Conductivity Limits for Direct Water-Cooled Generators

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ABSTRACT

For normal operation, a conductivity limit of ≤0.2 µS · cm^{-1} is an indirect indicator of correct pH and restricts undue corrosion. With protective additives, e.g., NaOH for alkaline treatment, a higher limit corresponding to the objective of the treatment is appropriate.

With too high conductivity the water inside the insulating hoses of high-voltage stator windings will warm up and if it boils there is a risk of electric flashover inside the insulating hose with damaging consequences. Therefore, a short-term action limit in the order of 10 µS · cm^{-1} has been set by the industry in the past.

With correct water flow, conductivity inside the insulating hoses at these values does not warm up the water significantly and there are no restrictions regarding the duration of such an event.

However, when cooling water flow is lost, the water inside the insulating hoses will warm up exponentially with time. The time until boiling has a strong (square) dependence on the rated generator voltage, as well as on the insulating hose length, and has a linear dependence on water resistivity. The spatial position of insulating hoses (hoses are mounted vertically, horizontally, or bent) is also of importance. In addition, the stationary cooling water inside the stator bars, as well as the entire stator winding, is subjected to critical temperatures, especially at high load conditions. Therefore, appropriate action must be taken prior to reaching the water boiling level. To avoid a costly stator winding breakdown, the cooling water flow must be restored at once. Otherwise, the generator has to be shut down completely as soon as possible.

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INTRODUCTION

As with any system employing water as a cooling medium, adequate water chemistry is required to avoid or properly manage corrosion and deposition and to ensure electrical insulation of the water path from generator stator windings to ground.

For direct water-cooled generators, each original equipment manufacturer (OEM) and each operator has its own water chemistry guidelines. Internationally approved standards have been set up by the International Council on Large Electric Systems (CIGRE) [1] and the International Association for the Properties of Water and Steam (IAPWS) [2].

An overview of generator water chemistry is given in Reference [3]. Key guidance parameters are conductivity, dissolved oxygen, and pH. As pH measurement in high-purity water is prone to significant errors [4], conductivity is usually used as a substitute parameter [3,5].

The present publication discusses the specifications for water conductivity in generator cooling systems.

Commonly, two conductivity limits are given, one for long-term normal operation and the other for short-term action.

The NORMAL OPERATION RANGE for neutral water chemistry is commonly understood as below 0.5 µS·cm^{-1}. Historically, it comes from the certainty that a conductivity of less than 0.1 µS·cm^{-1} is achievable without special efforts in a clean closed cooling system with water resistant materials and side-stream mixed bed purification. To give some operating margin, the first generation of direct water-cooled generators in the 1960s mostly had a limitation to less than 1 µS·cm^{-1}, where this value has no technical justification but was chosen for simplicity.

Alkaline water chemistry systems have a higher operation range because an addition of NaOH is required for a pH of between 8.5 and 9.0. A typical conductivity value is in the region of about 2 µS·cm^{-1}.

The usual SHORT-TERM ACTION LIMIT is in the order of 10 µS·cm^{-1}. Historically, it comes from the demand that heat-up of the water in the insulating hoses must be limited to avoid boiling, and

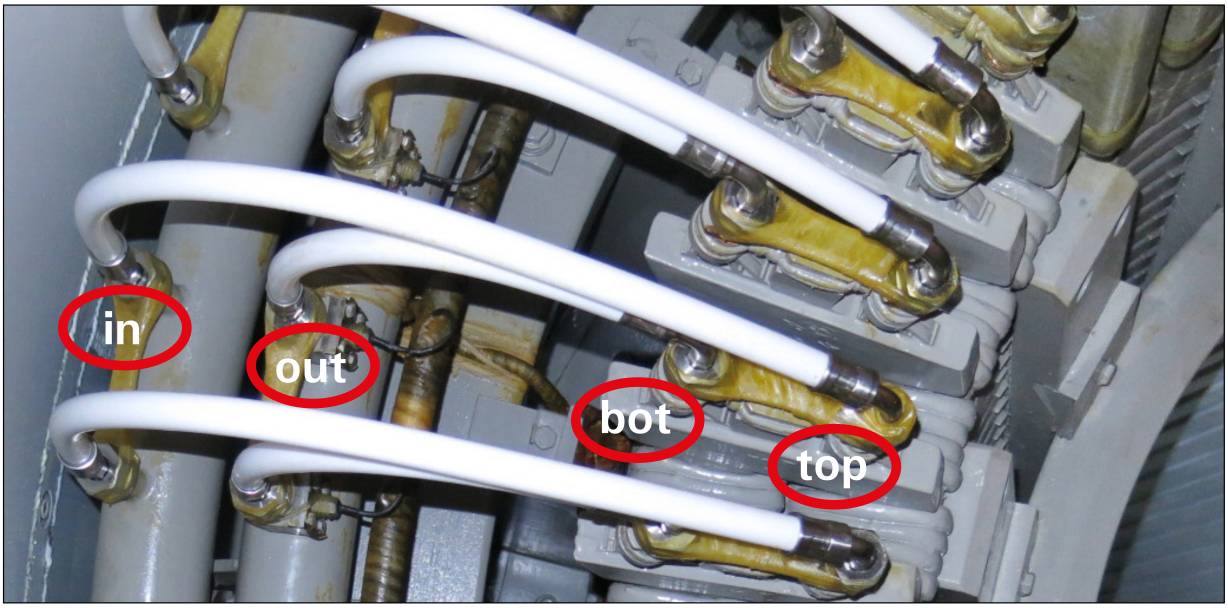

Figure 1:
Insulating hoses (white) to guide the cooling water from the cold-water manifold (in) into the top stator bar (top) and from the bottom stator bar (bot) out to the hot-water manifold (out). Only the ends of the stator bars are visible. Each top bar is hydraulically connected in series to a bottom bar at the other end of the stator (not visible). The manifolds are grounded, the stator bars are at high voltage. This is one of many possible configurations.

