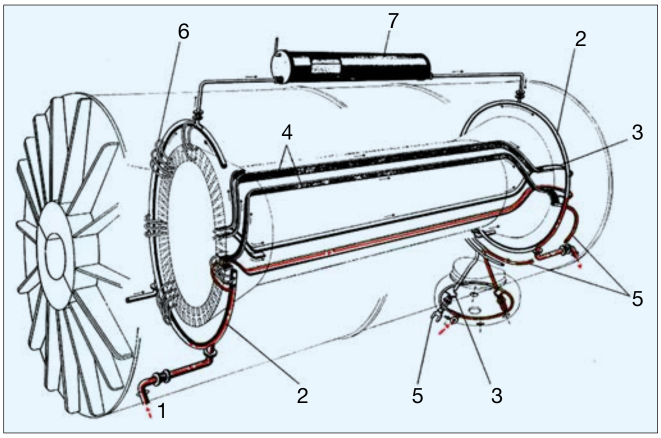
Once the issue was identified, analysis of stator bar outlet temperatures showed that the plugged bars were distributed in a non-random pattern. This pattern was consistent with the fact that when the stator is drained at the inlet and outlet manifolds without proper blowdown, only about one-third of bars actually drain; the other bars remain filled with water as their end windings and the connecting insulating hoses are bent upwards on both sides (Figure 1).

The drained bars are then left with a water film exposed to air. This has a two-fold effect: First, it exposes the wet copper to an effectively infinite and instant supply of oxygen and second, it also exposes the water film to CO_2, which lowers the pH in the water film, destabilizing and dissolving the oxide layer [2].

When the generator was taken into service again, those bars that drained showed higher temperatures than the ones that remained filled with water, indicating lower cooling water flow.

An emergency online chemical cleaning was able to prevent a forced outage during the peak summer season. The cleaning removed much higher amounts of oxides than normal (> 10 kg) [6]. Apparently, the bulk of the oxides was evenly distributed and had not been mobilized, or much more dramatic plugging would have been observed. Such large-scale mobilization could have happened very rapidly had conditions changed in the system.

Suitable layup procedures are time consuming, expensive and can be tricky to implement properly. However, the consequences of not following them can add costly outage time and require specialized work.



For clarity only 4 stator bars are shown.

1	Cooling water inlet
2	Water distributor ring
3	Electrically insulated water hoses
4	Stator bars
5, 6	Connection to phase connectors and bushings
7	Head tank (expansion vessel)

Figure 1:
Schematic of a generator stator. Only four bars are shown for clarity. Like the bars shown, approximately one-third of the bars will drain by gravity alone; the rest of the bars will remain filled as their bar ends or insulating hoses point upward and prevent draining.

The unit suffered further flow restrictions after about one year, necessitating additional cleanings to carry it over to a scheduled rewind. A known gas-to-water leak from the generator casing into the stator cooling water system was the likely culprit that time, introducing enough oxygen through impurities in the generator casing's hydrogen cooling to upset the oxide balance. A similar case is discussed later in this article.

It is likely that this condition was already active earlier and was the additional factor needed to cause significant plugging after years of insufficient layup with otherwise tight chemistry control.

System Cleaning during Rewind: Plant T2

One year later, the other unit, Unit Two of the same plant, suffered a catastrophic insulation failure that required a rewind and partial core restack to repair the machine.

The system was cleaned during this work in order to provide a clean system for the new stator winding. The stator was replaced with a bypass pipe. More than 2 kg of copper from oxides were removed during this cleaning. It is commonly assumed that the bulk of a system's oxides remain in the stator winding. It follows that Unit Two was also affected by the decades of neglected layup during outages, but it did not suffer such disturbances as Unit One with its extended outage and gas-to-water leak.

With less stringent chemistry control during operation, however, both units could have rapidly and heavily plugged.

Strainer and Filter Plugging

Apart from the cooling channels in the stator bars, other components prone to plugging are main-stream filters or strainers, or both. These often plug up before the stator does and can sometimes act as early-warning devices.

Strainers usually plug up by crystal growth from dissolved copper oxides, while letting most oxide particles pass through, unless crystals already block too much of their open cross-section. Filters with their much finer selectivity tend to collect particles, while crystals do not tend to grow readily.

This is because crystal growth depends on water velocity at a given ion concentration [2]. Typically, filters in SCWS applications have a large surface area, minimizing pressure drop and maximizing particle retaining capacity. This results in more manageable flow velocities at the filter surface. Strainers, on the other hand, often have a relatively small cross-section for the water to flow through, resulting in high flow velocities and turbulence, which in turn enhance crystal growth.

Destabilized oxide layer leads to repeated filter plugging: Plant H Plant H is equipped with a SCWS with high-oxygen chemistry and a single filter but dual strainers that can be swapped online. Two years after a rewind, the water in the system remained stagnant for more than a month when the stator remained filled without the pumps running.

