

Corrosion and Deposits in Water-Cooled Generator Stator Windings: Overview of Water Cooling of Generators

Robert Svoboda and Wolf-Dietrich Blecken

ABSTRACT

The most common and severe problem related to corrosion and deposits that has arisen with generator water cooling throughout its more than 50 years of history is plugging of copper hollow conductors. This article gives an introduction to a series of four additional articles to appear in this journal on these issues, in particular problems with copper hollow conductors. The main goal of this series is to give a detailed update on the mechanism, prevention, diagnosis, and removal of flow restrictions in water-cooled generator windings.

INTRODUCTION

With generator water cooling only few problem areas related to corrosion and deposits have emerged in more than 50 years of history. The most common and severe problem is plugging of copper hollow conductors. Other problem areas, mainly limited to specific designs, are crevice corrosion between the brazing and the hollow conductors ("clip-to-strand leaks"), plugging of strainers, and conductive deposits inside of insulating hoses.

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

BACKGROUND AND HISTORY OF GENERATOR WATER COOLING

Large generators have been designed using a variety of cooling methods over the years. Originally, and still to some extent today, such stator windings have been cooled with air or hydrogen. As generator output went up, the industry was forced to increase the specific utilization of the machines. Although voltage levels were raised, the stator current densities nevertheless increased. Cooling became a major consideration in the design of stator windings. The result was a substantial change in the way the windings were designed to achieve these higher outputs and also to keep the generators to a manageable size.

Although generator design is aimed at minimizing losses, a typical generator can have stator winding heat losses of

up to 1 % of its output; that is in the order of quite a few megawatts in large generators. These heat losses have to be removed from the system in order to keep the generator within design temperature limits set by international standards [6].

The heat removal ability of a cooling medium is determined by its specific heat, by the mass flow that can be achieved to the cooling surfaces, and by the heat transfer rate. Water has a high specific heat value and a high density, hence a high cooling ability.

Generators with direct water-cooled stator windings operate at temperatures considerably lower than units cooled by hydrogen or air. Thermal deterioration of the stator bar ground wall insulation properties is therefore reduced substantially, resulting in less heat stress, higher reliability, and longer life of generator components.

Already in 1914, C. A. Parsons and Company, UK applied for a patent on water-cooled turbo generator rotors, and one year later a water-cooled rotor was built and tested by General Electric Company (GE), USA. In both cases the field winding was indirectly cooled with the cooling water circulating through axial holes positioned below the rotor slots [7].

Because of the advent of hydrogen-cooled electrical machines (the first hydrogen-cooled synchronous condenser was commissioned in 1928 and the first hydrogen-cooled turbo generator in 1937), both indirect water cooling methods described above proved to be expensive and not efficient enough to warrant further development, and were subsequently abandoned.

Since 1956 some generators have been made with direct cooling of the stator winding with hydrogen and low viscosity transformer oils [8]. The first synchronous generator with a direct water-cooled stator winding was built by Metropolitan Vickers, UK (30 MW, 11.8 kV and 50 s^{-1} (3 000 rpm)). This unit was put in operation in 1956 at the "BOLD A" thermal power station in the UK [9]. Later, the "BOLD B" power station received another generator with a water-cooled stator winding (60 MW) built by General Electric Company (GEC), UK. Also in 1956, a turbo generator (12 MW, 6.3 kV and 50 s^{-1} (3 000 rpm)) with direct water cooling of both the stator and rotor windings was manufactured and tested in China [10]. These turbo generators can be regarded as prototype units because generators of this size typically were air-cooled in those days.

From the early 1960s, when direct water cooling for rotating electrical machines (turbo generators and hydro generators) was introduced on an industrial scale, about 20 original equipment manufacturers (OEM) individually developed their own type of generator cooling water system. This allowed the design and manufacture of extremely large generators (> 1 500 MW) in a single tandem shaft arrangement, rather than the more complex double shaft cross-compound arrangements.