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that a reasonably higher conductivity than the normal operation limit should be chosen to accommodate varying operation conditions without impairing plant availability. A value of $10\,\mu S \cdot cm^{-1}$ was chosen probably because we have 10 fingers on our hands. Another consideration was the measuring range of the then available analogue conductivity instrumentation, which often had a range of up to $10\,\mu S \cdot cm^{-1}$. It was desirable to have the alarm point distinctly within full scale.

Sometimes values like 9 or $8\,\mu S \cdot cm^{-1}$ were selected to have the alarm point well below full instrument range, but often also because management was just formally adding a safety margin.

This article is intended to give an update on the considerations which were made in the early days of generator direct water-cooling technology, in the 1950s and early 1960s.

NOMENCLATURE

For ease of reading, "water" will be used for the liquid phase of cooling water, and "steam" for its gas phase.

A "stator winding" consists of several winding elements referred to as stator bars. These bars are electrically connected in series and are – in the context of this report – direct water-cooled.

Symbol	Unit	Designation	Specific Use
U	V	voltage	Phase voltage = rated voltage/$\sqrt{3}$
R	Ω	resistance	Resistance of water-filled insulating hose
P	$W, J \cdot s^{-1}$	power	Power dissipated to the water inside insulating hose
σ	$S \cdot cm^{-1}$	specific conductivity	Conductivity of water inside insulating hose
L	cm	length	Length of insulating hose
A	cm^2	area	Cross section of insulating hose
M	g	mass	Mass of water inside insulating hose
$\dot{m}$	$g \cdot s^{-1}$	mass-flowrate	Water flow through insulating hose
ρ	$g \cdot cm^{-3}$	density	Density of water
T	°C	temperature	Temperature of water
s	$J \cdot g^{-1} \cdot K^{-1}$	specific heat	Specific heat of water, $s = 4.18\,J \cdot g^{-1} \cdot K^{-1}$
t	s	time	

Table 1: Symbols and units as used in this report.

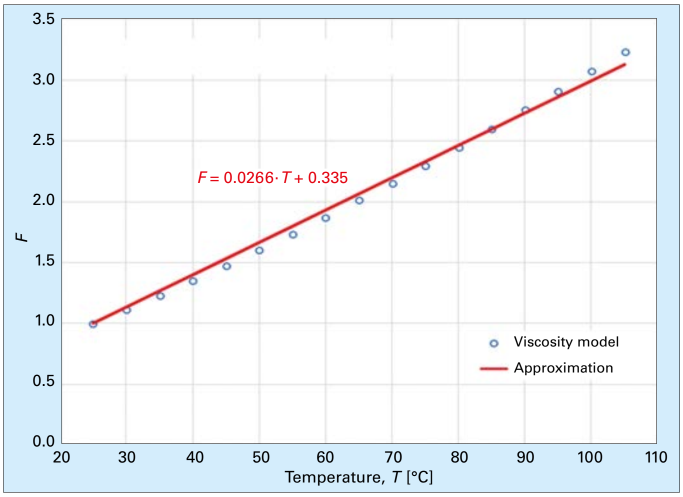

Figure 2:
Dependence of conductivity on water temperature. *F* is the factor for conductivity relative to 25 °C, *T* the temperature in °C. The points represent the "viscosity model" (see the Appendix), the line is a linear approximation for ease of use, with the formula $F = 0.0266 \cdot T + 0.335$ inserted.

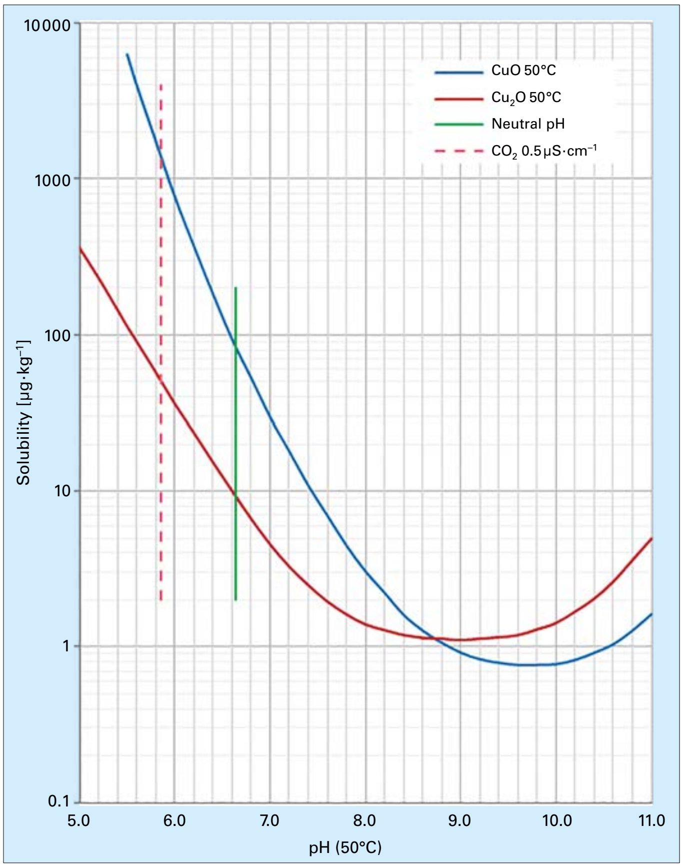

Figure 3:
Solubility of CuO and Cu_2O (µg·kg^{-1}) as a function of pH at 50 °C [10]. Indicated is – for 50 °C – the neutral pH, as well as the pH of water contaminated with 212 µg·kg^{-1} CO_2. This level of CO_2 corresponds to the old conductivity specification of 0.5 µS·cm^{-1} (25 °C). It is evident that this level of CO_2 increases the solubility by about an order of magnitude. CO_2 is a common impurity in high-oxygen systems and can also be present (in minor concentrations) in low-oxygen systems.

