

A CASE STUDY PAPER ON CORROSION OF ELECTRICAL CONDUCTORS IN PULP AND PAPER INDUSTRIAL APPLICATIONS

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ABSTRACT

Electrical equipment supplying and distributing energy is used in every pulp and paper industrial process. Many components made of various metallic and dielectric materials are vulnerable to corrosive atmospheres often present in the pulp and paper industrial facilities. Corrosion of electrical conductors may result in fast and irreversible deterioration, causing production loss and safety hazards. The paper reviews the most severe corrosion problems effecting conductivity of electrical contacts that result in overheating of electrical equipment used in this industry. A number of various protecting means are suggested to slow down corrosion of silver and copper and other metals most often used in electrical equipment. The paper discusses implementations and the value of various condition-monitoring techniques to provide timely maintenance of electrical equipment exposed to corrosive environments in the pulp and paper facilities.

Index Terms: Corrosion, Electrical Conductors, Monitoring, Resistance, Silver.

I. INTRODUCTION

THE PULP and paper industry, like other chemical process industries, is corrosion intensive. The total annual cor-rosion costs for the pulp, paper, and paperboard industry is approximately \$1.97 billion to \$9.88 billion (average \$5.928 billion per year). These estimates are between 1.2% and 6.0% of the total sales for the entire U.S. pulp and paper industry [1]. Each of the major manufacturing steps of paper production (pulp production, pulp processing, pulp chemical recovery, pulp bleaching, stock preparation, and paper manufacturing) has its own corrosion problems and its own sources of corrosive atmospheric components (gases, fluids, moisture).

Different corrosion-inducing media could vary, for example, from highly alkaline (pH 13–14) sulfide type in digesters and related machinery to highly acidic (pH 2) and oxidizing types in a bleach plant. Consequently, different equipment have been reported to face excessive corrosion or to fail prematurely because of rapid metal thinning, pitting and crevice corrosion, stress corrosion cracking, and intergranular corrosion. Selecting materials in the paper industry is, therefore, a tedious task and requires choosing materials that have resistance against these types of corrosion reactions.

Corrosion takes its toll on electrical equipment supplying and distributing energy at pulp and paper mills. Silver and copper are probably the most widely used contact materials available. They have the highest electrical and thermal conductivity of any known metals. As a result of silver's high electrical and thermal conductivity, contacts made of fine silver work well at currents in the light to medium range where light to moderate contact

pressure is available and low contact resistance is a requirement. Silver has the lowest cost of all precious metal contact materials, and it is readily formed into various contact shapes (rivets, buttons, etc.) due to its ductility. Silver plating is a very popular coating for various contact materials providing superior quality of corrosion protection for many types of environments. Therefore, the ability of silver to corrode in a specific environment should be well understood and mitigated as much as possible. Silver shows good resistance to oxidation and tarnishing except in the presence of sulfur. Sulfur-containing atmospheres will produce silver sulfide, which increases contact resistance.

This paper provides information on various forms of silver corrosion, explains how quality and thickness of silver plating effect corrosion rate and type, discusses the impact of corroded silver layers on electric contact conductivity, describes silver plating treatment techniques to reduce silver corrosion, and offers recommendations on cleaning of tarnished silver plating. Focusing mostly on silver corrosion, the paper also presents information on other metals corrosion in pulp and paper industrial environments.

II. FORMS OF SILVER CORROSION

2.1 Sulfuric Corrosion

Silver corrodes in environments containing various sulfuric gases such as H_2S , OCS , CS_2 , and SO_2 . The corrosive effect on silver of H_2S and OCS gases is about an order of magnitude stronger than that of CS_2 and SO_2 . Silver sulfide, the product of silver corrosion, can be formed by contact with SO_2 in moist air, but it requires SO_2 concentration two to three orders of magnitude higher than may be typically present in ambient environments. Hydrogen sulfide (H_2S) is usually present in paper and pulp processing due to process technologies. Even at minor concentration of H_2S , corrosion produces silver sulfide on the parts being in contact with the environment.



