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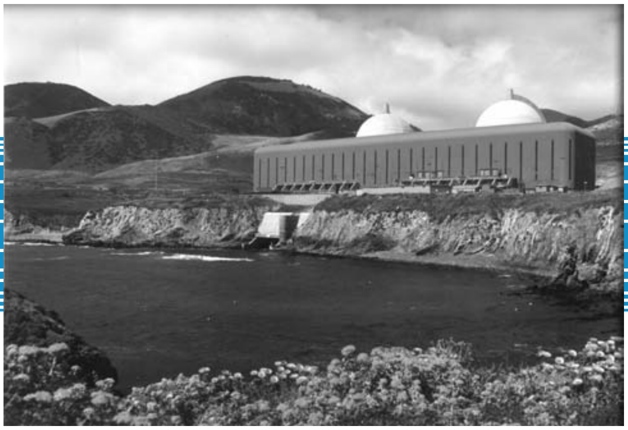
# Nuclear Maintenance Applications Center: Isolated Phase Bus Maintenance Guide

## Update to TR-112784

Plant
Maintenance
Support

Reduced
Cost

Equipment
Reliability



# Nuclear Maintenance Applications Center: Isolated Phase Bus Maintenance Guide

## Update to TR-112784

**1015057**

Final Report, December 2007

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

*Nuclear Maintenance Applications Center: Isolated Phase Bus Maintenance Guide: Update to TR-112784.* EPRI, Palo Alto, CA: 1015057.

# PRODUCT DESCRIPTION

This report provides information on design, operating experience, and maintenance practices associated with the isophase bus system. The information is meant to be useful for system engineers, component engineers, maintenance personnel, and their supervision in understanding and maintaining this system. This document is an update to *Isolated Phase Bus Maintenance Guide* (EPRI report TR-112784), and the scope has been expanded to include boundary components, such as potential transformers (PTs) and current transformers (CTs) that also affect system reliability. The Institute of Nuclear Power Operations (INPO) operating experiences that have occurred since the original report's release were gathered, analyzed, and evaluated to provide insights into recommended maintenance practices. Additionally, a table of maintenance tasks and frequencies has been provided for guidance in maintaining system reliability.

### Results and Findings

The isophase bus system continues to be a frequent contributor to industry operating experience. In addition, many components of the system are susceptible to age-related degradation or deterioration due to frequent manipulation, such as frequent removal of bus links for system isolation. This update is meant to provide additional guidance on system maintenance and testing to increase and extend system reliability through plant life extension.

### Challenges and Objectives

This report should be useful to system/component engineers who are unfamiliar with the design of the isophase bus system and the operating experiences that have impacted system reliability. This document is also useful to system engineers in evaluating the correct predictive and preventive maintenance activities for the system. Maintenance personnel should find the insights on improved and proper bolting techniques of electrical connections useful in reducing occurrences of high-resistance connections and repeat maintenance of them. The document also provides insight to system/component engineers and maintenance personnel in troubleshooting this system.

### Applications, Value, and Use

This document has been updated to improve the usefulness in determining the correct maintenance tasks based on insights from operating experience over the last 10 years. Additionally, maintenance personnel should benefit from insights provided on key inspections, inspection methodology, visual images of the component deterioration, and methods to improve the integrity/ease of installation/removal of large electrical bolted connections.

## EPRI Perspective

This report expands on the original guidance provided in TR-112784. Specifically, it provides maintenance tasks for many of the subcomponents of the isophase bus system as well as some ideas on improvements in the many bolted connections that have been problematic. The guide is meant to be a comprehensive source of historical design information, recommended maintenance tasks, and maintenance practices.

## Approach

The initial research was based on member feedback for improvements to the original document. A tremendous resource was a thorough review of industry operating experience and technical advisory group member experiences since the original report was written. Other material was gathered from existing EPRI research on maintenance task and frequencies that was not available when the original report was issued. Finally, input from the original author and an industry consultant was incorporated to provide additional insight specifically on improving bolted connections. The scope was expanded from the original document, which included the electrical bus, the bus duct cooling system, and monitoring, to include CTs, PTs, neutral bus, and miscellaneous subcomponents.