A direct water-cooled stator winding is hydraulically split up into "cooling circuits". Cooling circuits consist of either one single bar or of between two and six stator bars hydraulically connected in series, equipped with hollow conductors.

"Insulating hoses" are hoses made of electrically insulating material (e.g., polytetrafluoroethylene (PTFE)). They hydraulically connect stator bars (at high voltage) and cooling water manifolds (grounded) (Figure 1).

More related details on the design of a direct water-cooled generator are found in the Appendix and in References [6] and [7].

It is also understood that the system is essentially built up of copper and its alloys, stainless steel, and plastic materials, as well as some selected brazes, solders, and seals [1,8]. Unalloyed steels, aluminium, and zinc-coated steel would not fit into a proper water chemistry.

When not specifically mentioned otherwise, the discussion refers to hollow conductors made of copper.

While most considerations in this report relate to the stator winding, they are correspondingly also applicable to the field (rotor) winding, although there are a few different requirements [9].

For ease of practical use, the symbols and units will be applied as listed in Table 1.

Some of the parameters mentioned in Table 1 need a more detailed consideration.

"Phase voltage" (U). The phase voltage of a generator is usually called "line-to-neutral voltage" (sometimes also named "line-to-star point voltage") while the rated voltage is called "line-to-line voltage". The rated voltage is larger than the phase voltage by a factor of $\sqrt{3} = 1.73$. In other words: A generator with a rated voltage of 27 kV has a phase voltage of 15.6 kV. More details can be found in the Appendix.

"Specific conductivity of water" (σ). The conductivity is significantly dependent on the temperature of water (the increase with temperature is given in Figure 2, and is further detailed in the Appendix). It can be seen that, for example, a conductivity of 10 µS·cm^{-1} at 25 °C will be 19 µS·cm^{-1} at 60 °C and 31 µS·cm^{-1} at 105 °C. This means that with rising temperature the heat-up rate will accelerate, and the temperature will increase exponentially.

"Density of water" (ρ). This parameter is of use when the water flowrate is obtained as a volume-flowrate (e.g., m^3·h^{-1}), whereas the calculations presented below go by mass-flowrate.

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"Temperature" (T). As only relative temperatures are involved, °C will be used instead of K. The boiling point depends on water pressure and amounts to 105°C at 1.2 bar, for instance.

CONDUCTIVITY REQUIREMENTS FOR NORMAL OPERATION

No Use of Water Treatment Chemicals

Basically, there is only a negligible risk of corrosion resulting from typical impurities as long as the conductivity does not surpass a few $\mu S \cdot cm^{-1}$. Only when the pH turns acidic does the dissolution of copper increase strongly (Figure 3) [10].

Figure 4 shows the relation of pH to conductivity. It can be seen that with a conductivity of $0.5 \mu S \cdot cm^{-1}$, pH can be as low as 5.9. This pH is quite acidic and would increase – compared with pH=7 – copper solubility by almost an order of magnitude (Figure 3). This means that a value of $0.5 \mu S \cdot cm^{-1}$ is already quite high and risky if the water is acidic. The IAPWS guideline therefore limits conductivity to less than $0.2 \mu S \cdot cm^{-1}$ [2], which is easily achievable in properly designed and operated systems.

The conductivity limit of $0.2 \mu S \cdot cm^{-1}$ can be increased if it is certain that the water is not acidic. Attention must be paid when contact of the water with air cannot be excluded; elevated conductivity is then usually due to an ingress of carbon dioxide, which turns the water acidic. In any case, a limit above $0.5 \mu S \cdot cm^{-1}$ should be avoided, because it would indicate poor chemistry control in such a pure water system.

Generators with stainless steel hollow conductors are less sensitive to slightly acidic pH, but here the chloride concentration must be limited. Therefore, a conductivity of less than $0.3 \mu S \cdot cm^{-1}$ is specified for normal operation [2,11].

Alkaline Treatment, Use of Inhibitors

Corrosion is controlled here either by alkalization or by an inhibitor, each of which has its own specific relation to pH and conductivity. However, with the addition of chemicals the conductivity should be kept as low as reasonably achievable, and the short-term action limits – see below – must not be surpassed.

Alkaline treatment, for example, is achieved by injection of dilute NaOH solution into the cooling water to obtain a pH between 8.5 and 9.0 [2,12], with a target conductivity of $1.8 \mu S \cdot cm^{-1}$ and an upper limit of $2 \mu S \cdot cm^{-1}$.

Stainless steel hollow conductors do not significantly benefit from alkalization or inhibitors but would be compatible with their use.

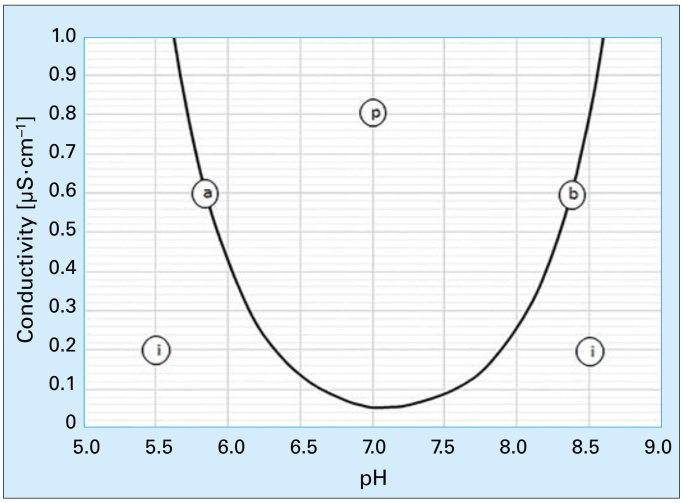

Figure 4:
pH and conductivity in generator cooling water, at 25°C [12]. (a) relation for strong acids, (b) relation for strong bases, (i) impossible region, and (p) region for all possible electrolytes.