Fig. 1. Tarnished silver plating on copper bus after various periods of storage at manufacturing facility: (a) 1 month, (b) 10 months, (c) 30 months, and (d) 5 years.

Hydrogen sulfide (H_2S) gas is almost always present in ambient air. Naturally occurring ambient levels of H_2S tend to be on the order of 0.11 to 0.33 ppb (parts per billion) [2]. In the United States, the concentration of H_2S is in the range of 0.02–5.0 ppb in urban and industrial areas, and in the range of

0.005–0.5 ppb in remote areas. According to estimates provided by the Environmental Protection Agency (EPA) [1], the concentration of H_2S in some selected workplaces is 0.054 ppm at a sulfate paper mill and 0.216–0.933 ppm at the sewage treatment plant of a sulfate paper mill. There is no precise definition of the minimum concentration of H_2S required for tarnishing to be observed on silver in whatever form the silver is exposed, either bulk or plating. Additional risk of sulfuric corrosion for specific electrical apparatus may come from outgassing of hydrogen sulfide or other sulfuric compounds from seals, gaskets, and other polymers within electrical units and closed housing. The amount of tarnishing is a function of the relative humidity (RH), ambient temperature (T), gas concentration, and time of exposure. Silver reacts with extremely low levels of H_2S in parts per billion and even in parts per trillion. Silver and H_2S react to form dark brown or black silver sulfide (Ag_2S), one of the most insoluble salts of silver; this is what causes tarnishing (Fig. 1).

2.2 Silver Whiskers

When there is a thick enough layer of Ag_2S and a high enough temperature, the process of growing thin filaments (whiskers) begins. Silver whiskers usually grow in certain areas of the switchgear where they are exposed to H_2S . They grow practically everywhere but more intensely in the areas with higher temperatures, such as bus joints and sliding contacts, outside edges, and corners of the contacts. Temperature gradients in these areas may encourage this phenomenon. Silver corrosion results in a high resistance, which produces more heat, which in turn stimulates further tarnishing and growth of whiskers (Fig. 2) [3]–[5]. This growth most often is found in electrical equipment installed at pulp and paper mills.

2.3 Red-Plague Corrosion

When silver is plated over copper, there can be an accelerated corrosion of the copper, through galvanic action, at pinholes



Fig. 2. Silver whiskers [5].



Fig. 3. Silver-flash plated copper bus shipped overseas [8].

or breaks in the silver plating. When stored or used in a moist or high-humidity environment, copper is susceptible to the formation of nonconductive cuprous oxide resulting in higher resistance of electrical conductors. Imperfections such as pinholes, pores, and breaks in silver plating allow moisture and oxygen to penetrate the plating. The presence of moisture in the region of exposed copper produces an electrolytic cell formed between the copper and the silver. Galvanic copper corrosion can progress indefinitely in the presence of oxygen, producing cuprous oxide (possibly some black cupric oxide) corrosion products. The cuprous oxide crystals, which have a characteristic red appearance, precipitate out onto the silver plating [6], [7].

Corrosion known as “red-plague” is identifiable by the presence of a brown-red deposit on the surface (Fig. 3). Copper wires with silver plating less than $1\ \mu\text{m}$ thick are susceptible to red-plague corrosion. An example of corrosion that may be identified as “red-plague” is shown in Fig. 3. Silver flash plating disappeared from a copper bus after being shipped overseas and left the copper unprotected and exposed to oxidation and corrosion [8].

