Grounding Strategies for High Voltage Shore Connection of Large Passenger Vessels

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***Abstract*—High voltage shore connection of large passenger vessels is an important way to improve energy efficiency and reduce local and global emissions, as well as noise. However, it is shown that the vessels' steel hulls will act as sacrificial anodes for the grounding systems in the ports, hence accelerated corrosion of the hulls may occur. The required protective earth (PE) conductor between the hull and the grounding system on shore could also introduce touch voltages above 30 V in case of a fault, posing a safety hazard. Based on field measurements and analyses, a grounding strategy with galvanic separation in the low resistance PE conductor is recommended. It is further advised to use active and passive cathodic protection, and to reduce the set point of the impressed current cathodic protection (ICCP) system to approximately 100 mV versus zinc. These measures will reduce the corrosion rate of the vessels' hulls during power delivery from shore, while avoiding transferred touch voltages.**

***Index Terms*—grounding; high voltage shore connection; galvanic corrosion; transferred touch voltages; air pollution**

I. Introduction

Reduced carbon dioxide (CO_2) emissions in the transport sector (on-shore and maritime) is vital to reach national climate targets and to develop green competitiveness [1]. Internationally, the European Union has targets of reducing greenhouse gas emissions from the European transport sector to 60 % below the 1990 level within 2050 [2]. Electrification of the maritime transport will be important for reaching these targets. Therefore, the development of hybrid and electric vessel technology and the corresponding infrastructure for electric power delivery from shore and for battery charging is promoted both nationally and on the European level.

Harbours are often located close to residential areas; hence the air and noise pollution should also be minimised. When vessels are docked, there is still an energy demand for various purposes on board, including power for lighting, heating, cooling and loading/unloading operations. This energy demand is currently largely covered by diesel generators on board, with low energy efficiency at low load, as well as high emissions of CO_2, nitrogen oxide (NOx), sulphur oxide (SOx) and particulate matter (PM). A way to improve air quality and to reduce noise is to shut down these generators and connect to the shore power supply for as long as possible, while in port. Supplying the vessels by the shore electrical systems is referred to as shore connection, cold ironing, shore-to-ship power, alternative maritime power or onshore power supply. This can reduce the emissions of SOx and PM by 90 % and the emissions of NOx and CO_2 by 50 % [3]. There is an increasing interest for such solutions for large passenger vessels, and several ports worldwide are being equipped with high voltage shore connection (HVSC). This technology can also be used for battery charging of hybrid and electric vessels.

Even though HVSC is a relatively well-developed technology, it has some inherent challenges. There have been examples of vessels suffering from severe corrosion while being electrically connected to shore, even if the existing standards and regulations have been followed [4]. The TN grounding system suggested in the IEC/ISO/IEEE 80005-1 standard represents a safe and effective solution with regards to fault detection and avoiding potential differences [5]. However, corrosion problems and ground fault interferences may arise due to the presence of the protective earth (PE) conductor, double grounded to the neutral point of the system and on the vessel. The corrosion problems arise because the hull represents a marine electrode which is connected to the ground electrode via the PE conductor, while being immersed in an electrolyte solution; the seawater [6]. The hull and the ground electrode thus form a steel-copper galvanic cell, and the current flow between these two electrodes favours the corrosion of the anode (the hull of the vessel), since steel is the less noble metal. The low resistance conductor between the vessel's hull and the ground network can also lead to transferred touch voltages higher than 30 V in the case of a fault, posing a safety hazard [7].