So far about 2 000 directly water-cooled generator stators have been produced worldwide, not including the former USSR and China, where reliable data are only partially available; see Table 1. Of these 2 000 generators, about 80 also have water cooling of the rotor. Some of these generators have reached more than 250 000 successful operating hours.

TECHNICAL FEATURES

The winding of a stator consists of Roebel bars that are embedded in the slots of the stator core (Figure 1). These stator bars consist of an array of isolated solid conductors and hollow conductors to provide water flow for cooling. At their end, the conductors are joined by brazing to a clip for electric connection. The hollow conductors are assembled in a water chamber for distribution of the cooling water, (Figure 2 and Figure 3). As the water chambers are at high voltage, they are hydraulically connected to the cooling water system with insulating water hoses (Figure 4), most commonly made of Teflon™. These figures show individual implementations that vary with design.

World Region	Turbo Generators		Hydro Generators	
	Stators	Rotors	Stators	Rotors
World (excluding former USSR & China)	1 900	40	120	45
Former USSR	700	20	100	40
China	1 500	?	5	5

Table 1:
Number of directly water-cooled generators worldwide. All numbers are approximate.

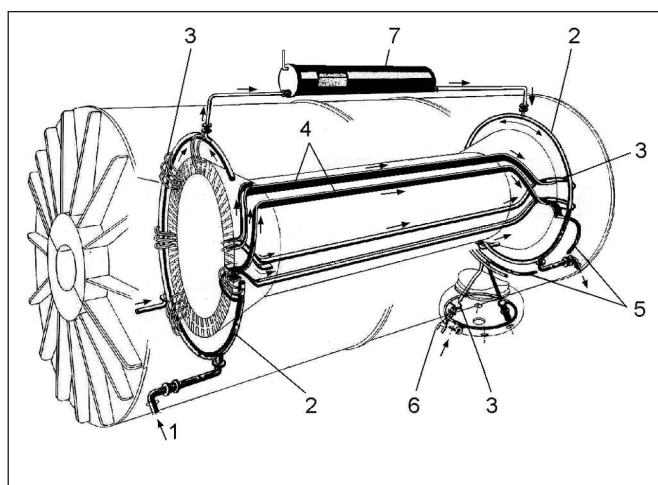


Figure 1:
Schematic view of a water-cooled turbo generator stator. For clarity, only four stator bars are shown.

- (1) cooling water inlet
- (2) distributor ring for cooling water
- (3) electrically insulating water connecting hoses
- (4) water-cooled stator bars
- (5) and (6) water-cooled phase connectors and terminal bushings
- (7) head tank (expansion vessel)

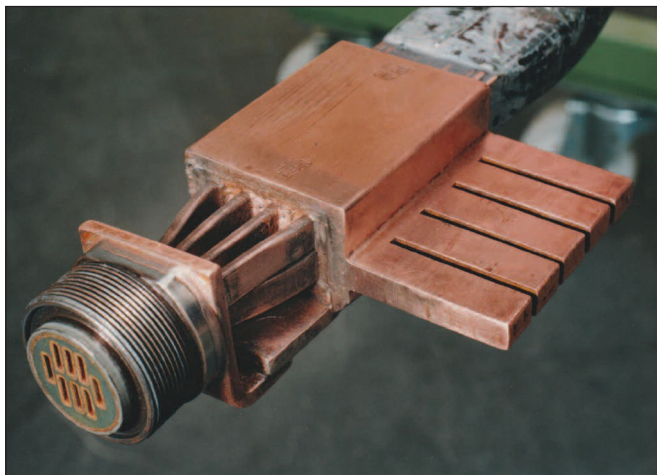


Figure 2: End of a stator bar. Specific design with separate clips for electricity and water. In the centre of the picture all solid and hollow conductors are brazed together for the electrical connection ("clip"). The hollow conductors are continued on the left in the picture, where they are brazed into an end plate onto which the water chamber with the water hoses (not seen in the picture) is later attached. The water chamber and clip arrangement varies with design.