2.4 Underplating Corrosion

When silver is plated over copper with some areas of bare copper exposed, the copper may corrode under the plating (“underplating corrosion”), as shown in Fig. 4 [9]. The finger clusters of a medium-voltage (MV) circuit breaker were silver plated only along the edges, which left large amounts of copper exposed. The circuit breakers (4160 or 13800 Vac) were installed in a vented air-conditioned trailer. Normally, these contacts cycled once daily, on in the morning and off at night. When the contacts were energized, the operating temperature inside the box was $75\ ^\circ\text{C}$ – $90\ ^\circ\text{C}$. When the contacts were cycled off, the box was cooled to ambient temperature overnight. There are two basic areas of a finger cluster (Fig. 4): area 1 is a silvery metallic color (typical of silver plate), whereas area 2 is green (typical of corroding copper). Corrosion products penetrated under the silver plating causing it to flake off [9].

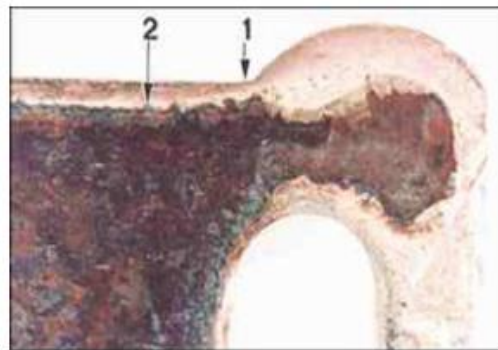


Fig. 4. Underplating Corrosion [9].

III. EFFECT OF SILVER PLATING THICKNESS AND QUALITY ON SULFURIC CORROSION

Ag_2S is the major product of silver corrosion in an atmosphere containing sulfuric gases. Tarnished silver is the very first step in silver sulfuric corrosion when the corrosion layer forms a dark thin film, which can be relatively easily removed with tarnish cleaner or multipurpose scouring pads. As soon as a significant layer of silver is consumed, silver sulfide is visible on the surface as a heavy dark gray or black flaking deposit. Formation of silver sulfide is linear with time.

It is known that corrosion resistance of electroplated silver strongly depends on plating quality. A specific type of plating bath may produce plating with higher or lower corrosion resistances. For example, plating with no surfactants at a lower current density would produce more loose and porous plating [10]. Surface conditions such as roughness and cleanliness play an important role in plating corrosion resistance. A combination of two conditions: 1) poor quality of the plating, which may be characterized as loose and porous, and 2) exposure to humid atmosphere that may result in red-plague corrosion.

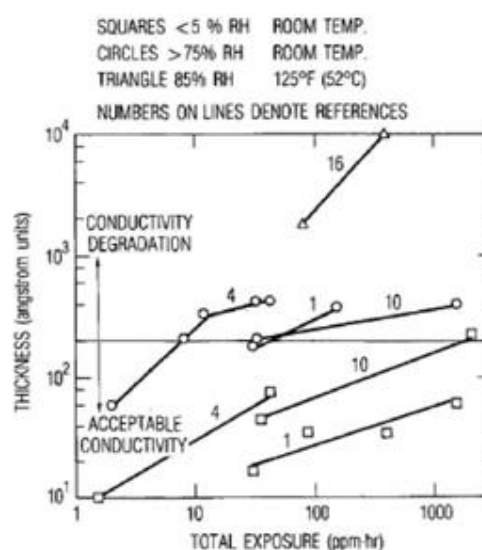


Fig. 5. Effect of silver sulfide growth on electrical conductivity as a function of total H_2S exposure and humidity [13].

Contact resistance is strongly influenced by the corrosion film thickness [11], [12]. It was determined that the silver coating thickness is the most important factor in corrosion resistance. If the silver coating is too thin or is of low quality, the corrosion film will include copper corrosion products, and its presence will always be detrimental to the contact. Contacts with a thin silver coating behave almost like unplated copper contacts. The thicker the silver plating the more that the base material is protected from corrosion because thicker plating is less porous and does not allow corrosive gas to penetrate. Silver flash, which usually has a thickness of tenths or even hundreds of microns, would be consumed in a corrosive atmosphere very quickly.