To minimise the corrosion problems, active or passive cathodic protection may be installed. To avoid any transferred touch voltages, a different grounding strategy for the HVSC equipment may be adopted, in which the low resistance conductor between the protective earth on shore and the vessel's

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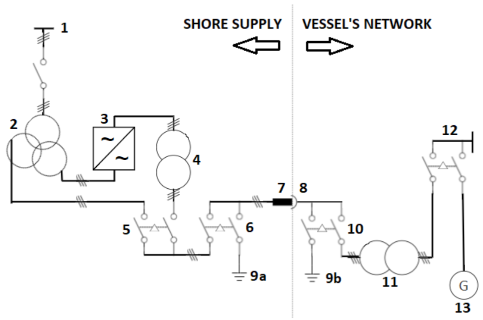

Fig. 1. Block diagram of a typical HVSC system arrangement. 1: Port grid, 2: shore-side transformer, 3: frequency converter, 4: ship transformer, 5: converter bypass, 6: shore-to-ship circuit breakers, 7: plug, 8: socket, 9a: shore-side grounding system, 9b: on-board grounding system, 10: on-board shore connection switchboard, 11: on-board transformer, 12: on-board receiving switchboard, 13: on-board generator.

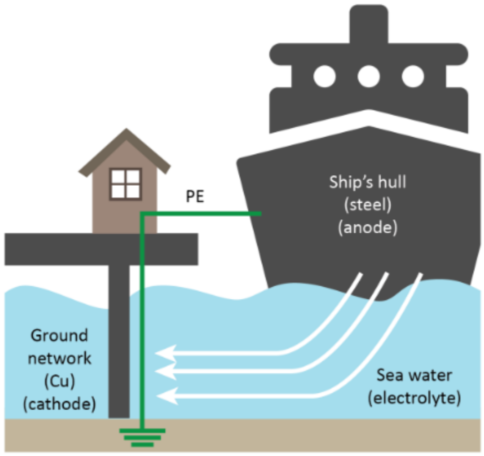

Fig. 2. The equivalent galvanic cell.

hull is broken. A solution compliant with the standard is the TN-island grounding system, in which a neutral conductor is used instead of the PE conductor [7]. This will also contribute towards minimising the corrosion problems.

This article presents field measurements of voltages, currents and galvanic potentials from large passenger vessels with HVSC, as well as an evaluation of the measurement results. Based on this, recommendations for reducing the corrosion rate of the vessels' hulls, while avoiding transferred touch voltages, are suggested.

II. System Description

A. High Voltage Shore Connection

The connection between the on-board system and the port electric grid is obtained through sockets placed on the dock [3]. Flexible cables from the vessel are connected to these sockets, moved by a cable lifter placed on board. International standards have been developed for this technique, since the circulation of vessels is global [5]. In Europe, the vessel frequency (typically 60 Hz) is often different from the grid supply system frequency (50 Hz). Fig. 1 shows a suggested configuration of high voltage shore connection systems in Europe which allows powering the vessel at 60 Hz by means of the converter, or directly at 50 Hz by the supply system.

The international standards do not prescribe a detailed procedure for connection/disconnection operations; hence each system must be provided with its own safety procedures. It is important that the circuit breakers both on shore and on the vessel are open during the connection operation, so that the power cable is not connected to any network voltage. Several automated control functions must be performed before the circuit breakers are closed. In a few cases, such as in the port of Oslo, an automatic connection does not require the assistance of port personnel [7].

B. Galvanic Corrosion and Cathodic Protection

Galvanic corrosion requires two different metals (electrodes) immersed in a current-carrying solution (electrolyte), interconnected by a current-carrying conductor (Fig. 2). The more noble metal will then act as a cathode, while the less noble metal acts as an anode. The galvanic series determines the nobility of metals [6]. For example, copper is a more noble metal than steel. Hence, steel will corrode more easily than the copper, and "sacrifice" itself for the copper. The difference can be measured as DC potentials between the metals, or as DC potentials versus a reference electrode. The rate of corrosion depends on which materials are connected, as well as the size ratio between them. Regardless, such a connection is unfortunate for the less noble metal.

When a vessel with a steel hull is connected to the grounding system on shore via the low resistance PE conductor, galvanic corrosion will occur because current can flow between the hull and the grounding system on shore with return through the seawater. Vessels with an aluminum hull will experience more accelerated corrosion than those with a steel hull, since aluminum is less noble than steel. Vessels made from non-uniform materials will also suffer from galvanic corrosion.