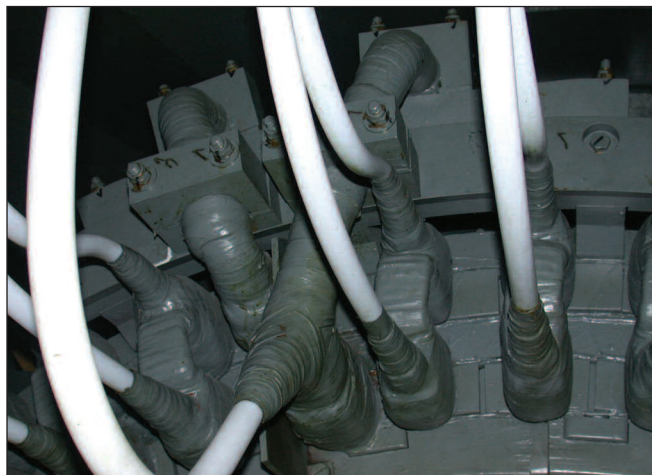


Figure 4: Electrically insulating Teflon™ water hoses connected to the water chambers of the stator bars. The hose arrangement varies with design.



Figure 3: View into the water chamber of a stator bar after some periods of operation. First traces of oxide deposition can be seen in the hollow conductor ends. The water chamber arrangement varies with design.

Turbo Generators

Large water-cooled turbo generators are of 2 or 4 pole design and the horizontal type of construction. The stator windings consist of between 36 and 60 slots (2 pole units) or between 60 and 120 slots (4 pole units). Stator bars are up to 12 m long with a stator axial core length of 8 m. Maximum stator bore diameters for 50 Hz units are about 1.4 m for 50 s⁻¹ (3 000 rpm) generators and 2.0 m for 25 s⁻¹ (1 500 rpm) generators. Bore diameters of 60 Hz units are slightly smaller.

Typical voltages are between 21 kV and 27 kV, resulting in rated currents of up to 48 kA.

Stator windings of large turbo generators are directly water-cooled and operate in a hydrogen environment. For large turbo generators every single stator bar (or 2 bars in series) is connected in parallel with the cooling water supply system. For leakage protection the hydrogen pressure inside the generator casing under normal operating conditions is higher than the system water pressure.

The majority of stator cores and field windings (rotors) are hydrogen-cooled, but some rotors are also water-cooled. The highest turbo generator output figures at present are 2 235 MVA for 25 s⁻¹ (1 500 rpm) units (2 000 MVA for 30 s⁻¹ (1 800 rpm)) and about 1 400 MVA for 50 s⁻¹ (3 000 rpm) units (1 200 MVA for 60 s⁻¹ (3 600 rpm)), according to public information given by various OEMs.

Hydro Generators

For over-speed protection matters the hydro turbine manufacturers in the majority of cases call for high moment of inertia figures, which are usually achieved by increasing the generator rotor mass and diameter. This makes it impossible for the generator suppliers to fully utilize the water cooling technique for potential reduction of generator dimensions and manufacturing costs. Nowadays application of an improved air cooling is feasible even for the highest output figures, and therefore water cooling has been applied to a lesser extent to hydro generators.

The majority of large water-cooled hydro generators are of the vertical type of construction with between 10 and 80 salient poles and operate in air. The stator windings of large hydro generators usually consist of between 120 and 600 slots. Stator bars are up to 6 m long with a stator axial core length of up to 4 m. Cooling circuits have either 4 or 6 stator bars that are hydraulically connected in series. Typically, the inlet of two cooling circuits is connected to one common water hose. For correct supervision of cooling circuit water temperatures it is important, however, to have one individual hose connected to each outlet. A hydro generator with 600 slots and 6 stator bars hydraulically connected in series would have 100 inlet and 200 outlet water hoses, plus a certain number of hoses for phase connectors and terminal cooling.