IV. EFFECT OF SILVER CORROSION ON CONTACT RESISTANCE

Silver sulfide is not a conductive material, and having a contact surface covered with a corrosion layer may decrease electrical conductivity significantly. The effect of corrosion on electrical properties of the contact depends mainly on the thickness of the corrosion layer. A less harmful and relatively benign stage of silver corrosion, leading to formation of a very thin layer of silver sulfide, is called silver tarnish. Silver will not tarnish when it is kept in a vacuum or when it has a coating on top to isolate its surface from the atmosphere. Silver sulfide is not an insulating substance; it is a semiconductor and may, therefore, conduct electricity. However, because the electrical resistivity of silver sulfide (Ag_2S) is $\sim 100\,000$ times higher than that of silver ($15 \cdot 20 \mu\Omega \cdot \text{cm}$ for Ag_2S versus $1.6 \times 10^{-4} \mu\Omega \cdot \text{cm}$ for Ag), its presence reduces the surface conductivity of the silver even if a very thin film is formed.

To what extent silver tarnish would affect electrical conductivity depends on the thickness of the tarnish. When silver contacts are used, one of the factors improving performance is that silver is soft. When silver is rubbed against another contact, it cleans itself and it smears, so good metal-metal contact can be sustained. However, if the contacts are not designed with this wiping action, there could be a longer term problem with an accumulation of low conductivity sulfides. The influence of sulfide corrosion on electrical contact was studied in detail in [13] because of growing concern for safety of satellites stored on the ground for a long time before launching. Presented in [13], Fig. 5 shows the correlation between duration of exposure to H_2S (in ppm-hour) and the thickness of the corrosion film, depending on temperature and humidity. This graph can be used to evaluate the approximate "safe" storage time in an environment with a very low concentration of H_2S where the electrical contact performance remains acceptable.

Initially, sulfur rapidly attacks the silver surface. Once the sulfide layer becomes continuous (100% of the surface is covered), growth takes place on the sulfide surface. Thereafter, corrosion is limited by the rate at which the sulfur-containing gas gets to the surface or by the rate at which silver, a highly mobile ion, diffuses through the sulfide layer. Most electrical connectors can tolerate some sulfide on their surfaces. Silver sulfide grown on a pure silver surface is soft and malleable, easily pushed aside even under low load. Although the thickness at which tarnish begins to noticeably degrade the electrical properties of the circuit is not well established, the silver sulfide layer becomes continuous at a thickness of about 150 \AA . Tests examining the electrical conductivity of silver seem to indicate that 200 \AA would be a reasonably conservative estimate of the thickness at which electrical properties begin to deteriorate.

For example, in urban and industrial areas, the concentration of H_2S is found in the 0.02–5.0 ppb range. Then, at a lower value of H_2S contamination, electrical properties of the contact most likely would not be deteriorated by

the tarnish film formed for a lifetime. However, at the higher end (5.0 ppb), the tarnish film formed in only 2000 hours (83 days or less than 3 months) at room temperature and RH > 75% is thick enough to deteriorate electrical properties of the contact. Tarnished film will grow faster at higher temperatures.

The data on corrosion film thickness forming on silver in three classes of field environment according to mixed flowing gas (MFG) test specifications is given in [14]. In a mild Battelle Class II environment (with 10 ppb of H₂S), corrosion film with thickness more than 1000 Å on silver will form in less than 1 year. Therefore, corrosion film on silver after exposure to a mild environment may lead to an increase of contact electrical resistance to more than 10 mΩ for only 1 year. For a harsher environment with 2 ppm H₂S, corrosion film 500 Å thick is formed within only 1000 hours (~40 days) [15].

V. EFFECT OF THE CURRENT LOAD AND MECHANICAL LOAD ON CORRODED CONTACT RESISTANCE

The relationship between contact resistance and exposure time to the H₂S gas was also studied in [16]. In Fig. 6, the contact resistance is shown as a function of the film thickness and time of exposure to 3 ppm of H₂S at 40 °C and 80%–85% relative humidity (RH).