Special Consideration for Components Using Direct Current

Generator stator windings operate with alternating current (AC), whereas direct current (DC) is applied to field (rotor) windings.

When applying DC, galvanic currents cause dissolution, and the deposition of metals is possible. The strength of such galvanic effects increases with the conductivity of the electrolyte, in our case the cooling water with its impurities and additives. The use of high-purity water minimizes galvanic effects.

Galvanically induced material loss on components is in practice insignificant in the generator cooling water system. Deposition of conductive material on the insulating hoses, however, can take place in some configurations.

Conductive deposits on insulating hose inner surfaces of direct water-cooled rotating field windings have been reported and were attributed to galvanic deposition. These field windings were subject to an alkaline water treatment with a water conductivity of between 1 and $2 \mu S \cdot cm^{-1}$; DC voltage in this case was 300V [9].

Basically, galvanic effects require only several hundreds of millivolts or a few volts between the electrodes to become significant. In generators, however, we must deal with hundreds of volts DC. Nevertheless, the occurrence of damaging galvanic effects is limited to a few special areas like insulating hoses connecting generator field windings and water-cooled rectifiers.

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It is therefore not possible to determine a general water chemistry specification limit to avoid damaging galvanic effects. Preventative measures are thus required to avoid unexpected failures. Visual inspection of sensitive components will give insight into materials attack and deposits. Regular measurements of the electrical resistance of insulating hoses will reveal possible build-up of conductive deposits (i.e., copper layers). Alternatively, sensitive components will have to be replaced during regular preventative maintenance.

CONDUCTIVITY LIMITS AND REQUIRED ACTIONS FOR GENERATOR PROTECTION

The electric conductance of water causes the generation of heat across the insulating hoses. It is important to keep the water temperature below the boiling temperature because a steam blanket presents an environment for electric flashover, followed by the destruction of the insulating hose and subsequent generator outage. Due to its mechanism, flashover cannot occur in water (liquid phase). The acceptable conductivity limit depends on the design and operating conditions. Usual limit values for safe generator operation are between 5 and 20 $\mu S \cdot cm^{-1}$, as specified in [2].

It is important that the required actions also follow the OEM specifications. When surpassing the conductivity limit, some designs demand immediate tripping of the generator to protect it, in other cases with some delay. Sometimes a manual generator trip within a specified time span is also called for. Other designs link the shutdown requirement with the simultaneous loss of cooling water flow. Because in all cases the insulating hoses are at risk, these considerations of course apply equally for all hollow conductor materials.

To eliminate the risk of insulating hose flashover, the generator first has to reduce power to zero and must be separated from the system, followed by de-excitation, that is, complete unit shutdown.

It must be mentioned that steam in the insulating hoses does not necessarily lead to flashover, but nevertheless presents a significant risk factor that should be avoided in view of the possible extent of damage. In some cases, the risk has even been evident when a high test voltage was applied to a suspect stator winding after a generator shutdown. Under dry conditions the winding may pass the high-voltage test, but under wet conditions, contamination on the insulating hose surfaces will be conductive. Depending on the type of contamination and its conductivity, the moist air inside the translucent hoses may visibly glow under AC high voltage [13], indicating a local gas discharge. On the other hand, there have been generators with water boiling in the winding and in the insulating hoses without there being a flashover. Nevertheless, it must be assumed that water boiling in the stator winding will most likely result in localized overheating damage or premature aging of the insulation system, and possibly also spallation of oxide layers.

In the following, a method for the calculation of the heat-up of the water inside the insulating hoses under consideration of the water conductivity is presented. These calculations do not consider a two-phase medium when boiling, and backflow of water to or from the water manifolds. Additionally, the heat transfer by the cooling gas is also not accounted for. All these parameters would increase the time until boiling. The calculation results therefore are on the safe side.

Heat Loss Generated inside a PTFE Hose

The insulating hose filled with conductive matter represents a conductive body with cylindrical geometry and its resistance is

$$R = (1/\sigma) \cdot L/A \tag{1}$$

The power generated follows Ohm's law:

$$P = U^2/R \tag{2}$$

Heat-up of Water: With Water Flow

The question here is how many degrees the water will heat up by passing through the insulating hose.

The resulting heat-up of the water is given by the equilibrium of power input (power generated) and power output (removed by the flowing water):

input P
output $\dot{m} \cdot s \cdot \Delta T$

ΔT is the associated rise in temperature.

The resulting heat-up of the water is:

$$\Delta T = P/(\dot{m} \cdot s) \tag{3}$$

Together with Eqs. (1) and (2), we arrive at

$$\Delta T = U^2 \cdot \sigma_T \cdot A/(L \cdot \dot{m} \cdot s) \tag{4}$$

where σ_T is the conductivity of the water at temperature T. As will be seen, the heat-up is only minor and therefore T can here be set equal to the generator outlet temperature. σ_T is then determined by Eq. (8).

Heat-up of Water: No Water Flow

The question here is how fast the water heats up inside an insulating hose and how long it will take to boil.

The resulting heat-up rate follows the specific heat of water:

$$\Delta T/\Delta t = P/(M \cdot s) \tag{5}$$

where M is the mass of water involved inside an insulating hose:

$$M = A \cdot L \cdot \rho \quad (6)$$

Eqs. (1), (2), (5), and (6) can be summarized as follows:

$$\Delta T / \Delta t = U^2 \cdot \sigma_T / (L^2 \cdot \rho \cdot s) \quad (7)$$

where σ_T is the conductivity of the water at temperature T.

The cross-section area (A) and with this the hose diameter cancel out in Eq. (7): a larger diameter will generate more heat, but this will also have to heat up the correspondingly larger amount of water.