The dissolved oxygen in the bars will be consumed in such a situation, while diffusion from the generator inlet and outlet is not likely to replenish it fast enough, particularly if the system remains mostly closed. Local conditions in the winding will then go through transient oxygen concentrations until all the oxygen is used up. Such concentrations result in increased copper release rates (Figure 2) [2].

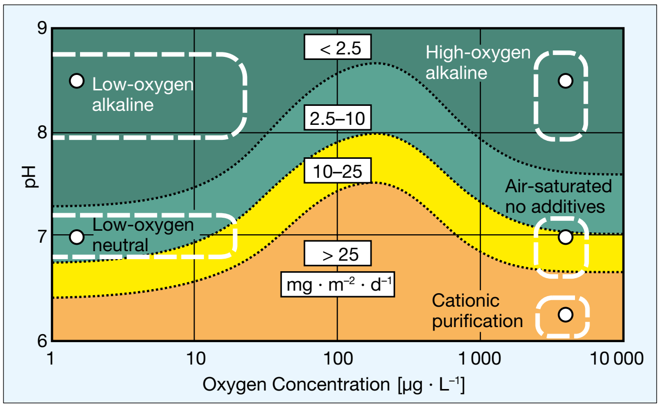


Figure 2:
Summary of copper release rate as a function of oxygen concentration and pH; operating areas of the different water chemistry regimes (temperature 45 °C, flow velocity 2 m · s^{-1} [2].

Six months later, the main system filter started to plug up, leading to a forced outage. For the next six years, filters were proactively changed during outages, until filter plugging frequency started to increase so much that the unit ran into forced outages twice.

This increase in copper oxide particle load that was plugging the filters led to the suspicion that the oxide layer in the stator had become unstable during the episode with insufficient layup. It was assumed that replacing this oxide layer with a fresh, stable oxide layer would solve the problem.

This can be achieved by chemically cleaning the system, followed by building a new copper oxide layer with a controlled reoxidation on the fresh copper surfaces. The chemical cleaning also cleans the filters, rendering a forced outage for their replacement unnecessary.

With constant feeding of particles, filter pressure drop usually increases exponentially, that is, slow at the beginning and more rapid later. This case was no different, and only very rapid mobilization prevented a forced shutdown.

The chemical cleaning was aimed at replacing the old oxide layer; however, it also brought a 7 % improvement in stator pressure drop at constant flow. Stator inlet pressure was not monitored during normal operation, so the prior slow deterioration of stator pressure went unnoticed and was masked by the repeated filter plugging.

Nineteen months later, filter pressure drop started increasing again. It is thus likely that the root cause was still active, or that layup was just one of several factors that caused the filters to plug up. Another chemical cleaning provided relief, but 15 months after that, the filters plugged up again.

In the course of the investigations it was found that the existing filters were operating at 50 % over their optimal flow velocity range. They also tended towards surface loading with the particles present in the system, which can dramatically lower a filter's capacity. This effect can also be partly attributed to excessive flow. The filters already plugged up with minor quantities of copper oxides, which further supports this line of thought.

However, the second, almost identical, unit of the same plant did not run into the same plugging problems. Two main differences between the units were found. Unit One had slightly increasing and higher than normal make-up water consumption, which may bring in contaminants. However, make-up is routed into the demineralizer bypass and passes through the demineralizer before entering the system proper.