Corrosion film thickness will grow up to 500 Å with exposure less than 100 minutes, as shown in Fig. 6. However, the contact resistance of the contact with such a film depends on the contact load (force), varying from 1 to 100 g. This means that Ag₂S is mechanically weak. In [17], the load was found to also strongly affect the contact resistance and the size of the contact areas, i.e., contact resistance was lowered with increasing current load. Also, it was determined that despite their high resistivity, thin corrosion films on silver do not always cause high contact resistance in high-current applications.

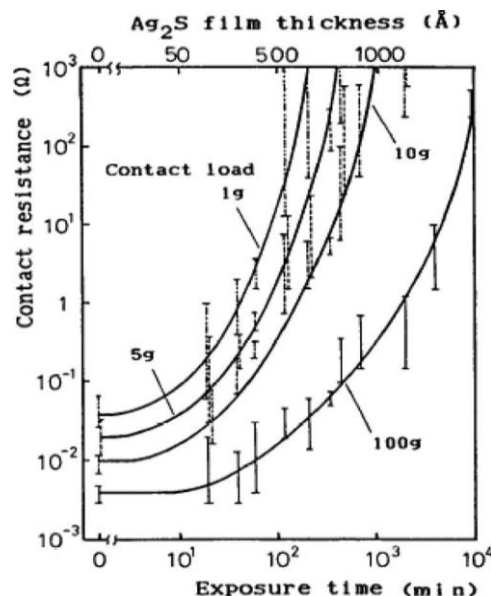


Fig. 6. Effect of H₂S exposure time on contact resistance [16].

Depending on the thickness, silver tarnishing can have various degrees of severity. A slightly yellow discoloration should be not considered as seriously damaging for contact electrical properties. Conductivity is not affected by light yellowing. In other cases, tarnishing can be dark brown and black. This coloring can be

partially or totally depending on the conditions of storage or use (finger marks, opened packing, etc.). If the discoloration is in constant evolution, the presence of a source of sulfuric gas in the immediate environment of the products should be considered. In this case, conductivity has the high-est chance to degrade rapidly. Some factors could accelerate the development of silver tarnishing during exploitation of the equipment, such as elevated temperature, high humidity, ultraviolet light (UV), and rate of ozone in the atmosphere, among others. Additional sources of sulfuric gases may be due to inappropriate packing because certain cardboards contain sulfur. The packing material should pass a special silver tarnish test [17] to ensure that there is no additional silver tarnishing.

The reactions of atmospheric pollutants with silver-based contact materials also produce corrosion products that adversely affect the contact's electrical behavior. In [18], three silver-based contact materials—Ag/Cu/Ni, Ag/Ni, and Ag/MgO/NiO—were exposed to an accelerated corrosion environment containing SO₂, H₂S, NO₂, and Cl₂, with maintained elevated temperature and high humidity. Both electrical degradation and corrosion film growth characteristics were studied as functions of exposure time. Contact resistance increased rapidly with the formation of growing corrosion film, consisting mostly of silver chlorides and silver sulfides. Due to the detrimental effect of silver tarnish on electrical contact performance, it is important to protect silver plating from corrosion. If corrosion film is already formed, it should be properly removed from the contact surfaces. Different techniques have been developed to delay contact corrosion, but whatever kind of antitarnish treatment is applied, the treatment should not interfere with the electrical properties of the coating.

VI. TECHNIQUES OF SILVER PROTECTION FROM CORROSION

All known developed antitarnishing methods can delay silver corrosion but cannot eliminate it. None of these methods satisfy all applications. The most important requirement for any type of silver-plating treatment used in the electrical industry is to not adversely affect electrical resistance. Various methods using application of protective films such as lacquers, oils, and inorganic deposits such as metal oxides on silver plating [19] cannot be used for electrical contacts. The most frequently used antitarnishing technique in the electric and electronic industry is metal coating applied by immersion or electrochemistry.