The length of the insulating hose, however, has a deciding influence on the heat rate in the water. Reducing the length by a factor of 2, for example, halves the resistance and in consequence creates twice (2 times) the heat. At the same time, there is only half the quantity of water in which the heat is absorbed, adding another factor of 2 to the heat-up, which will then be 4 times as large.

As the water heats up significantly (to the boiling point), the temperature dependence of conductivity must be considered:

$$\sigma_T = \sigma_{25} \cdot 0.0266 \cdot \Theta \quad (8)$$

$$\Theta = (T + 12.6) \quad (9)$$

where Θ is an auxiliary parameter ("virtual temperature") as defined in Eq. (9), σ_T is the conductivity of the water at temperature T, and σ_{25} is the conductivity at 25 °C. Eq. (8) is derived in the Appendix.

For practical application, the temperature T is relevant, but for use of the formulas below the virtual temperature Θ has to be used.

It is evident that

$$\Delta T = \Delta \Theta \quad (10)$$

Eqs. (7) and (8) can be summarized as follows:

$$\Delta \Theta / \Delta t = a \cdot \Theta \quad (11)$$

$$a = 0.0266 \cdot \sigma_{25} \cdot U^2 / (L^2 \cdot \rho \cdot s) \quad (12a)$$

where a is an auxiliary constant for a simpler processing of the equations. For the present purpose, a value of $\rho = 0.97\,g \cdot cm^{-3}$ can be used, and together with $s = 4.18\,J \cdot kg^{-1} \cdot K^{-1}$, we arrive at

$$a = 0.006\,560 \cdot \sigma_{25} \cdot U^2 / L^2 \quad (12b)$$

Solving differential Eq. (11) gives the heat-up of water as a function of time:

$$\Theta_t = \Theta_0 \cdot e^{a \cdot t} \quad (13)$$

where Θ_0 is the virtual temperature to start with (at $t=0$) and Θ_t the virtual temperature at time t after start. The actual temperature can then be calculated using Eq. (9).

Conversely, the time from start to boiling (t_b) is as follows:

$$t_b = \ln(\Theta_b / \Theta_0) / a \quad (14)$$

where Θ_b is the boiling temperature and Θ_0 the start temperature.

EXAMPLE

The above theoretical considerations will be illustrated by using them in a calculation example. The following results are obtained with Eqs. (4), (11), (13), and (14) and the parameters listed in Table 2.

The normal operation figures regarding water conductivity are between 0.2 µS·cm^{-1} (no additives) and 2.0 µS·cm^{-1} (alkaline treatment). The following example therefore – in contrast – describes an out-of-normal situation, whether due to a failure in water chemistry or due to controlled conditions during special activities.

Regarding heat-up of the water and with the generator in operation, the most critical insulating hoses are the ones hydraulically attached to stator bars which are electrically connected to the phase voltage terminals X, Y, and Z ("phase terminal bars"). With 27 kV rated voltage, the phase terminal bars are at 15.6 kV relative to ground. All other hoses are electrically connected to proportionally lower phase voltages.

The starting point for the calculation of heat-up in the insulating hose is the water temperature at the outlet of the cooling circuits. However, a certain variation in cooling circuit outlet temperatures among the bar outlet temperatures is possible. Pressure drop and water flow differ

Parameter	Value	Unit
Rated generator voltage	27	kV
Length of insulating hose	80	cm
Inner diameter of insulating hose	1.8	cm
Total cooling water flow	135	T·h^{-1}
Number of parallel (outlet) insulating hoses	48	–
Water temperature at inlet manifold	40	°C
Water temperature at phase terminal bar outlets	60	°C
Boiling point of water	105	°C
Conductivity of water at 25 °C	10	µS·cm^{-1}

Table 2:
Parameters used for the example (2-pole generator with 48 slots).

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slightly between all the cooling circuits because of stator bar hollow conductor constrictions at the transposition areas and other manufacturing tolerances; pressure drop will also vary with the degree of fouling in the water path [14]. Also, some cooling circuits are additionally connected to electrical ring connectors, which results in a certain flow reduction and slightly higher water outlet temperatures. The water temperature at the outlet manifold, however, can be assumed to be close to the mean value of all cooling circuit outlets.

An outlet temperature of 60°C has been chosen as a typical value for a generator operating at high load. The boiling point of water corresponds to a water pressure in the generator of 1.2 bar.

Water Heat-up with Normal Water Flow

Under normal water flow, the water will be heated up by 0.046°C when passing the insulating hose of a phase terminal bar. Even with a deteriorated water flow of only 10% rated flow, the temperature increase will be only 0.46°C. Alternatively, an increase in conductivity to 100 $\mu S \cdot cm^{-1}$ will have the same effect.

The heat-up of water is therefore negligible as long as some cooling water flow is present and conductivity is within reasonable limits. The quantitative relations are given in Eq. (4).

Time to Boiling at Sudden Total Loss of Cooling Water Flow

With sudden total loss of cooling water flow, it will take 193 s for the water to heat up from 60°C to the boiling point at 105°C (Figure 5). The temperature rise will be exponential. At the beginning, the temperature rises by a rate of 0.2 $°C \cdot s^{-1}$, and upon reaching the boiling temperature by 0.3 $°C \cdot s^{-1}$.

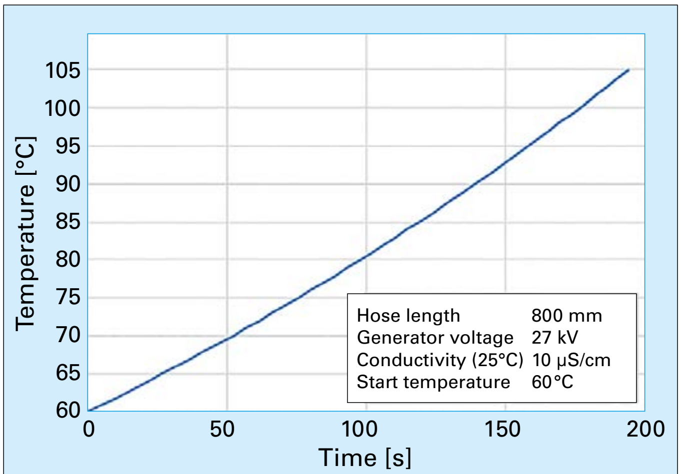

Figure 5:
Calculated increase in water temperature in the insulating hose after loss of cooling water flow.