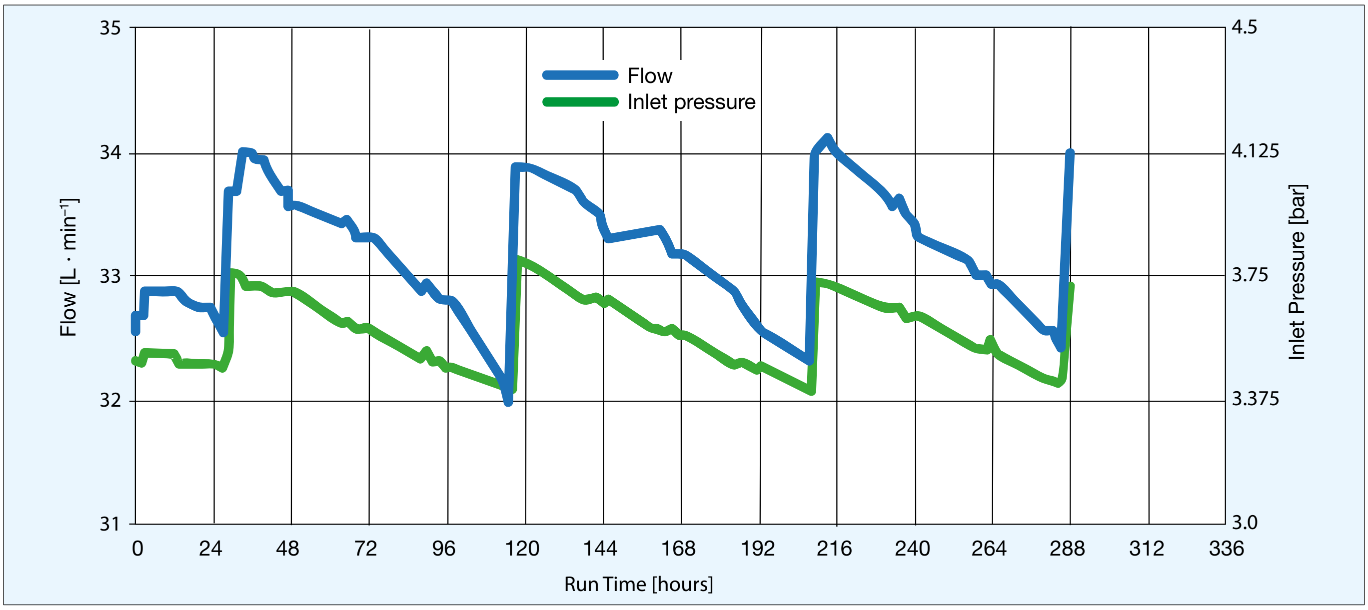


Figure 3:
Flow and inlet pressure at the stator winding over time in plant H. Outlet pressure is atmospheric and approximately constant. Every four days the main system pressure control valve opens and increases flow to the stator. The reason for this is that the pressure control valve is tied to the generator casing hydrogen pressure and reacts to the regular manual hydrogen top-ups to the generator.

The other difference is that during the cleaning on Unit One, a fluctuation in stator cooling water flow was observed (Figure 3). The frequency of these fluctuations coincided with plant operations personnel replenishing generator casing hydrogen gas approximately every four days.

The flow regulating valve of the SCWS is partly controlled by generator gas pressure to ensure that stator inlet pressure does not exceed gas pressure. This is a safeguard so that in the case of leaks no water can enter the generator casing. When gas is replenished, casing pressure increases and allows the flow regulating valve to open more. This results in a relatively abrupt increase in cooling water flow, and thus an increase in water velocity in the hollow conductors.

It is unclear whether velocities exceeded what is considered a normal range. However, such increases in flow velocity can disturb an oxide layer.

Unit Two had similar fluctuations, but their amplitude was several times lower than at Unit One.

It is thus likely that a combination of factors was at work: The margin to handle excessive particle load was lowered by using a filter type that was not ideal. The flow fluctuations destabilized the oxide layer, leading to particle release that the handicapped filter could not handle.

Repeated strainer plugging: Plant SA The generator for Unit Two of Plant SA was put in service in 1992 and was rewound in 2003. The old stator cooling water system with high-oxygen chemistry was left in place. Then, after a scheduled outage in 2017, stator cooling water flow started decreasing. The reason was found to be that a strainer upstream of the stator was plugging up. As system flow was controlled by a pressure regulating valve upstream of the strainer, flow was throttled as pressure increased in order to maintain inlet pressure at the set value.

Three months after the outage, the condition had deteriorated to a point that made a strainer change necessary. Unfortunately, the strainer was laid out as a single mainstream component with no bypass, so the plant had to be shut down for more than a day to access and replace the strainer.

However, the strainer started plugging up again soon after. As the next scheduled outage was still more than a year in the future, an alternative to shutting down the system was needed. Online chemical cleaning provided such an alternative and even the chance to restore a stable oxide layer and eliminate one potential root cause.

This chemical cleaning restored flow through the system completely by bringing back pressure drop across the strainer to normal values. It also improved pressure drop across the stator by around 5 %, which indicated that the stator winding was already plugging up as well.

The improvements were only of a temporary nature, however, and the problem had to be controlled with subsequent chemical cleanings during the fuel cycle until a more permanent solution could be implemented in the next refuel outage. A total of five cleanings were carried out, two of which were targeted strainer cleanings, aimed at leaving the oxide layer in the stator itself intact. One forced outage due to a reactor coolant pump alarm offered an additional opportunity to swap strainers.

Extensive troubleshooting accompanied these cleanings. The most likely reason for the plugging was a combination of factors:

- Layup during outages was not always ideal, and in some cases the system was exposed to extended periods of stagnant conditions.
- Originally, the rectifiers were water-cooled in a side loop of the same system as the generator. A few years before plugging occurred, the generator was upgraded with air-cooled rectifiers and their cooling water loop was closed off, resulting in increased flow (and thus increased flow velocity) through the generator stator. To restore nominal flow through the stator, the isolated bypass stream was reopened in the outage before the problems started.
- The unit's hydrogen drier required regular flushing of its standby cartridge with air. This air was then routed directly into the stator tank vent pipe (Figure 4). As the stator vent pipe is an open connection between the stator expansion tank and the atmosphere, significant amounts of this purge air would reach the stator tank gas space. The CO_2 contained in this air would upset the pH in the cooling water temporarily.
- The active air injection system was equipped with CO_2 scrubbers which were not functional. This meant that CO_2 was continuously injected into the system as well.