6.1 Conversion Treatment

The purpose of a conversion treatment (passivation or anti-tarnishing treatment) is to delay the appearance of tarnishing. Conversion coating is a generic term for any process that converts the surface of a part into a coating. For example, chromating is a process whereby metal parts are immersed in a solution containing chromates and other chemicals to convert the surface into a thin film that enhances corrosion resistance. In this process, Chromium VI is present in solution, and if this treatment is applied, Cr IV will be present in tarnishing and passivation layers on silver coatings. Until recently, conversion treatment complied with requirements of European directive 2002/95/CE (Restriction of Hazardous Substances [RoHS] directive [20]) of the European Parliament and European Union (E.U.) Council of January 27, 2003. This directive, in effect since July 1, 2006, restricted the presence of hazardous substances in electric and electronic equipment, and hexavalent chromium (Chromium VI) was among them. RoHS principles and their reach are global. The directive indicated that anything covered by RoHS entering the E.U. must be in compliance. That includes cables made in China, parts molded in the United States and PCBs made in Japan. If it is destined for the E.U., it is impacted by RoHS. It is

not just the E.U. that is taking steps to reduce toxins in electronic devices. California's Electronics Waste Recycling Act (EWRA) of 2003 (SB 20, Chapter 526 [21]), Maine's Electronics Waste Law (April 2004), and the Midwest E-waste Policy Development Initiative (April 2006) echo the RoHS directive.

6.2 Chromium-Free Tarnish-Preventative Processes

Antitarnish processes without heavy metal ions are designed to add value to silver and silver-plated substrates by preserving the as-plated appearance and minimizing tarnishing of the surface. The parts are immersed into liquid concentrate, which after treatment leaves a thin invisible organic film on the plated surfaces that generally has no influence on the surface resistance of electrical contacts. This protection is effective for only 6–12 months; therefore it would be a reasonable treatment to protect electrical contacts from tarnishing in storage. In-service protection of the surfaces will be only temporary; it will not prevent corrosion in the long run. According to technical specifications, some solutions seem appropriate for use in electrical applications. However, because some chemicals provide a top coat (or sealer) on the parts, they should be tested to prove that film application does not deteriorate electric continuity.

6.3 Vaporized Corrosion Inhibitors

Another type of temporary protection of silver plating is a vaporized corrosion inhibitor (VCI) [22]; these compounds also do not have a significant effect on electrical contact resistance. VCI emitters can be placed within electrical enclosures to retard internal corrosion as long as air exchange with the outside environment is limited. VCIs release a chemical vapor into the enclosed still air space to form a molecular film settling on metal surfaces as a barrier layer that limits an excess of corrosive gases to the plating surface. Providing protection for 1–2 years, each container is effective within a surrounding area up to 6 feet in radius. Similar vapor-releasing compounds are also available as tapes or spray-can formulation for use on surfaces in the open air. Several effective VCI products are widely available.

6.4 Lubrication

Use of lubricants is widely accepted as an effective means of protecting silver-plated contacts from corrosion [23]. However, the benefits of using lubricants for corrosion inhibition were overlooked for many years because prospective users were skeptical that a nonconductive substance could be applied onto contacts without interfering with conduction. The choice of lubricant for corrosion protection should be based on thorough qualification of the product for survival long term and the ability of such products to provide friction and wear reduction.

Very few lubricants have been identified that provide exceptional long-term corrosion protection, yet do not produce any adverse effect on connector surfaces. An example of a lubricant that proved useful for corrosion protection for connectors made or plated with precious metals is six-ring polyphenyl ether (PPE) or its mixture with a microcrystalline wax, although the wax content should be controlled. Many products, such as synthetic soap greases and other commercial greases, have been tested and proven useful for bolted contact application.