Quite a few directly water-cooled hydro generators were either decommissioned or later replaced by updated units. At present about 130 large water-cooled hydro generators of between 190 MVA and 840 MVA are still in service with voltages of between 12 kV and 23 kV. Hydro generators with bore diameters of up to 19 m and rotors with mass figures of up to 2 000 t are in operation. The field windings (rotors) of about 30 large hydro generators are also water-cooled.

In addition about 40 so-called bulb generators with the horizontal type of construction and outputs of only 20 to 40 MVA are also equipped with direct water cooling of stator and rotor windings. All of these units are still in operation. With pole numbers of between 64 and 116, an application of air-cooling is in most cases insufficient because the space inside the generator housing is extremely limited.

PROBLEMS RELATED TO CORROSION AND DEPOSITS

In the early days of direct water cooling from 1960 to 1965, only little consideration was given to the chemistry of the generator cooling water. The conductivity of the water had to be restricted in order to limit phase-to-ground currents. In order to prevent magnetic particles from entering the generator winding, the cooling water system had to be free of unalloyed steel, which greatly simplified the requirements on water quality. However, it was evident that the cooling water systems had to be operated with demineralized water, which also eliminated concerns regarding corrosion of the structural materials [11,12].

As already mentioned earlier, cooling of the generator bars is achieved by inserting strands with small cooling channels between the solid copper strands used for conducting electricity, commonly termed hollow conductors. These hollow conductors are traditionally made of copper, but stainless steel is also used.

There is no problem regarding corrosion with the use of stainless steel in high-purity water [13].

With copper, only few problem areas have emerged [14,15]:

- Plugging of copper hollow conductors
- Crevice corrosion in the brazing between hollow conductor and water chamber ("clip-to-strand leaks")
- Plugging of strainers at the generator inlet
- Deposits on insulating hoses

While clip-to-strand leaks are essentially specific to a certain OEM series of generators, it is not an issue of water chemistry, rather its solution is in the use of a more stable braze [15]. Strainer plugging is also specific to one OEM.

The build-up of deposits inside the insulating hoses for AC applications like stator bars is slow and usually settled by the long-term replacement of the hoses. In case of very low oxygen levels, such deposits are more frequent with water-cooled DC applications like field windings or rectifiers.

The main chemistry related issue is therefore plugging of copper hollow conductors by copper oxides. It is estimated that about 10–20 % of the 2 000 water-cooled generators worldwide (not including the former USSR and China) suffer from related flow restrictions sooner or later within the first 25 years of operation.

This article is the introduction to a series of four additional articles to appear in this journal on corrosion and deposits in water-cooled generators [1–5]. The main aim of this series is to give an update on the mechanisms, prevention, diagnosis, and removal of flow restrictions in water-cooled generator windings.

REFERENCES

- [1] Svoboda, R., Blecken, W. D., "Corrosion and Deposits in Water-Cooled Generator Stator Windings: Overview of Water Cooling of Generators", *PowerPlant Chemistry* **2018**, 20(5), this article.
- [2] Svoboda, R., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 1: Behaviour of Copper", *PowerPlant Chemistry* **2018**, 20(5), this issue.
- [3] Svoboda, R., Chetwynd, R., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 2: Detection of Flow Restrictions", *PowerPlant Chemistry* **2018**, 20(6), to be published.