## Keywords

Isophase bus
Segregated bus
Non-segregated bus
Turbogenerators
Electrical equipment

# ABSTRACT

This document is an update to *Isolated Phase Bus Maintenance Guide* (EPRI report TR-112784), issued in 1999. The first eight sections of the report are a review of the history and design characteristics of the various bus designs that are used in the power industry. These sections are relatively unchanged because there have not been any major advancements in bus design. Section 9 has been expanded to include boundary components of the isophase bus, including potential transformers (PTs), current transformers (CTs), neutral buses, neutral transformers, and miscellaneous equipment at the PT housing.

Section 10 has been added to summarize and discuss operating experience that has occurred between the issuance of the original guidance and the present time. The number of events indicates that the isophase bus continues to experience reliability issues, in addition to age-related degradation and less-than-optimum maintenance practices. The primary source of the operating experience review was data gathered through the Institute of Nuclear Power Operations (INPO) web site. Some operational experience was gleaned from the Internet web group GETURBGEN. Finally, members of the technical advisory group provided additional operating experience.

Section 11, "Maintenance," combines the previous guide sections on visual inspections and testing. The new section covers these items and also discusses other on- and off-line periodic inspections. In addition, tables have been added with recommended maintenance tasks, frequencies, tests, and expected test values. This table is provided as a maintenance basis to compare to the current maintenance basis. Frequencies are meant for guidance and can be modified based on individual utility design, operating experience, environmental conditions, or maintenance history.

Finally, Appendix A has been added. It is a technical paper submitted by James Bothwell that provides some insight into many of the issues identified in operating experience with bolted connections. Recommendations on improvements to bolted connections are provided that will alleviate some of the common problems with these critical connections.

# ACKNOWLEDGMENTS

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The Electric Power Research Institute (EPRI) thanks James E. Timperley and James S. Bothwell for their contributions to this work.

The following are members of the EPRI technical advisory group (TAG):

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EPRI is grateful for the TAG members' contributions to this report.

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# 1

# INTRODUCTION TO HIGH-CURRENT BUS SYSTEMS

There are several types of conductor arrangements used to transfer power from a generator to its load. Although, in a power plant, the normal power flow is from the generator to the load (switchyard), the same interconnecting bus can be used to back feed the plant upon loss of the startup transformer (infrequent evolution). Most smaller generators use cables; however, voltages over 13 kV and currents over 5000 amperes usually make cables uneconomical. Instead, a metal-enclosed bus is used to transfer power from most large machines. As illustrated in Figure 1-1, there are three basic types of metal enclosed buses:

- Non-segregated phase
- Segregated phase
- Isolated phase

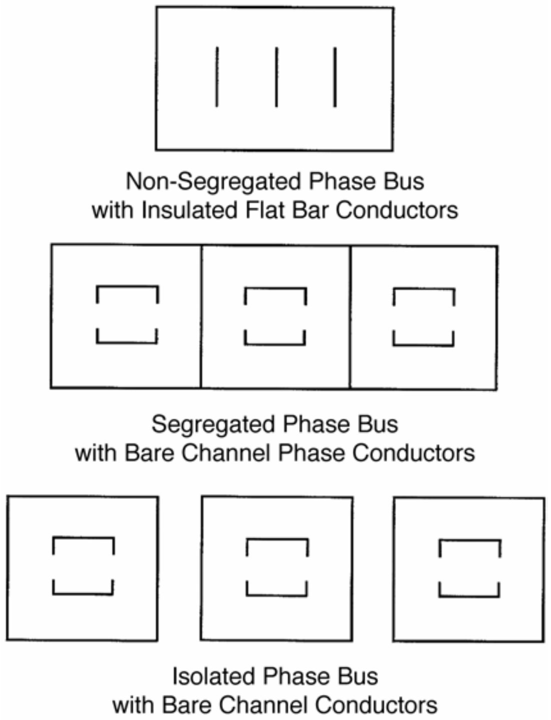

**Figure 1-1**
**Types of Isolated Phase Buses**

# 2

# EVOLUTION OF THE ISOLATED PHASE BUS

Early designers of the station bus realized that the short-circuit current in phase-to-ground faults could be limited by introducing a neutral impedance, so that phase-to-phase faults could not be limited. Thus, they focused on designing station layouts that would prevent phase-to-ground faults from developing into phase-to-phase faults.

A common method used to eliminate phase-to-phase faults involved constructing concrete barriers between phases. This construction, while an improvement in reducing the frequency of phase-to-phase faults, was difficult to keep free from contamination by rodents. In addition, some operators felt it actually increased the frequency of phase-to-ground faults. It was not ideal in terms of safety to personnel or in ease of extension or relocation. However, most early power plants used this technique. Some of these 13-kV arrangements were very elaborate and expensive.

The next design improvement for the station bus tried supporting each conductor on insulators and enclosing them within a common metal cage or shield. The compactness of this type of bus, together with its ease of installation and safety to personnel, has made it ideally suited for all metal-enclosed switchgear. This arrangement, *non-segregated phase bus*, works well if there are limited fault current magnitudes. Non-segregated phase buses have become the standard for switchgear and many auxiliary bus systems.

At larger loads, where voltages and short circuit magnitudes are high and load currents are over 5000 amperes, it is necessary to use tubular or channel conductors, both to carry the high load currents and to withstand the magnetic forces encountered during a fault. Often wrapped or pressed-on insulation for this type of bus is economically impractical.

At larger loads, it has been customary to use only air insulation and to support the conductors on porcelain insulators. Generators installed through the early 1960s employ this design. Typical sizes were 15,500 V at 5000 amperes. This arrangement, however, violates the original desire of designers to limit phase-to-phase faults.

To prevent phase-to-phase faults with this construction, designers spaced the phase conductors far enough apart so that metal barriers could be located between phases. Thus, the *segregated bus* resulted. One of the weaker points of the segregated phase construction was the possibility of the phase-to-ground arc burning through one of the metal inter-phase barriers, thereby developing into a phase-to-phase fault or double phase-to-ground fault. Protection against burn-through is provided when each phase conductor is enclosed in its own metal housing and the three enclosures are then separated by air spaces. With this arrangement, even though an arc burns through the side of one enclosure, ionized gases cannot burn into adjacent enclosures. With this *isolated phase* construction, there are two basic types of bus: non-continuous and continuous.

# 3

# ISOLATED PHASE BUS, NON-CONTINUOUS ENCLOSURE

With the isolated phase bus, non-continuous enclosure design, the enclosures are electrically non-continuous throughout their length. Succeeding enclosure sections are insulated from each other. This insulation is required to prevent circulating currents from flowing through the high-resistance joints at interfaces between enclosures and between the enclosure and supporting steel beams. The resistive heating losses ($I^2R$) loss at these joints could raise temperatures to unacceptable levels. The three enclosures of each three-phase group are insulated from each other, except at one end where they are connected together and grounded, as shown in Figure 3-1.