VII. CORROSION OF OTHER METALS IN ELECTRICAL EQUIPMENT

Steel with zinc plating is the material often used in laminated arms, plates, bolts, fasteners, mounting plates,

and circuit breakers. An example of extensive rusting of bolts and laminated arms in circuit breakers is shown in Fig. 7(a)–(f). Zinc is a sacrificial barrier to protect the base steel, which will sacrifice itself and eventually disappear before the base metal starts to corrode. Zinc plating protects the underlying steel by forming a “galvanic cell,” which results in zinc corroding preferentially to the steel. Zinc plating is usually used as a functional indoor coating. By itself, 5–8 μm of zinc plating will likely withstand no more than 12 h of salt spray protection per ASTM-B117 testing. When a clear chromate topcoat is present, this protection is increased to 24–36 h, whereas a yellow chromate top coating (yellow zinc) can achieve protection up to approximately 96 h.



Fig. 7. Corrosion spots on steel parts from the breaker: (a)–(c) white deposit and pits on the surfaces of the plates of laminated arms; (d)–(f) white deposit and brown corrosion products on the mounting plates and bolts (“red rust”).

When freshly galvanized steel is exposed to pure water (condensation, rain, or dew), water will react with the zinc and progressively consume the coating. Zinc is oxidized and changed to white rust, which is a basic compound of zinc carbonate with zinc hydroxide, which is white and is called in the technical literature “white rust” or “wet storage staining” and zinc corrosion. It is seen as a bulky white powdery deposit that forms rapidly on the surface of the galvanized coating under certain specific conditions [24]. White rust causes considerable damage to zinc plating and is always detrimental to its anticorrosion properties. Steel corrosion is most possibly the result of previous exposure of the units to the moisture, followed by corrosion and degradation of the protective zinc plating. Therefore, in pulp and paper facilities with elevated moisture levels, this kind of zinc plating corrosion in electrical installation may be expected.

Aluminum bus bars are often used in electrical equipment; however, using aluminum in pulp and paper applications without protective plating may be controversial because of the ready corrosion of aluminum in salty and humid atmospheres. Ventilating fans on totally enclosed fan-cooled motors that are continually exposed to fast-moving air loaded with whatever contaminants the surroundings contain are notoriously subject to corrosion. At one time, aluminum was the standard material, with bronze as an alternative, when corrosion resistance was stipulated. In some paper mills, however, a process residue known as “black liquor” is corrosive to bronze as well, leading to the use of malleable iron instead [25].

VIII. CONDITION MONITORING TECHNIQUES FOR ELECTRICAL EQUIPMENT IN CORROSIVE ENVIRONMENT

In pulp and paper facilities where electrical equipment is often exposed to corrosive environments, there is a concern that extensive corrosion of conductive path may lead to increased electrical resistance and therefore to additional heat runaway that may result in serious equipment overheating.

IR thermography is widely applied for annual or semi-annual thermal inspection of electrical equipment using an infrared camera to detect points of overheating and to indicate a conduction fault [26]. To have visual access to the conductors inside the switchgear enclosure, it is necessary to have openings in the metal barriers of the cubicles. This is not always acceptable because it downgrades the degree of personnel protection and workplace safety. It is possible to make some metal walls “transparent” for *IR* emission by installing inspection *IR* windows made of quartz, a material transparent to infrared rays. Although this is effective in some applications, there are still multiple points to which visual access is impossible. The periodic nature of *IR* inspection is the main limiting factor with this practice.

Another way to monitor temperature using *IR* emission of a heated surface is to monitor the temperature with non-contact *IR* thermometers. *IR* sensors are installed in close vicinity to the target and send signals to a remote personal computer [27]. The smaller the target area, the closer to the target the sensor should be. This limits the sensor’s applicability and the targets of interest. Another downside of using *IR* noncontact sensors is the need to run the cables from each sensor to the receiving units.