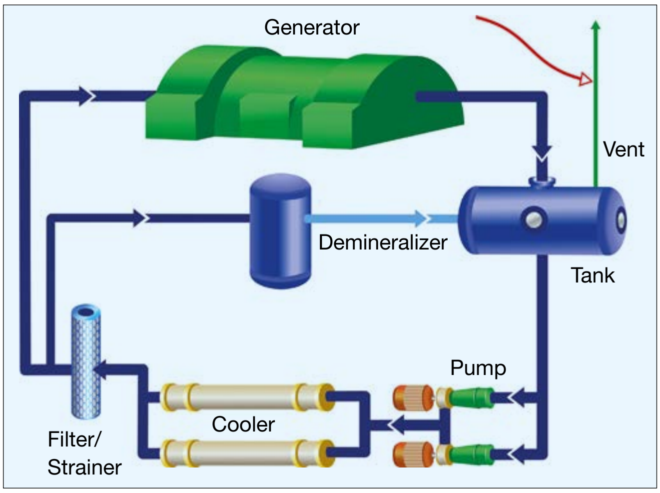


Figure 4:
Simplified stator cooling water system. The location where the hydrogen drier flushing line is tied into the stator expansion tank vent line is marked with a red arrow.

Finally, the strainer itself had such a small open cross-section that flow velocities and turbulences were likely excessive. Strainer size was specified by mesh size, which does not directly correlate with the total open cross-section available for the water flow. This cross-section varies both with wire strength and the weave used. There are indications that the original system was designed for a plain weave, while the strainers in use had a Dutch weave, which has a smaller open cross-section per m^2 at a given selectivity (Figure 5).

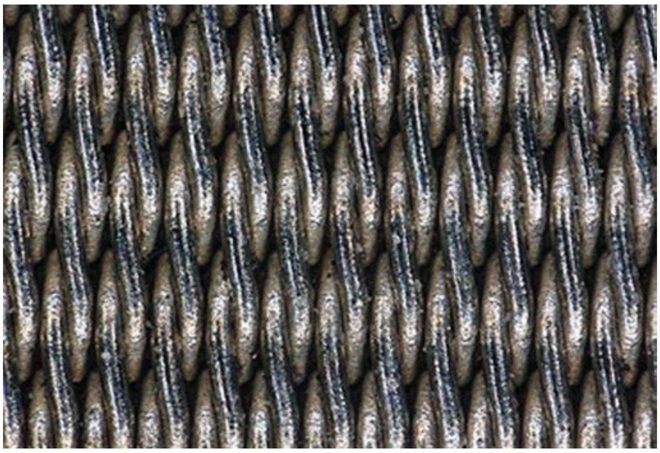


Figure 5:
Dutch weave strainer mesh resulting in smaller open cross-section than a plain weave mesh as was originally specified. This results in higher flow velocities through the strainer mesh.

It is likely that any one of these causes was not enough to cause plugging, but that the combination and slow deterioration over the years brought the system towards a tipping point. This would then start a feedback loop, where the available cross-section in the strainer is continuously reduced by crystal growth, resulting in accelerating flow reduction.

The solution was to install strainers with a larger open cross-section (a plain weave strainer basket was used). At that opportunity, the single strainer vessel was replaced by parallel dual strainers that can be switched over during operation, allowing online strainer swaps. After more than six months of operation, this was not yet necessary.

Increasing strainer and filter plugging: Plant OG Plant OG was equipped with both a single strainer (since upgraded to a duplex-strainer setup) and single filter in the SCWS main stream. Soon after commissioning, both started plugging up. In Unit One, predominantly the strainer was affected, while Unit Two had mostly its filter affected.

There was no direct measurement for stator inlet pressure. The inlet pressure from the strainer upstream of the generator had to be used instead, but this reading integrated strainer and stator winding pressures, thus masking any pressure rise in the stator winding itself.

After six years of increasingly frequent strainer and filter swaps, stator bar temperatures in Unit Two started rising to a point where it became evident that the winding was starting to plug up (Figure 6). A chemical cleaning was car-