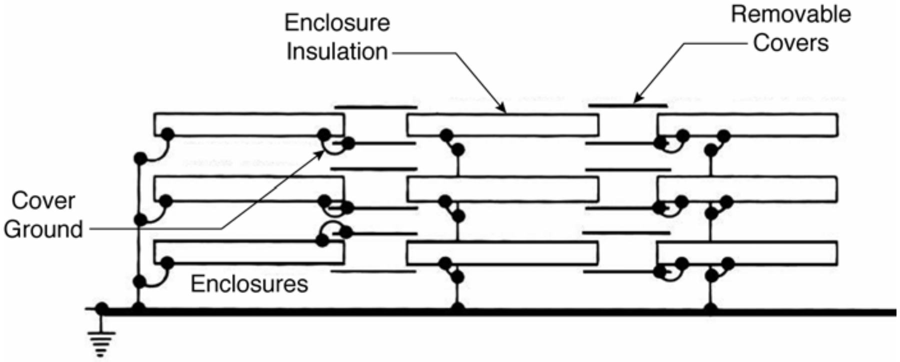

**Figure 3-1**
**Circulating Currents Design for Non-Continuous Bus Enclosures**

One important advantage to this design is that these enclosures have internal circulating currents in them that greatly reduce the mechanical stress that develops on support insulators during fault conditions. Because large generators usually have the capacity for very high bus fault currents, this is an important benefit. Because of eddy currents in the enclosure, fault current forces on insulators can be reduced by as much as 90% of the value that would result if an enclosure were not present. The result is that only single cantilever, widely spaced insulators are required for conductor support [1].

Although the non-continuous type of bus provides shielding against magnetic forces due to short-circuit currents, the external magnetic field, due to normal load currents, remains at substantial value. Tests have shown the external magnetic field to be approximately equal to 70% of that generated by conductor current. In addition, when conductor currents are high, induced voltage across enclosure insulation can be dangerously high for personnel. The largest non-continuous enclosure designs are in the 9300-ampere/16,500-V range. Circulating currents in adjacent structures are a serious problem when phase currents approach 10,000 amperes. In resolving these issues, the development of a minimum-flux or *continuous* enclosure design of isolated phase bus resulted, as shown in Figure 3-2.

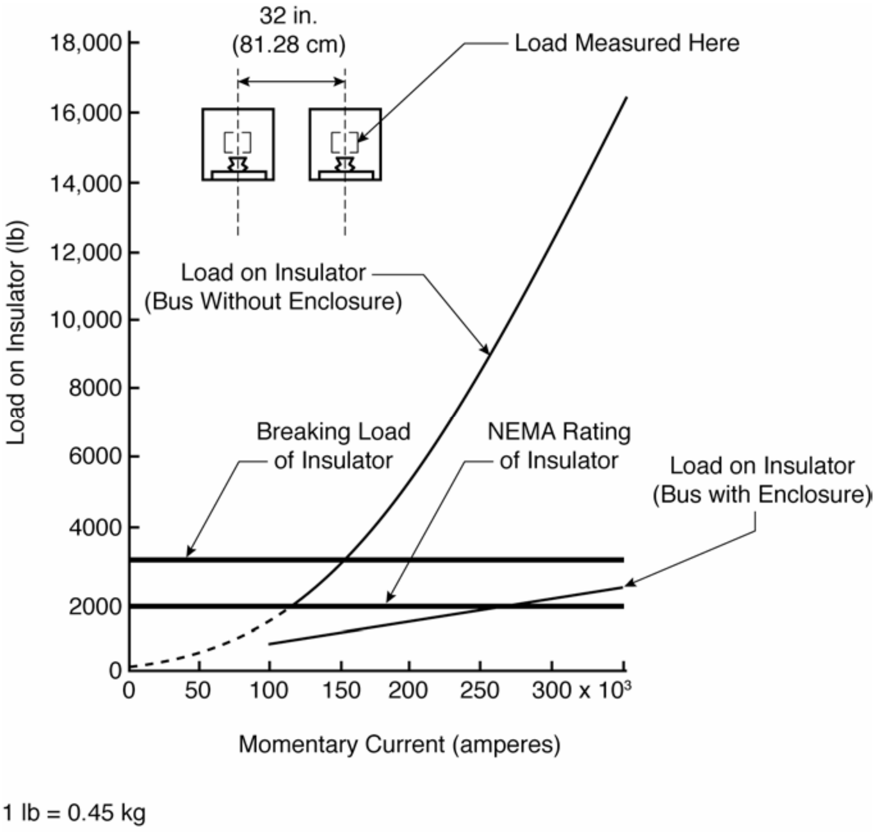

**Figure 3-2**
**Comparison of Fault Current Stress on Bus Support Insulators for an 8-ft (2.44-m) Section of Conductor**