- [4] Bauer, T., Svoboda, M., Svoboda, R., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 3: Removal of Flow Restrictions", *PowerPlant Chemistry* **2019**, 21(1), to be published.
- [5] Bauer, T., Svoboda, M., "Corrosion and Deposits in Water-Cooled Generator Stator Windings, Part 4: Operating Experience with Flow Restrictions in Stator Cooling Water Systems", *PowerPlant Chemistry* **2019**, 21(2), to be published.
- [6] *International Standard: Rotating Electrical Machines – Part 1: Rating and Performance*, **2017**. International Electrotechnical Commission, Geneva, Switzerland, IEC 60034-1:2017.
- [7] Fechheimer, C. J., "Liquid Cooling of A-C Turbine Generators", *Transactions of the American Institute of Electrical Engineers* **1947**, 66(1), 553.
- [8] Longwell, R. I., "Experience with Water-Cooled Stator Winding Leaks", *Proc., Maintaining the Integrity of Water Cooled Stator Windings*, **1995** (Atlanta, USA). Electric Power Research Institute, Palo Alto, CA, USA, EPRI TR-105504, 12.3.
- [9] "Turbo-Generator with Water-Cooled Stator Windings", *The Engineer* **1956**, 202(5264), 854.
- [10] Mang, C. Y., "Twenty-One Year Development in Turbine Generators with Water-Cooled Stator and Rotor Windings", *IEEE Transactions on Power Apparatus and Systems* **1982**, PAS-101(3), 610.
- [11] Busch, H., Kretzer, R., "Betriebserfahrungen mit wassergekühlten Statorwicklungen bei Drehstromgeneratoren", *Proc., VGB Conference Speisewassertagung*, **1968** (Essen, Germany). VGB Technische Vereinigung der Grosskraftwerksbetreiber, Essen, Germany, 27 [in German].
- [12] Seipp, H.-G., "Das Korrosionsverhalten von Kupfer in wassergekühlten Generatorwicklungen", *VGB Kraftwerkstechnik* **1979**, 59(3), 245 [in German].
- [13] Svoboda, R., Picech, C., Hehs, H., "Experiences with Stainless Steel Hollow Conductors for Generator Stator Water Cooling", *PowerPlant Chemistry* **2003**, 5(4), 211.
- [14] *Guide on Stator Water Chemistry Management*, **2011**. International Council on Large Electric Systems, Study Committee A1, CIGRE Working Group A1.15, Paris, France.
- [15] *Turbine Generator Auxiliary System Maintenance Guide Volume 4: Generator Stator Cooling Water System: 2013 Update*, **2013**. Electric Power Research Institute, Palo Alto, CA, U.S.A., EPRI 3002000420.

THE AUTHORS

Robert Svoboda (Ph.D., Physics, University of Vienna, Austria, postdoctoral studies on reactor metallurgy in Saclay, France) joined the chemical laboratory of Alstom Power, Baden, Switzerland, in 1969 (formerly part of Brown Boveri & Cie), where he headed the Power Plant Chemistry Section, and in 1992 the Power Plant Chemistry Department in Mannheim, Germany. Since his retirement in 2007 he has been staying active as a consultant. His work is concentrated on water chemistry, corrosion, and radiation technology. He has extensive experience with generator water cooling; since 1989 he has chemically cleaned more than 70 generators and has been responsible for another 80 generator cleanings. Robert Svoboda is an Honorary Fellow of the International Association for the Properties of Water and Steam. He is also a member of the International Advisory Board of the *PowerPlant Chemistry* journal.

Wolf-Dietrich Blecken (Dipl.-Ing., University of Applied Sciences Berlin, Germany) joined the design office of Siemens Dynamowerk Berlin, Germany, in 1961. He prepared designs for large hydro generators and was involved in the implementation of resulting contracts. His experience covers both conventionally designed hydro generators and direct water-cooled units. As senior project engineer he conducted, planned, and prepared written reports on plant upgrade/uprate potential for equipment between hydro generator coupling and high-voltage transmission lines (i.e. complete power trains). He also commissioned hydro generators and conducted guarantee and acceptance tests, including for deionized cooling water systems, for generator ratings of up to 840 MVA. Since retirement he has provided consulting services with Hydropower Consult.

CONTACT

Robert Svoboda
Svoboda Consulting
Rosenauweg 9A
5430 Wettingen
Switzerland
E-mail: r.svoboda@swissonline.ch

Wolf-Dietrich Blecken
Hydropower Consult
Hutweide 64
91054 Buckenhof
Germany
E-mail: info@hydropower-consult.com