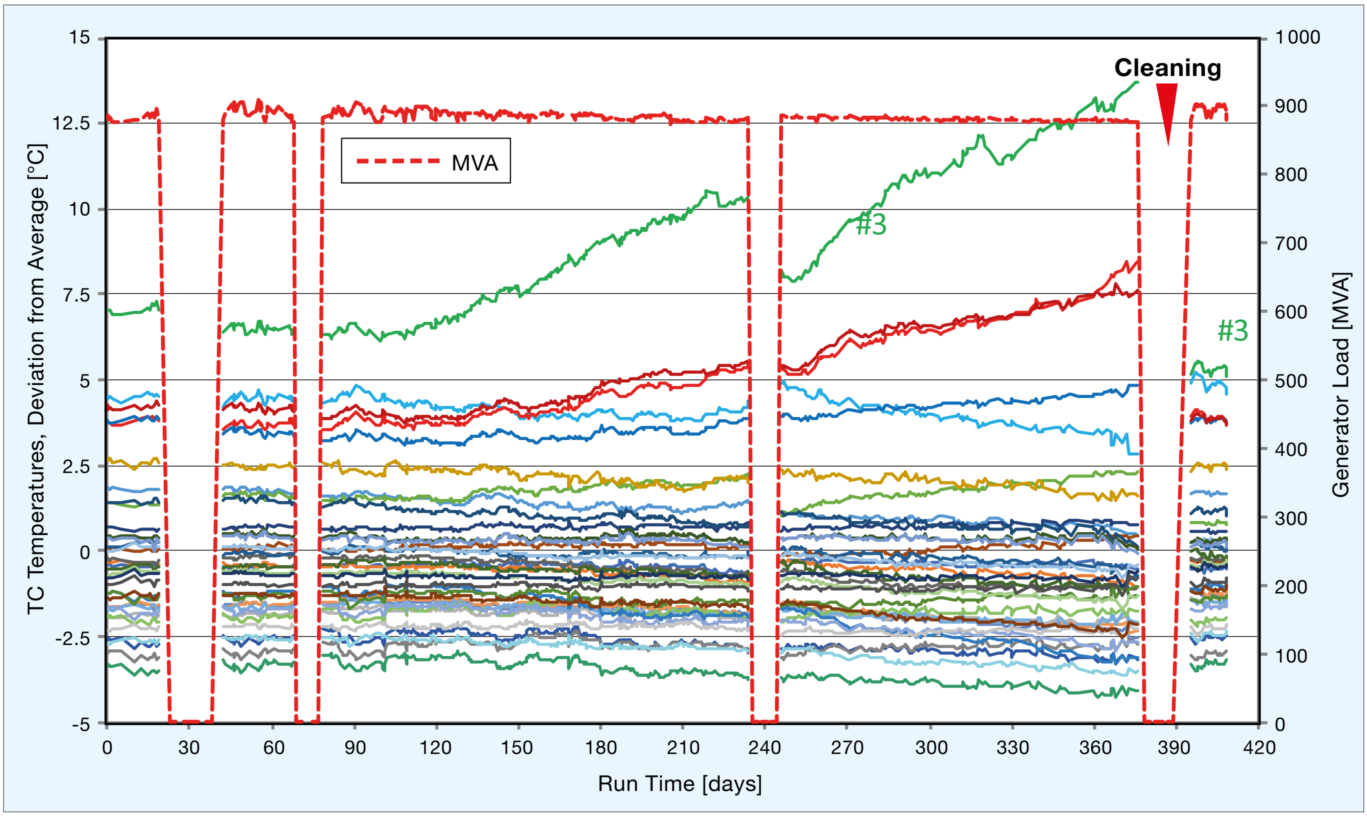


Figure 6:
Temperatures of thermocouple elements at the outlet insulating hoses in plant OG. Each insulating hose combines the outflow from a pair of separate top and bottom bars. Shown is their deviation from average normalized to a standard load of 880 MVA. The dashed red line (MVA) represents the actual generator load; the dips indicate periods where the plant was shut down. It is evident that not all bars are plugging up equally. Some of the hottest pairs may have several hollow conductors completely plugged. This was also reflected in the results from ultrasonic flow testing.

ried out. This was successful, but a few bars were still left with slightly increased temperatures. Ultrasonic flow tests confirmed the results.

In the future, a targeted cleaning for the affected bars will have to be carried out to restore full cooling capacity. In this case, by the time temperatures indicated a problem, plugging seems to have advanced to complete plugging in some hollow conductors. Part of the problem was that pressure drop across the stator as an additional indicator was not monitored.

After this, Unit One was cleaned preemptively before stator winding plugging became apparent. Ultrasonic flow testing confirmed a slight flow improvement and that all bars were successfully cleaned.

Proactive Cleaning Prevents Possible Heavy Plugging: Plant S

Two-unit plant S had only limited instrumentation on its low-oxygen chemistry stator cooling water systems. After 15 years of operation, copper oxide deposits were found on Unit A's strainer. The 80-micron duplex strainer is used as the only main-stream filtration element in this design.

Unit A A proactive approach was chosen in order to prevent stator plugging or even damage to the winding. This consisted of ultrasonic flow testing on the individual insulating hoses supplying cooling water to the stator bars, visual inspections of the hoses and water boxes by borescope and preparing all contingencies for a chemical cleaning if signs of plugging were found.

Figure 7:
Stator bar inlet water box with copper oxide deposits as found during visual inspections at plant S. The areas around the hollow conductor inlets are particularly affected, as they lie in an area of high turbulence and flow velocities.