## 3.1 Design Features

The isolated phase non-continuous enclosure bus was an intermediate development between the segregated phase bus and minimum flux designs. Although very common in the late 1950s and early 1960s, its use declined as phase currents increased. By its design, each enclosure section must be fully insulated and grounded at only one point. A variety of sheet insulation, bushings, and rubber gaskets are used to keep out contamination and eliminate unwanted circulation currents. Because the external magnetic field is very strong, shorting rings are required around all adjacent steel beams. Bus support hardware is usually aluminum to help reduce heating. In some designs, a heavy ground bus follows the enclosures to help decrease stray circulating currents. The original equipment manufacturer (OEM) often provides very detailed information on the design features of each bus. These documents should be located and referred to when repairs are needed.

## 3.2 Potential Problems

Insulation deterioration has proven to be a significant maintenance problem of the isolated phase non-continuous enclosure. Materials available to designers 40 years ago were very limited in performance. Stray currents in adjacent structures and pipes and through floors can be expected. Very high temperatures result when two or more enclosures short together. Insulation between enclosure sections is usually integrated into the removable covers and may be rubber- or cork-based. There are often scores of insulating sleeves, washers, and bushings of cotton-based material used at the enclosure supports for electrical insulation. Voltages are low (30 V or less), so failure is usually thermal/mechanical in nature. Deterioration of bolted connections follows the same pattern as discussed in Section 12.

## 3.3 Testing and Maintenance

Internal conductors and outer enclosures should be inspected and tested as suggested in Section 11. Operating temperature limits are the same as those given in Section 8. Thermography is the best technique used to find problems.

Maintenance usually consists of replacing burnt, crushed, dried, or cracked insulation. A wide variety of modern materials such as epoxy, polyester-glass laminates, neoprene-impregnated cork, or silicone rubber-based products are now available to execute permanent repairs. OEM support is available, but a local custom plastic fabrication shop, motor repair shop, or switchgear repair facility might be able to build the needed hardware faster at lower prices.

Isophase enclosure insulation resistance can be tested to ground or to an adjacent enclosure by lifting the dedicating ground connection and testing with a low-voltage Megger[1].

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[1] Megger is a registered trademark of AVO Biddle.

# 4

# ISOLATED PHASE BUS CONTINUOUS ENCLOSURE

When the conductor enclosures are electrically continuous and shorted together at both ends, circulating currents almost equal to the phase currents are induced in the enclosures, in opposite directions. The resulting magnetic fields tend to cancel each other. If the enclosure resistance was zero, the resulting magnetic fields would sum to zero. In the practical bus, the enclosure does have resistance so that some flux must escape in order to drive current through the enclosures. Laboratory and field tests have shown the external flux to be approximately 5% of that which would exist if the enclosures were absent. Thus the magnetic shielding of a continuous enclosure bus is 95%, compared to the 30% of the non-continuous enclosure bus.

Quantitatively, this means that for an isolated phase bus with a nominal rating of 20,000 amperes, the external magnetic field of the non-continuous enclosure bus would be equivalent to 0.3 × 20,000 = 6000 amperes for an open bus. Support beams would usually require protection against excessive inductive heating. No such protection is required with the continuous enclosure design. Here, the external field would be the same as a 0.05 × 20,000 = 1000-ampere bus. The fact that no enclosure insulation is required ensures that voltages generated in the continuous enclosures and appearing between enclosure and ground will be low, and, in practice, they are usually less than 1 V. The voltage drop along an enclosure will mainly be the resistive voltage drop due to $I^2R$ losses. Because of the low resistance of the enclosure, voltage drop will also be low. Dangerous voltages that can develop with the non-continuous enclosure are nonexistent with the continuous enclosure bus. An additional benefit of this principle is a further reduction of at least 25% of the forces on the insulators during fault conditions. An illustration of the circulating currents in continuous enclosures is provided in Figure 4-1. A cross-section of an isolated phase bus is shown in Figure 4-2.