Reducing generator load lowers, at best, the stator bar outlet temperature down to the inlet temperature. This will increase the time to boiling. Equation (14) gives a value of 323 s at very low load, compared to 193 s at full load.

It must be remembered that the risk of flashover persists as long as the excitation is active. Reducing load to lower the water inlet temperature and/or to rely on external gas cooling may buy some time to boiling inside the insulating hoses, but it does not eliminate the risk. Either cooling water flow must be restored quickly, or the unit must be shut down completely.

Other questions can also be answered with this model, such as:

- What length of the insulating hose is required if the time to boiling should be – for example – 90 s? Eq. (14) gives a value of 54 cm.
- What conductivity is acceptable if the time to boiling should be – for example – 90 s? Eq. (14) gives a value of 22 $\mu S \cdot cm^{-1}$.

OTHER ASPECTS RELATED TO CONDUCTIVITY

Insulation Testing on the Stator Winding

For safe operation, as well as prior to high-potential (hi-pot) testing, generator operators have to rely on correct stator winding insulation resistance figures. The insulation resistance of air-cooled or of hydrogen-cooled stator windings can be as high as 1000 MΩ and above. For the determination of insulation resistance, special DC equipment is used when units are in the commissioning phase, and it is occasionally used for inspections, when the generators are in maintenance later.

All hi-pot testing, regardless of whether AC or DC, is executed with stator or field windings in completely dry conditions (windings and PTFE-hose inside surfaces dried out) [13].

Testing can also be performed with normal cooling water flow and normal conductivity figures provided that the test equipment is suitable.

The water resistance of all parallel water columns inside the PTFE hoses in practice amounts to a value of less than 1 percent of the true stator winding insulation resistance. It therefore is impossible to directly measure the correct insulation resistance data.

Reference [15] describes a procedure whereby the DC set – preferably an anode battery – is connected to the stator winding, as well as to the cooling water manifolds. This special circuit eliminates the water resistance portion of the PTFE hoses. However, both cooling water manifolds have to be mounted isolated from ground, but must be solidly grounded using copper stranded wires when the generator is in normal operation or when hi-pot testing is performed. In addition, both manifolds have to be isolated from the cooling water system by the installation of two insulating distance tubes.

According to international standards, new stator windings have to be high-voltage tested at power frequency and by application of twice the rated voltage plus 1 kV. For a generator with a rated voltage of 27 kV this results in an AC test voltage of 55 kV, held for a test period of 1 min. Each phase is tested individually, with the other two phases grounded.

When a stator winding is high-voltage tested, the full test voltage of 55 kV is active on every single insulating hose belonging to this particular phase, in contrast to normal operation conditions where only the hoses connected to the phase terminal bars are at the highest voltage of 15.6 kV. It is therefore of paramount importance that correct cooling water flow is maintained during high-voltage tests.

Insulation Resistance of the Field Winding

For safe operation, generator field windings have to be connected to a reliable ground fault protection. The insulation resistance of air-cooled or hydrogen-cooled field windings can be as high as 1 000 MΩ and above. For direct water-cooled field windings, however, it is out of question to determine true insulation resistance figures, because it is impossible to properly isolate the rotating cooling water supply pipework from ground. The respective field ground fault resistance can be as low as 100 kΩ and even less. This reduced margin of insulation resistance to ground has to be taken into account when the electronic ground fault protection is set.

In practice the ohmic resistance of a water column inside a 25 cm long insulating hose with an inner diameter of 18 mm, for instance, results in a value of only 5 MΩ at 2 $\mu S \cdot cm^{-1}$ (alkaline water treatment).

Considering the required number of hydraulically parallel PTFE hoses, a ground resistance figure for a direct water-cooled field winding is therefore considerably lower. Under the assumption that a total of 64 parallel insulating hoses are installed, we arrive at a field winding ground protection resistance of a mere 80 kΩ. This value is in line with various data obtained for direct water-cooled field windings when commissioned.

For high-voltage tests on field windings of up to 500 V excitation voltage, international standards stipulate the use of AC voltage for a duration of 1 minute and with a figure of ten times the rated field voltage.

Miscellaneous

Malfunctions in cooling water plants have to be taken care of. They are usually indicated by alarms of the associated instrumentation. This can be as little as an alarm only for information, but with no further action required. Other alarms have to be associated with a proper action, such as – for instance – if the mixed bed is exhausted and must be replaced. An automatic trip contact, in contrast, is far more serious, because the integrity of generator components may be at risk if the cooling water flow is lost and cannot be restored.

PRACTICAL APPLICATION

As we have seen, the heat-up of water in the insulating hoses is negligible as long as some cooling water flow is present, and conductivity is within reasonable limits.

With loss of cooling water flow, the heat-up in the insulating hose is progressive and with time will reach boiling. At the same time, however, the stator bars will also heat up. This can lead to thermal aging or degradation of the stator bar ground wall insulation, or in extreme cases (which have indeed happened) to a meltdown at the affected stator bars. Generally, generators have protective instrumentation to avoid such overheating by the implementation of standard shutdown procedures.

At full load and simultaneous loss of cooling water flow, the heat-up of the stator bars is most likely faster than the heat-up of the water in the insulating hoses. To prevent stator winding overheating, it is therefore necessary to fully de-energize the generator, disconnect the generator from the grid, and shut off excitation within a short time. At low load, however, where the stator temperatures are less dependent on water cooling, the heat-up in the insulating hoses may become predominant instead.