While ultrasonic flow tests did not return any results out of the norm, a failed Hipot test indicated problems. Visual inspections confirmed this suspicion and found partial plugging in the hollow conductor inlets (Figure 7). The stator bar insulating hoses had deposits that were analysed as consisting almost completely of metallic copper.

A chemical cleaning was carried out; it removed relatively large amounts of copper from the system and restored full flow and resistance across the insulating hoses.

Based on these results, condition-dependent preventive cleanings were planned for both units. In Unit A, six years after the first cleaning, almost identical amounts of copper were removed from the system. Another six years later, the amount doubled. No signs of plugging could be seen, and no changes that could explain the discrepancies were observed.

Unit B After the first cleaning on Unit A, a preventive cleaning was scheduled for Unit B. Different than at Unit A, this cleaning yielded only very minor amounts of copper. This was despite the machines being of identical design and no obvious differences being observed during their lifetimes. Similar machines do not necessarily perform the same.

Because of the low oxide yield, the interval for the next preventive cleaning on Unit B was set to nine years. Apart from slight deviations in ultrasonic flow tests in the preceding outages, no indications of plugging were seen.

However, visual inspections on the individual cooling water hoses revealed deposits on their insides (Figure 8). They were cleaned with bottle brushes and about half a kilogram of oxides was removed from the hoses. These deposits consisted mostly of Cu_2O. The chemical cleaning on the whole system yielded the highest amount of copper oxides so far encountered by the experienced team. More than 12 kg of copper from oxides were removed.

Figure 8:
Heavy copper oxide deposits inside an insulating hose supplying water to a stator bar. These deposits were analysed as being mostly Cu_2O.

These oxides were apparently evenly distributed throughout the system, thus only forming a layer a few µm strong in the hollow conductors. Had these oxides been disturbed and released, they could have plugged up the machine rapidly and catastrophically.

Dissolved oxygen content was monitored before the cleaning and no abnormal values were detected. The oxygen was consumed by the copper before it could increase readings enough to raise eyebrows.

The experiences with both units led to several upgrades around the stator cooling water system, both in instrumentation and in procedural changes. Better data monitoring, reporting and improved layup were the result.

Small System Design Flaws Disturb Cooling Water Chemistry: Plant SD

This six-unit plant suffered continuous problems with plugging, necessitating repeated chemical cleaning on all their machines. All six SCWSs were designed to be run under a low-oxygen regime, with a dead-end head tank that is open to air above the turbine deck, and a detraining tank on the stator cooling water skid level in order to remove gas bubbles from the cooling water before they enter the stator. A common source of gas bubbles is hydrogen permeating into the cooling water system from the generator casing through the insulating hoses or through leaks.

A detraining tank of this design will collect gas and periodically vent it to atmosphere via a solenoid valve and through a pipe that is routed to the machine hall roof. The vent line is filled with system water up to the level of the water in the head tank thanks to the principle of communicating vessels. If vented gas volumes are not large, the gas will bubble up through the standing water until it reaches head tank level and then vent out to the air.

In the case of plant SD, hydrogen leakage into the system was large enough to fill or almost fill the detraining volume. The gas volume that subsequently vented was too large in relation to pipe diameter, so that it displaced the water column vertically until the pipe discharged all of its approximately 20 L of cooling water through the roof vent. This process repeated every four hours, which led to over a hundred liters of water being lost each day.

This water was replenished by the automatic make-up refill, which brought in oxygenated water. Over the course of a year, this process can introduce up to 365 g of oxygen in 44 m^3 of oxygen-saturated make-up water – enough to oxidize up to 2.9 kg of copper to Cu_2O. This was in the order of magnitude of what was removed after a year of operation, and enough to start plugging up the machine significantly.

The solution was to install an expansion vessel in the vent pipe, as has already been installed in other plants of similar design (Figure 9).

Figure 9:
Head tank and expansion vessel for the stator water detraining tank vent line. The expansion vessel is the small vessel to the left of the larger head tank. It prevents the standing water in the line from escaping through the vent if large amounts of gas are released at once.

Hydrogen Leak Increases Dissolved Oxygen Levels in SCWS: Plant DH

Plant DH operated with low-oxygen SCWS chemistry, with no apparent chemistry excursions over the years. After 23 years of operation with tightly controlled chemistry, a suspected air leak temporarily increased dissolved oxygen levels, which almost immediately led to an increase in pressure drop across the stator.

Chemical cleaning restored pressure drop and flow to normal values, and thus removed the symptoms; the leak was repaired a few months later. However, less than a year after that, several stator bar outlet temperatures started to trend upwards, with one bar particularly hot. This time, plugging seemed to have affected individual bars rather than the whole winding.