Passive cathodic protection is a method for protection of metals against galvanic corrosion. The metal to be protected acts as a cathode in a circuit where the voltage usually arises by contact with a sacrificial anode mounted on the protected construction. The sacrificial anode consists of a less noble metal, for example zinc, and will slowly dissolve during current delivery. Impressed current cathodic protection (ICCP) is another way of protecting metals against galvanic corrosion. A power supply applies current to the steel surface through anodes on the vessel. Reference electrodes, such as zinc (Zn) or silver/silver chloride (Ag/AgCl), are used to regulate the current for protection during different conditions. Both theory and practice show that for a steel structure in seawater to be sufficiently protected against corrosion, the potential must be below -800 $mV_{Ag/AgCl}$ (200 mV_{Zn}). Cathodic protection with sacrificial anodes (passive) and with impressed current (active) use the same principle for protection of the metal. In both cases, the metal is also painted to limit the need for protection current or to limit the sacrificial anode consumption. The painting has the additional advantage that the hull friction

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Fig. 3. Damage to the hull painting of Color Fantasy [4].

TABLE I
SUMMARY OF VOLTAGE AND CURRENT MEASUREMENTS [4]

Vessel	Superspeed 1	Superspeed 2	Magic	Fantasy
Port	Kristiansand	Larvik	Oslo	Oslo
Date	18.04.2016	10.05.16	10.05.16	11.05.16
$\mathbf{U_{0DC}}$ **[mV]**	130-150	30	250-300	370
$\mathbf{U_{0AC}}$ **[mV]**	3-4	40	110	110
$\mathbf{I_{0DC}}$ **[A]**	6.7	0.2	2.8-3.7	3.0-4.0
$\mathbf{I_{0AC}}$ **[A]**	0.2	-	-	0
$\mathbf{I_{0DC,Load}}$ **[A]**	8.7	-	5.8-6.5	8.0-10.0
$\mathbf{I_{0AC,Load}}$ **[A]**	0.55	-	0.8-1.0	0.2
Load [kW]	1280	-	2800	2248

resistance is reduced.

C. Transferred Touch Voltages

The low resistance conductor between the vessel's hull and the ground network can also introduce transferred touch voltages. Ground fault interferences are originated by the grounding system common to the primary and the secondary side of the onshore transformer substation. When a ground fault happens on the primary side of the transformer substation, the double grounding connection of the PE causes a touch voltage transfer to the ship-side system with a value related to the tripping settings of the protective device on the primary side [7]. The voltages admitted might therefore be higher than the 30 V prospective touch voltage limit prescribed by the international standards for the interface area between the shore and the vessel.

III. MEASUREMENTS

Color Line was the first shipowner to establish high voltage (11 kV) shore connection in Norwegian ports, and experienced accelerated corrosion on the hulls and propellers of their vessels, even though the international standards were followed (Fig. 3). Measurements were therefore performed in order to clarify the reasons behind the accelerated corrosion and to suggest measures to minimize the problem. All the vessels in the study are painted and have cathodic protection in the form of internal ICCP systems. Color Magic and Color Fantasy are supplied by the same HVSC system, but might have different loads on board, while Superspeed 1 & 2 are located in other ports.

When large passenger vessels lie at berth, there will always be some form of galvanic connection between the PE on shore and the vessels. Compared to the required PE conductor, the other connections to ground, such as bridges and ramps, will have a relatively high resistance. During the measurements it was observed that connection and disconnection of the bridges and ramps had only a small impact on the potential difference between the hull and the PE on shore, as well as on the AC and DC currents in the PE conductor between shore and vessel. This impact is therefore neglected, and all the values presented here are measured when the vessels are docked normally with bridges and ramps in the operating position.

In a symmetric three-phase AC grid, the three phase voltages will have the same absolute value and a phase shift of 120° with respect to each other. The sum of the three instantaneous values will be zero: $U_{0AC}=0$. Furthermore, if there is no DC potential versus the ground network, there will be no DC voltage or current between the hull and the PE when no current is flowing in the phase conductors: $U_{0DC}=0$ and $I_{0DC}=0$. According to the HVSC standard, the power supply is via three single-phase cables with outer metallic screens. In principle, the AC currents in the central conductors give rise to equal and opposite currents in the outer screens. If the three phase currents are fully symmetric, the sum of the instantaneous currents will be zero: $I_{0AC}=0$.