It is also relevant if the stator winding drains when the cooling water flow is completely lost, but some or all insulating hoses remain filled with water. This depends on the position of the stator water tank. With a head tank positioned above the generator, it is likely that the stator winding will stay filled with water, but with a stator water tank below the generator, it is likely that a part of the winding will drain. Although heating up water – when drained – is no longer possible, the insulat-

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ing hoses are then immediately filled with moist air (or hydrogen), which regarding flashover is probably not much different from steam, with all the dangerous consequences mentioned in this report.

CONCLUSIONS

- For normal operation, conductivity should be kept below 0.2 μS·cm^{-1} to narrow the cooling water pH range.
- With protective water additives, a higher conductivity, corresponding to the intended treatment, is possible. For example, alkaline treatment operates with constant water conductivity and a pH between 8.5 and 9.0; a conductivity limit of up to 2 μS·cm^{-1} is appropriate here.
- The water conductivity inside insulating hoses increases slightly with temperature, but there is no problem at all if undisturbed water flow is present. Nevertheless, a limit in the order of 10 μS·cm^{-1} has been mutually agreed upon by the industry.
- In the severe case of total loss of cooling water flow, the stationary water column inside the insulating hoses will heat up exponentially with time, eventually leading to electric flashover and hose destruction. Also, at high generator output, the stator bar temperature rise can lead to insulation breakdown, resulting in a costly generator outage. Therefore, in both cases the generator protection system must fully de-energize the generator at once, followed by disconnection from the grid and excitation shut-off.

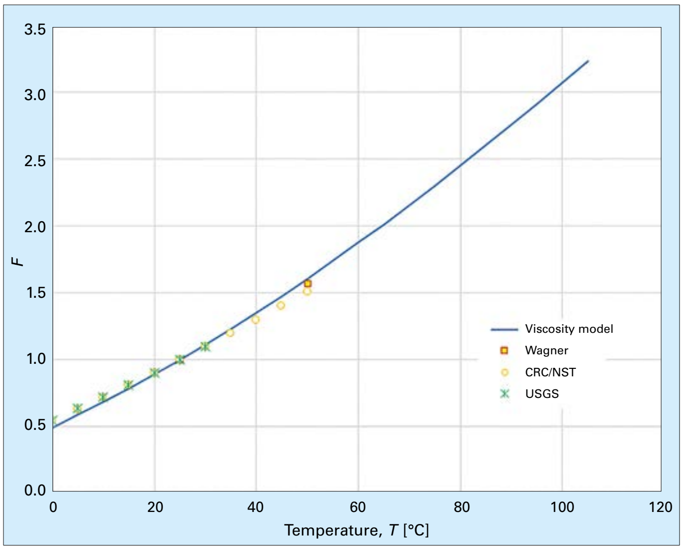

Figure 6:
Dependence of the conductivity of electrolytes in water on temperature: Comparison of measured data with the model calculation. *F* is the factor relative to 25 °C. The blue line postulates direct proportionality to the product of the reciprocal value of viscosity and the density of water ("viscosity model"). The CRC [19] and United States Geological Survey (USGS) [20] values are for a 0.01 m KCl solution; Wagner [18] has one reference point at 50 °C.

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APPENDIX

Temperature Dependence of Conductivity

It is known that the conductivity of aqueous electrolyte solutions is dependent on temperature. In laboratory instruments and in chemistry instrumentation, an increase rate around 2 %/°C relative to 25 °C is commonly used. Available data on conductivity and instrument design features consider only temperatures of up to 50 °C. There is little information on the conductivity increase rate between 50 °C and 100 °C.

Basically, the conductivity is inversely proportional to the viscosity of water [16,17]. The density of water also plays a role; for the same liquid, the ion concentration (mol·L^{-1}) and thus conductivity is proportional to the density. Altogether, conductivity is therefore proportional to the product *F* of the reciprocal value of viscosity and the density of water ("viscosity model"). Figure 6 displays *F* as a function of temperature, as well as available measured data for a 0.01 m KCl solution. With weak electrolytes, the temperature dependence of dissociation must also be considered. Reference [18] explores this subject in more detail.

Even though the fit between theoretical and measured data ([19,20]) is not fully satisfactory, the viscosity relation seems to be the best available information for the full temperature range between 25 °C and 100 °C. Figure 2 gives a closer look. It includes the linear approximation for the data, where the equation is

$$\sigma_T = \sigma_{25} \cdot (0.0266 \cdot T + 0.355)$$

or $\sigma_T = \sigma_{25} \cdot 0.0266 \cdot (T + 12.6)$

Electric Configuration of a Generator Stator Winding

The winding schematic diagram in Figure 7 best explains the design principles of a three-phase stator winding. This diagram describes the stator winding of a 2-pole generator with a total of 96 stator bars which are installed in 48 stator slots.

The Roebel bars, bearing the name of their inventor, are the active elements of the stator where the voltage is induced. These bars consist of a package of numerous solid copper conductors

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and hollow cooling channels which are systematically warped along their length to reduce circulating currents and, correspondingly, losses.

The "rated voltage" in our model calculation is assumed to be 27 kV. This voltage generally refers to the voltages between two phases, which are larger by a factor $\sqrt{3}=1.73$ than the voltages of the phase terminals X, Y, or Z to neutral N, which are called "phase voltages". Therefore, the rated voltages – also called "line-to-line voltages" – are active between generator terminals X-Y, Y-Z, and Z-X, while the phase voltages are present between X-N, Y-N, and Z-N.

Electrically, each phase of the stator winding consists of a certain number of winding elements (stator bars) connected in series. The phase voltage increases from the "neutral bar" (first bar) to the "phase terminal bar" at full phase voltage, in our case 15.6kV. Each generator phase in our model case consists of 2 electrically parallel phase circuits, each with 16 stator bars electrically connected in series. These 16 stator bars generate a phase voltage of 15.6kV, of which 8 bars are linked with the magnetic flux of pole no. 1 and the other 8 bars are magnetically linked to pole no. 2.