This pattern repeated three times over the next years, and several chemical cleanings were carried out to prevent forced outages. Minor fluctuations in dissolved oxygen were observed, but they generally remained within specifications (an upper limit of 20 µg · kg^{-1} dissolved oxygen for low-oxygen SCWS chemistry [8]). Correlating with increasing oxygen content, conductivity showed slight increases, indicating possible CO_2 ingress.

Extensive troubleshooting efforts narrowed down the possible root cause to be air entering the SCWS through a gas-to-water leak in the stator casing. This air came in the form of impurities in the stator hydrogen cooling gas. Hydrogen purity tended to drop from 99.5 % to 95 % within a week. At this purity, and assuming the impurities are mainly air, a relatively moderate gas-to-water leak of 100 L per day would be sufficient to bring in enough oxygen to create the amount of oxides removed in the cleanings.

If those leaks were at the stator inlet, the affected bars would plug up more than others, as observed.

The main suspect for the relatively fast deterioration of hydrogen purity in the stator casing was found to be the older, relatively simple seal oil system that allowed excessive amounts of air to be carried into the casing.

Accidental Change in Chemistry Regime and Cascading Effects Cause Two Rewinds: Plant SB

The high-oxygen design SCWS at plant SB was run at low-oxygen conditions for 14 years because its constant load operation did not permit sufficient gas exchange with the atmosphere through the expansion tank vent. However, during a refuel outage, the system was exposed to air and went through intermediate dissolved oxygen concentrations. This transient zone is characterized by increased copper release rates and can lead to rapid plugging (Figure 2) [2].

A sudden decrease in cooling water flow by 30 % after an outage forced the unit into load limitations during peak demand time.

In order to restore the decreased flow and to remove the old oxide layers that were formed under low-oxygen conditions, an online chemical cleaning was carried out. The choice of a method employing ethylenediaminetetraacetic acid (EDTA) was made due to the capability to conduct such a cleaning while the unit was in operation, and because of the compatibility of the method with Loctite leak repairs. This cleaning provided only temporary relief, however, as the unit started plugging up again shortly after. At the time, it was not understood that for a system to run successfully under high-oxygen conditions, a suitable, stable oxide layer needs to be applied on the blank copper surface after the cleaning.

The system was returned to a low-oxygen regime after a second cleaning by applying a nitrogen blanket on the stator water expansion tank, which allowed the unit to run trouble free until a rewind ten years later. This rewind offered another opportunity to return the stator cooling water system to the originally specified high-oxygen regime. This was the beginning of more frequent plugging of the duplex main system strainers, and five years after the rewind, strainer plugging frequency increased further.

In this design, stator winding inlet pressure is not monitored directly. Instead, a pressure monitoring point is installed upstream of the strainer, thus integrating strainer, stator winding and system pipe pressure drop. A careful analysis of the data revealed that the winding itself had indeed also been plugging up for over a year already. The trend had accelerated rapidly after the previous outage a few months before.

The stator plugging was masked by frequent strainer swaps and pump changes until it had progressed so far that an extended chemical cleaning, although successfully cleaning most stator bars, was not able to restore full flow in some bars. Load had to remain limited to 85 % of full load, up from 65 % from before the cleaning. The utility chose to carry out another rewind several months later.

As one hypothesis for the root cause that was put forth by the original equipment manufacturer (OEM) was that oxide deposits left in the system during the first rewind were responsible for the plugging, a thorough system cleaning was carried out during the rewind. Another, modified, stator bar design was used.

Overall, the cost for lost output and penalties, troubleshooting and finally the emergency rewind was considerable.

Severe Plugging Necessitates Combined Mechanical and Chemical Cleaning: Plants SD, P, HE, OP

In several other cases, chemical cleaning on the entire system could not sufficiently restore flow through all the stator bars because too many individual hollow conductors were completely plugged, or the oxide deposits had gotten too hard and compact. More invasive methods had to be applied in order to avoid the expense of a rewind. Depending on the water box design, mechanical cleaning may require unbrazing the water box itself (Figure 10). Sometimes, a targeted chemical cleaning on individual bars alone can be successful.

- In one of plant SD's six units, a targeted chemical treatment on the few heavily fouled bars was successful. Initial attempts with a mixture of sulfuric and phosphoric acids and hydrogen peroxide did not bring significant improvement. Concerns about winding integrity prompted another approach with EDTA, again supported by hydrogen peroxide. This solution was successful, while being gentle on system materials. The hollow conductors were individually tested for flow and all found to be open.
- Plant P found copper oxide deposits at the hollow conductor ends while conducting borescope inspections. Initially, only mechanical cleaning was planned to remove these deposits, as the OEM's chemical cleaning method was found to be too aggressive. It was decided to follow up with a chemical cleaning with EDTA. The mechanical cleaning was undertaken with piano wires that could be guided toward the required location, and then the deposits were scraped off. Rather than merely opening up flow channels, it was attempted to remove as much of the oxides as possible. This left scratches on the surface, which may act as starting sites for renewed oxide growth.
- Borescope inspections revealed several heavily fouled stator bar inlets at plant HE. In order to open up their hollow conductor inlets, a gentler method for mechanical cleaning was investigated, and the plant ended up with a bespoke wide water jet nozzle that could be mounted to the insulating hose fitting on the water box. A rotating seal allowed the jet to be moved across the surface. This method was successful in opening up the water channels, but oxides were left inside the hol-