In order to determine whether there were driving voltages between shore and vessel that could lead to accelerated galvanic corrosion, U_{0AC}, U_{0DC}, I_{0AC} and I_{0DC} were measured by disconnecting the three cable screens from the PE and short-circuiting them to a temporary, insulated bus bar. This bus bar could then be connected to the PE as needed during the measurements. Measurements of the potential differences between the vessels, the seawater and the grounding system on shore were also carried out during connection or disconnection of the onshore power supply.

IV. RESULTS

A. Currents and Voltages Between the Vessel and the Grounding System on Shore

Table I presents a summary of the voltage and current measurements between the grounding system at the respective quays and the hulls of the vessels. $I_{0DC,Load}$ and $I_{0AC,Load}$ are the DC and AC currents flowing in the cable screens when currents are flowing in the phase conductors and the vessels are drawing the stated load. Even though the measured voltages are small (in the range of mV), the DC currents are substantial (in the range of A) since the resistance of the cable screens connected in parallel is very low (in the range of mΩ).

The measurements on Superspeed 2 in Larvik stand out because of the low values of U_{0DC} and I_{0DC}. The currents were not measured during load consumption, due to the vessel's short time at berth and problems with the connection of the power supply. For the other vessels it was shown that the

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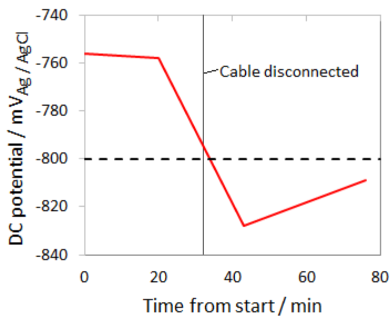

Fig. 4. Measured galvanic potential at the bow of Superspeed 1 at the quay in Kristiansand [4]. The cable was disconnected after approximately 30 minutes.

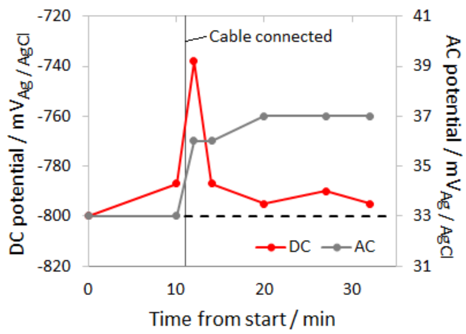

Fig. 6. Measured galvanic potential at the port side of Color Magic at the quay in Oslo [4]. The cable was connected after approximately 11 minutes.

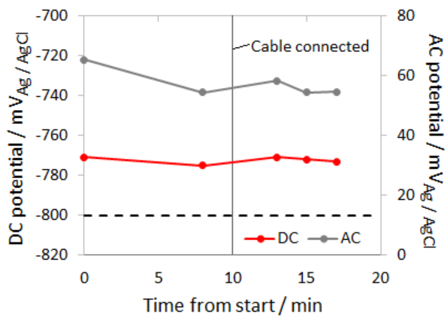

Fig. 5. Measured galvanic potential at the bow of Superspeed 2 at the quay in Larvik [4]. The cable was connected after approximately 10 minutes.

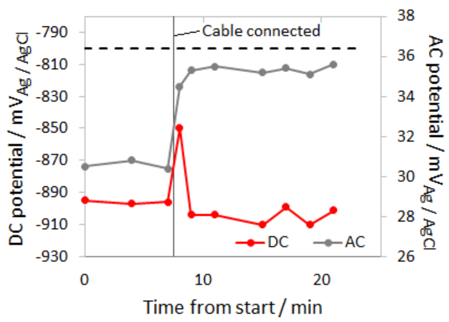

Fig. 7. Measured galvanic potential at the port side of Color Fantasy at the quay in Oslo [4]. The cable was connected after approximately 8 minutes.