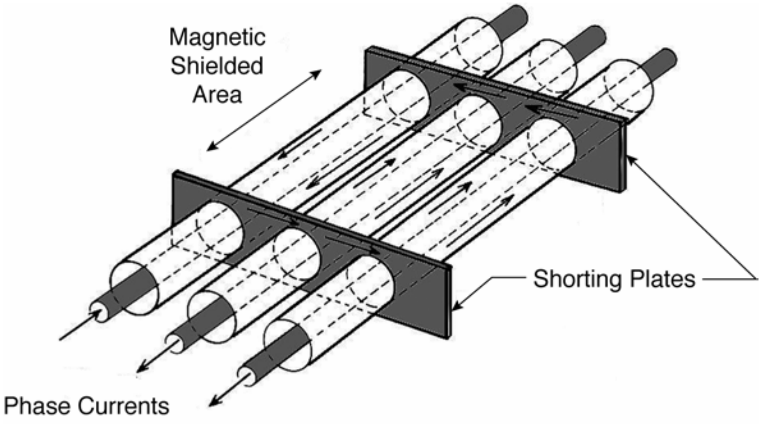

**Figure 4-1**
**Circulating Currents in Continuous Enclosures**

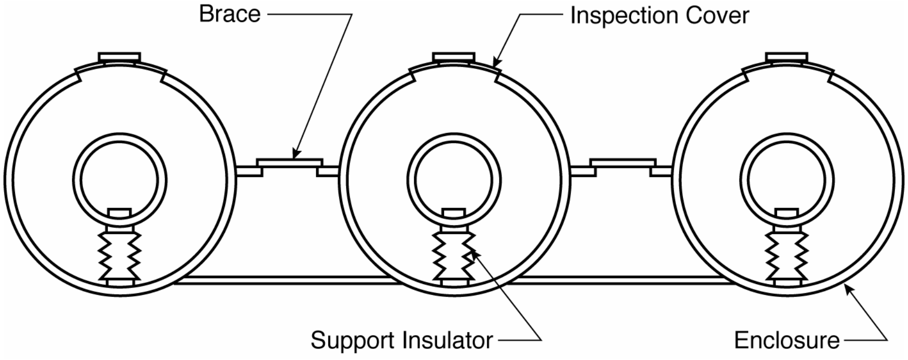

**Figure 4-2**
**Cross-Section of Isolated Phase Bus**

# 5

# BUS DESIGN CONSIDERATIONS

Conductor and enclosure shape in high-current buses has been chosen for maximum efficiency. The “skin effect” or penetration depth of an alternating current into a conductor is an important design consideration. Optimum 60-Hz thickness for an aluminum conductor is about 0.72 in. (1.83 mm) and, for a copper conductor, about 0.55 in. (1.40 mm). Material arrangement is also important [2]. Likewise, the enclosure shape has been optimized to reduce losses. Round or tubular enclosures provide the best use of material for high mechanical strength, maximum space utilization, and minimum circulating current loss. A comparison of ampacity and conductor shape is shown in Figure 5-1. A comparison of square and round enclosures is provided in Figure 5-2.