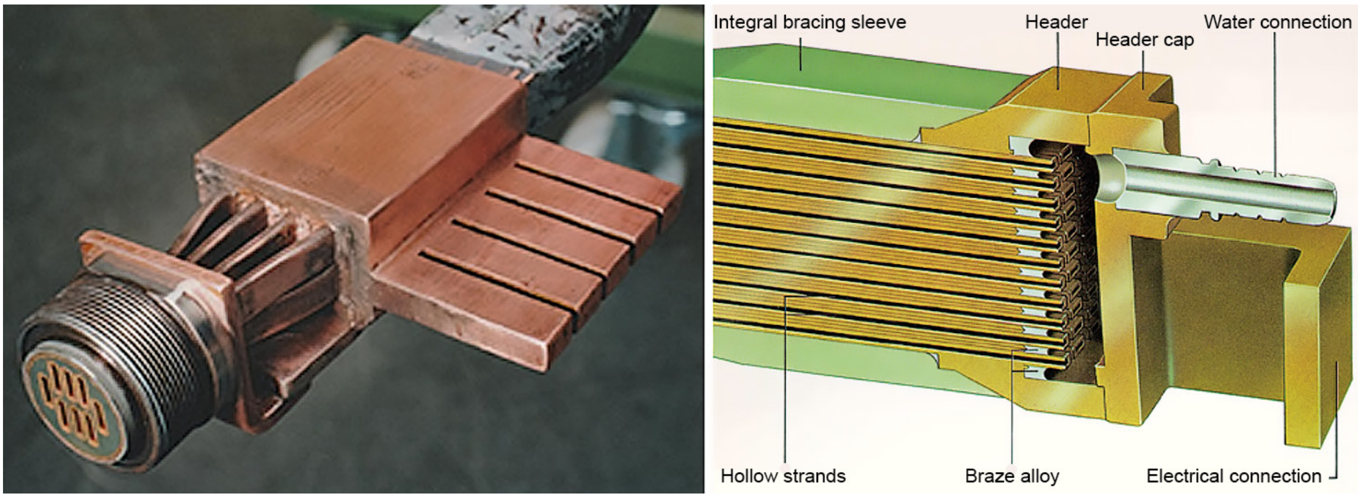


Figure 10:
Different designs of stator bar water boxes. The design on the left allows relatively easy access to the hollow conductor inlets, while the design on the right poses greater difficulty to reach all openings [1,9].

Figure 11:
Stator bar inlet water box as found (left), after mechanical treatment with a metal rod to open flow passages (middle), and finally after targeted chemical cleaning (right) [10].

low conductors. These were removed with a following chemical cleaning.

- Plant OP's generator cooling systems were specified with a generous margin, possibly to keep the option for future power uprates open. Stator cooling water temperatures remained cool and unnoticeable throughout the unit's operation, until visual inspections during a major outage revealed heavily fouled hollow conductor inlets (Figure 11, left). Several bars had almost half of their hollow conductors completely blocked. Targeted single bar chemical cleaning on all bars combined with mechanical cleaning on the most heavily fouled bars was the most promising solution.

  Access to the face plate with the hollow conductor inlets was open and direct, so the tool of choice for the initial mechanical cleaning was a simple wire, as using a drill was found to be too damage-prone. The hardness of the well-aged deposits made this difficult, however, and only an application of a suitable cleaning solution softened up the deposits enough that a channel could be poked through.

  Once flow was established, the chemical cleaning was able to remove all copper oxides from the bars, leaving them in pristine condition (Figure 11).

In all cases, a full system chelant cleaning was carried out after reassembly. It is evident that these cases involved significantly higher effort and cost compared to dealing with the issues earlier in the plugging process.

CONCLUSIONS

Problems with stator winding cooling water system plugging are not always immediately obvious with the often limited instrumentation on most systems. Good instrumentation and monitoring practices help catch problems early in their development, when it is easier to remedy the issues, and less intrusive options are available.

Plugging that goes unnoticed, is being ignored or is not treated proactively can turn into an expensive situation that can only be resolved with great effort. Acting early can prevent major losses later on.

Prevention in the form of a tight chemistry regime, particularly during outages, and procedures tailored to keep conditions in the system stable and within their design parameters should be the first priority. Preventive cleanings give a condition assessment of a system and can resolve potentially critical situations before they develop into a problem.

Once plugging occurs, the cause is often not readily obvious, and several factors can be active at once. Nonetheless, eliminating the root cause is necessary if removing the blockage should be more than just a temporary remedy.

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