DC current increases with the load on board. This might be due to asymmetrical loading between the phases, or to power electronic loads. For Superspeed 1 in Kristiansand, almost 9 A (DC) is flowing between shore and vessel at 85 % load. In Oslo, approximately 10 A (DC) is floating between the quay and Color Fantasy at 50 % load, while the DC current between the quay and Color Magic reaches 6.5 A at 62 % load. The AC currents are negligible in comparison.

B. Potential Differences Between the Vessels, the Seawater and the Grounding System on Shore

The potential measurements performed on Superspeed 1 at quay in Kristiansand show that when the 11 kV cable is connected to the vessel, the potential is higher than -800 mV$_{Ag/AgCl}$. This can lead to corrosion of the vessel. In Fig. 4 it can be seen that the potential drops below -800 mV$_{Ag/AgCl}$ when the power cable is disconnected from the vessel. Interestingly, the ICCP system does not apply more current when the connection of the cable causes a potential increase. However, it should be noted that the hull of Superspeed 1 was painted approximately a week before these measurements, and that the ICCP system had only been active for around 12 hours when the measurements were carried out.

Potential measurements performed on the hull of Superspeed 2 do not show any significant change in potential before and after the connection of the 11 kV cable (Fig. 5). However, the measured potential is always above -800 mV$_{Ag/AgCl}$ with a significant AC component (approx. 60 mV$_{Ag/AgCl}$). This means that parts of the hull of Superspeed 2 might corrode even without HVSC.

Fig. 6 shows that the DC potential measured at the port side of Color Magic increases when the 11 kV cable is connected, but decreases to the same level after a few minutes. The reason for the potential increase is that current starts to flow in the cable screens. The potential then decreases because the ICCP system starts to deliver more current to reduce the potential. It can also be seen that the measured AC potential increases when the power cable is connected. Color Magic started drawing load during the measurement period, but this had no significant impact on the measured potentials.

The potentials measured at the port side of Color Fantasy (Fig. 7) are similar to what was observed for Color Magic. The difference between these two vessels is that the set point for impressed current in the ICCP system of Color Fantasy is approximately 100 mV lower as compared to Color Magic. This change was made around a week before the SINTEF measurements were carried out. The difference can be easily observed by comparing Figs. 6 and 7. For Color Fantasy, the potentials were also measured at several points around the vessel. The results of these measurements are presented in Table II. It can be seen that the potentials at different points on the vessel vary significantly with respect to the set point of the ICCP system, which is approximately -900 mV$_{Ag/AgCl}$ for Color Fantasy.

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TABLE II
MEASURED POTENTIALS AT DIFFERENT POINTS OF COLOR FANTASY [4]

Point of Measurement	Potential / $mV_{Ag/AgCl}$
Bow	-1000
Port side (towards the sea)	-910
Starboard side (towards the quay)	-875
Aft	-855

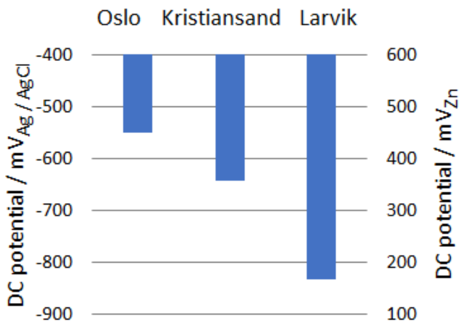

Fig. 8. Measured galvanic potential in the ports of Oslo, Kristiansand and Larvik without HVSC [4].

Fig. 8 presents the large differences in the potentials of the different quays, measured between the reinforcing steel and the seawater. At the quay in Larvik, the potential is lower than at the other quays. This is because sacrificial anodes are installed to protect the steel structures at the quay. The figure further shows that the quays in Oslo and Kristiansand do not have sufficient cathodic protection because the potentials are higher than -800 $mV_{Ag/AgCl}$ (200 mV_{Zn}). Hence, steel structures in the ports of Oslo and Kristiansand will corrode, independent of the high voltage shore connections.