The most advanced distributed fiber optic temperature sensing [28] is used to monitor the temperatures of cables and HV transformers. Applying fiberoptic modifications to an existing power distribution system would require substantial modifications to the equipment with subsequent design verifications and testing. The application of such a system—while very reliable and inexpensive for new equipment—becomes cost prohibitive for existing equipment.

Many of these issues may be resolved by using wire-less technology for continuous contact condition monitoring [29]–[31]. The most important advantage of using wireless technology to monitor the thermal condition of energized equipment is eliminating cables and wires from the system. Another important benefit of wireless technology is much lower installation costs than other types of online monitoring equipment. Wireless systems work well in difficult or dangerous-to-reach locations or in moving applications. Wireless sensors can be installed directly on the surfaces of the elements of the current-carrying path in many strategically important points inside MV and LV switchgear [32], [33] such as finger clusters, cable connections, and the like. (Fig. 8).

An example of the temperature of energized electrical contacts measured online is shown in Fig. 9.

During this period of temperature monitoring in Fig. 9, overheating of one of the phases (A) of the MV circuit breaker was registered, triggering an alarm. The breaker was deenergized, removed from the cell, maintained, tested, and returned safely to service. This example shows that continuous online temperature measurement allows timely identification of the problem areas that can lead to substantial equipment damage.

Direct measurement of the electric contact temperature using continuous temperature monitoring of energized equipment provides valuable information, which may be used to determine the true condition of the contact in service [34]. Analyzing the correlation between the contact temperature measurement, ambient conditions, and

load allows abnormal conditions to be identified in a timely fashion so that operation and maintenance personnel can be notified of a potential problem [35].



Fig. 8. Wireless sensors installed on finger clusters and cable connections in MV and LV switchgear.

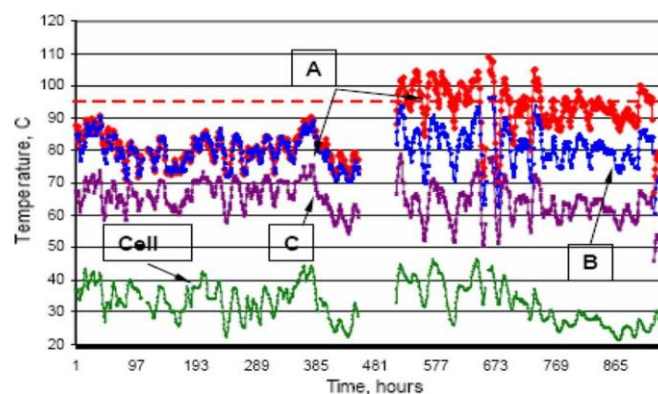


Fig. 9. Temperatures of finger clusters on three phases (A–C) of MV circuit breaker and inside the cell.

Practical applications of different techniques of temperature measurement demonstrate the importance of condition monitoring of energized equipment for proper and timely condition-based maintenance, preventing possible disruption of electrical service, particularly in corrosive environments. Using continuous wireless temperature monitoring of energized electrical equipment may substantially reduce downtime and maintenance costs.

IX. CONCLUSION

- 1) Corrosion of electrical equipment in pulp and paper facilities is a continuous and costly problem. Exposure of various metals used in electrical apparatus to corrosive gases, vapors, and elevated humidity cause a rise of electrical resistance followed by extensive heat runaway.
- 2) Sulfuric corrosion of silver used as bulk or as plating for corrosion protection of other electrical conductors is typical for pulp and paper facilities. Several alternatives of silver corrosion protection are suggested to

minimize an effect of silver exposure to hydrogen sulfide at pulp and paper mills.

- 3) Continuous online temperature monitoring is presented as a valuable means to determine aging and deterioration of energized electrical contact due to exposure to a corrosive environment. It allows corrective measures to be taken to timely prevent equipment failure.

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