Hydraulic Configuration of a Generator Stator Winding

A "cooling circuit" is an arrangement of one bar, or several bars, hydraulically connected in series between the water inlet and outlet manifold (Figure 8). These cooling circuits are linked to the

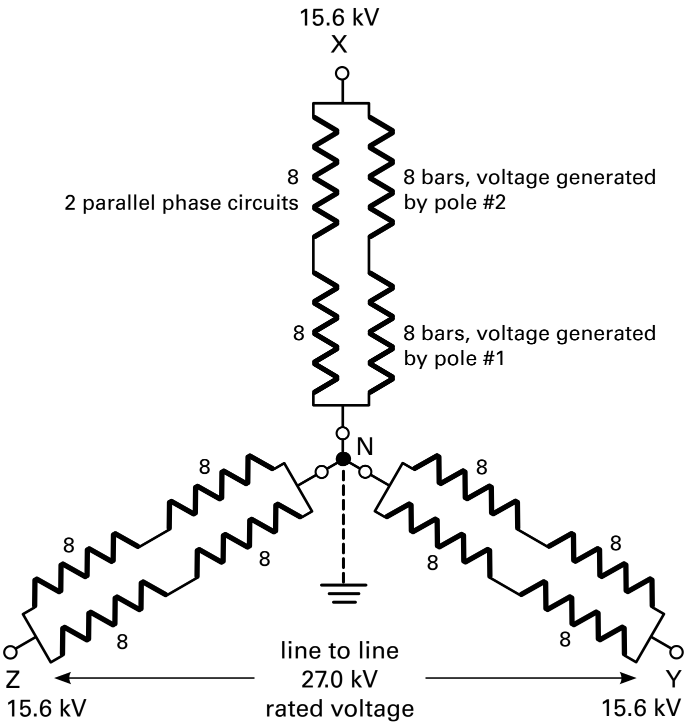

Figure 7:
Example of a stator winding electric configuration. Three-phase stator winding with two parallel phase circuits. 27 kV rated voltage, 48 slots / 96 Roebel bars. Each of the twin phase circuits consists of 16 stator bars that are electrically connected to one another in series. The ends of the phase circuits are either connected to neutral N (zero voltage), or to one of the phase terminals X, Y, or Z. This is one of many possible configurations. For generator protection, the neutral N (also called the star point) is normally grounded by one of various methods available.

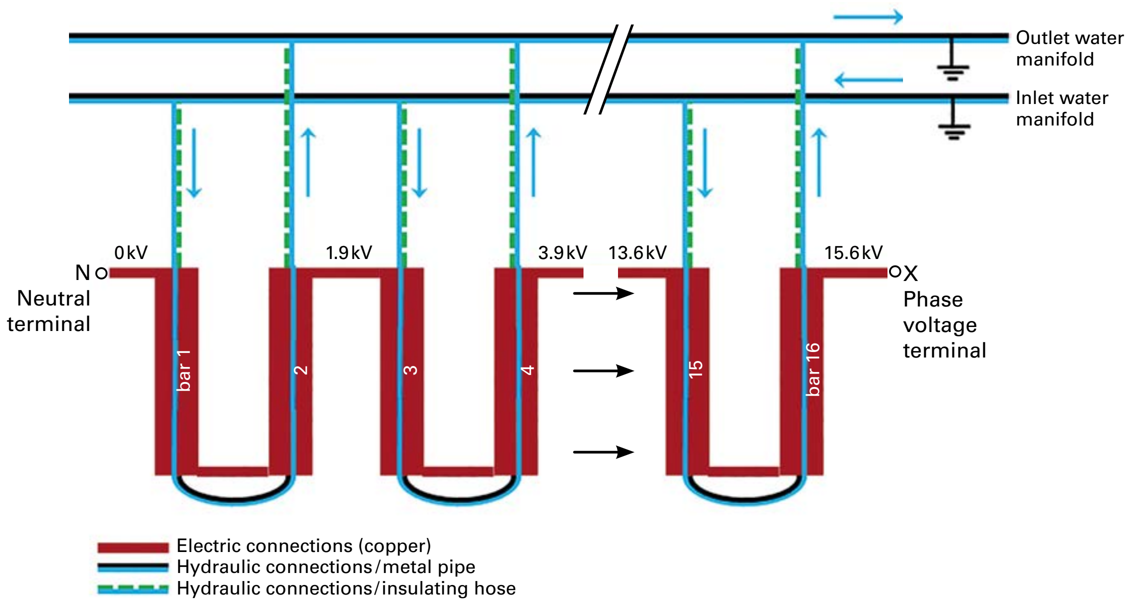

Figure 8:
Detail of Figure 7: Shown is one phase circuit with 16 bars electrically connected in series. Bar 16 is a 15.6 kV phase terminal bar connected to a phase voltage terminal, i.e., X, Y, or Z. Groups of two stator bars hydraulically connected in series are each shown as cooling circuits; all phase voltage circuits therefore consist of 8 cooling circuits. As the stator winding has 6 such phase voltage circuits, there are 48 cooling circuits with insulating hoses on both ends. This is one of several possible configurations.

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grounded cooling water manifolds by use of insulating hoses, usually made of PTFE (commonly referred to as Teflon™). Turbo generator cooling circuits usually consist of one bar, or two bars hydraulically connected in series, but cooling circuits of large hydro generators consist of four or six bars hydraulically connected in series. As can be seen in Figure 8, one of the insulating hoses hydraulically connects the end of a zero voltage (neutral point) stator bar to the cold-water manifold (bar no. 1), while the last insulating hose in line links the full phase voltage stator bar end with the hot-water manifold (bar no. 16). All other insulating hoses connect stator bars with proportionally different voltages. This 2-pole generator has a total of 48 cooling circuits.

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