The DC currents flowing in the PE conductor (I_{0DC} in Table I) are caused by the potential differences between the quays and the vessels. These can be found by subtracting the DC potentials in Figs. 4-7 from the DC potentials at the respective quays (Fig. 8). A good comparison with U_{0DC} in Table I is observed.

V. DISCUSSION

The measurement results show that the potentials of the hulls of Superspeed 1 and Color Fantasy are below -800 $mV_{Ag/AgCl}$ when the cable is disconnected, hence the vessels seem to be protected against accelerated corrosion when they are not connected to shore power. For Color Magic, the set point of the ICCP system should be lowered in order to give better protection. The potential of the hull of Superspeed 2 is also too high to give optimal protection against corrosion.

For Color Fantasy, all the measured potentials are below -800 $mV_{Ag/AgCl}$, hence accelerated corrosion of this vessel is not probable after the lowering of the set point of the ICCP system. The corrosion damages observed on Color Fantasy might however be partly due to a too high set point of the ICCP system over time.

For Superspeed 1, a DC current of 6.7 A is flowing in the power cable when it is connected to the vessel, even if no load is drawn (Table I). This is due to the potential difference between the shore-side ground system and the hull, and causes corrosion damage on Superspeed 1. The cable connection also results in a short-term potential increase of the hull. For Superspeed 1 it seems like the ICCP system is not working correctly, since no extra current is applied when the potential is increased. The reason for this might be that the vessel was painted only a week before the measurements were conducted.

For Superspeed 2, no significant DC current is flowing between quay and vessel when the power cable is connected without load consumption. The reason for this is that both the quay and the vessel have cathodic protection. The driving voltage in the circuit between the ground system on shore and the hull is therefore low. Still, it should be noted that the measured potential is approximately 30 mV higher than the normal limit for cathodic protection (Table I and Fig. 5).

The main difference between Color Magic and Color Fantasy is that the set point of the ICCP system is 100 mV lower for Color Fantasy, compared to Color Magic. This results in a higher current flowing in the PE conductor of Color Fantasy than in that of Color Magic, since the driving voltage is higher when the potential difference increases. For both vessels, the ICCP system reduces the potential within a few minutes after currents start to flow in the power cable, which is expected. The corrosion damages observed on these two vessels is probably caused by a combination of too high set points of the ICCP systems and the currents flowing in the cable screens when the vessels are connected to shore.

An important observation from these measurements is that the low resistance connection between the hull and the ground system on shore will lead to accelerated corrosion of the hulls, even if the ICCP settings are optimal. This is because a small potential difference between quay and vessel is sufficient to drive a substantial current in the PE conductor. However, it is difficult to explain the damages observed on the propellers. The propellers in the study are made of an alloy more noble than steel, hence the hull will act as a sacrificial anode for the propellers. Furthermore, no measurement results indicate that the potential is high enough for the propellers to corrode.

In order to avoid accelerated corrosion and transferred touch voltages, it is necessary to separate the two grounding systems on the shore side and the vessel side. A technical solution is to convert the double grounding system required by the IEC/ISO/IEEE 80005-1 standard to the TN-island grounding system [3]. This can be achieved by placing an isolation transformer on board or alternatively inside the transformer substation on shore. In the first case, with the neutral grounded on the vessel's hull, the PE conductor is not necessary, but this solution can be too expensive for maritime companies [3]. In the second case, the interconnecting conductor between the shore and the vessel does not operate as a PE conductor, but as a neutral conductor, since it is not connected to the grounding system inside the transformer substation (Fig. 9). In both cases, fast protective devices should be installed both on shore and

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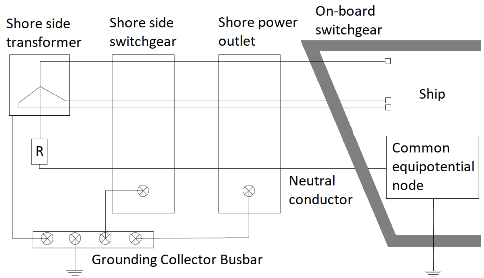

Fig. 9. The TN-island grounding system [3].

on the vessel, in order to maintain the electrical safety. In this way, the supply will be disconnected at the first ground fault.

So far, only the effects of connecting a single vessel to the onshore power supply have been discussed. Based on the corrosion theory and the measurement results, it is expected that the conditions will get more complicated if several vessels are connected to the same onshore power supply. If the vessels have different set points of the ICCP systems, currents will flow between the vessels and it is difficult to predict how the ICCP control systems will respond. It is probable that the vessel with the lowest set point (lowest potential with respect to the sea) must protect all the vessels that are connected to the same onshore power supply.

VI. Conclusions and Further Work

SINTEF's measurements of voltages, currents and galvanic potentials at different quays highlight several issues that must be taken into account if a major rollout of HVSC systems is to take place. Otherwise, both vessels and steel constructions at the quays will suffer from accelerated corrosion, and transferred touch voltages could arise in case of a ground fault.

The performed measurements show that the steel constructions in the ports of Oslo and Kristiansand are not sufficiently protected against corrosion. The ground system on shore will in different ways be in contact with the steel constructions. The galvanic, low resistance conductors between the protective earth at the quay and the vessels' hulls are required by the standard, but lead to accelerated corrosion of the steel hulls, which constitute sacrificial anodes for the copper grounding system. It is necessary with specific measures for the HVSC systems in Oslo and Kristiansand in order to avoid accelerated corrosion of the vessels' hulls.

The port of Larvik has cathodic protection in the form of sacrificial anodes, resulting in a lower (approx. 1/10) galvanic potential difference between the hull and the protective earth at the quay than in the other two ports. Immediate measures for the HVSC system in Larvik do therefore not seem necessary. Corrosion damage might still occur in Larvik, but the corrosion rate will probably be lower here than in Oslo and Kristiansand.

Based on the measurement results, it is recommended that passive cathodic protection in the form of sacrificial anodes should be installed at all quays. The sacrificial anodes should be made of a metal less noble than the metal of the vessels' hulls, such as zink or aluminum alloys, and they should be in contact with the sea water. In addition, all vessels should be painted and have active cathodic protection in the form of internal impressed current cathodic protection (ICCP) systems. The ICCP set point should be lowered to -900 $mV_{Ag/AgCl}$ (100 mV_{Zn}), in consultation with the paint suppliers. This is to ensure that the whole hull will have a potential lower than -800 $mV_{Ag/AgCl}$, the limit for sufficient cathodic protection, at all times. However, the most important way to reduce corrosion damage is to minimise the DC potential difference between the vessel and the quay.

In SINTEFs opinion, the remedy which will be easiest to implement to avoid the accelerated corrosion of the vessels with HVSC is to break the galvanic, low resistance conductor between the protective earth on shore and the hulls. This will also protect against transferred touch voltages. A prerequisite for such a solution is that the safety of personnel and electrical installations is safeguarded in accordance with the requirements of standards and regulations. This can be achieved by installing fast protective devices on both sides of the power cable. The PE conductor can be broken by placing an isolation transformer either on the vessel or on shore. This results in the TN-island grounding system, which is compliant with the IEC/ISO/IEEE 80005-1 standard [7]. This grounding system is used for low voltage shore connection (LVSC), and suggested in the standard for HVSC of cruise ships [8]. The use should be extended to large passenger vessels, due to the reduced risk of corrosion and transferred touch voltages.

The TN-island grounding system has the additional advantage that a common ground point for all vessels in the harbour is avoided. Galvanic connection between several vessels can lead to dangerous situations, hence the double grounding system required by the HVSC standard is problematic.

Further studies are required to explain the corrosion damage observed on the propellers. It might also be necessary to carry out further measurements on Superspeed 1, to ensure that the ICCP system is working as expected.

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