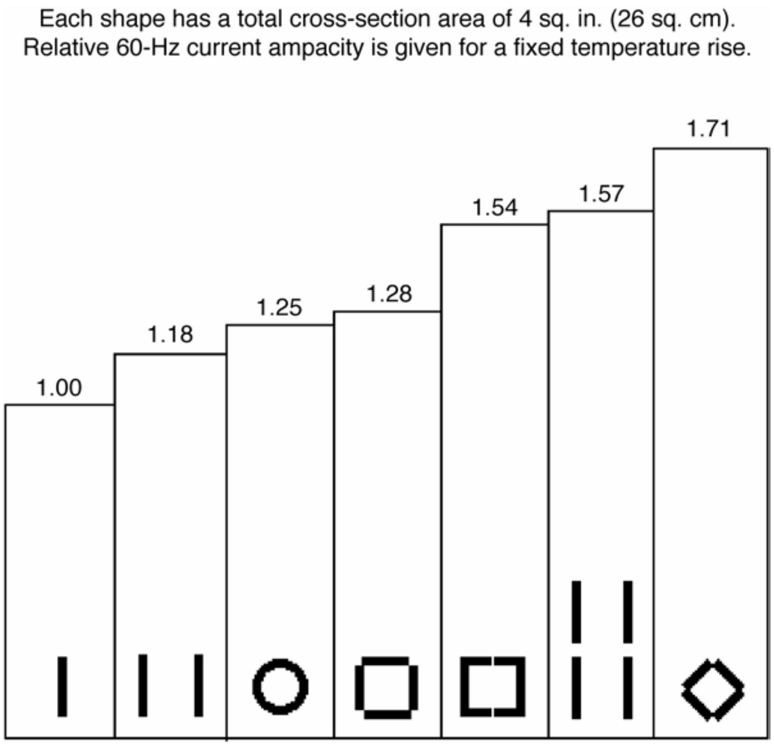

**Figure 5-1**
**Comparison of Ampacity and Conductor Shape**

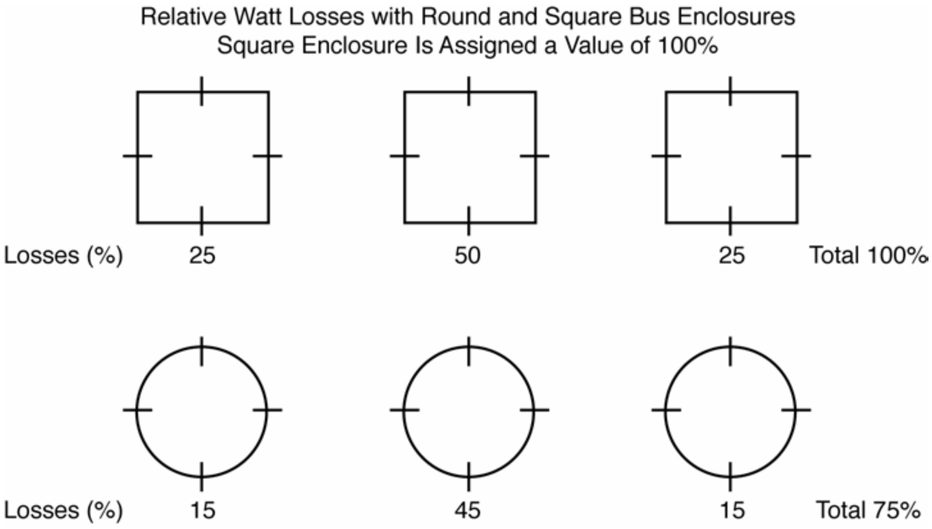

**Figure 5-2**
**Enclosure Design**

# 6

# BUS COOLING SYSTEMS

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Forced cooling is not usually economical below 15,000 amperes unless there are severe space limitations. A self-cooled generator bus, for example, requires aluminum conductors 19 in. (483 mm) in diameter for a 15,000-ampere rating. A forced air-cooled bus of the same size could be rated for 30,000 amperes. A generator water-cooled phase ring copper bus, for example, including mica insulation, is less than 4 in. (102 mm) square with the same 15,000-ampere capability.

A round center phase enclosure develops three times the circulating current loss as either of the other two outside enclosures. Natural convection and radiation cooling are restricted due to the proximity of adjacent enclosures. This is why forced air-cooled bus arrangements often discharge all air through the center phase and return air through both outside phases.

Because all three phases are forced-air cooled, air crossovers are necessary. With crossover ducts added between enclosures, violation of the air space metal separation desired for phase-to-phase fault protection occurs. This is why all air crossover ducts are supplied with deionizer grids to prevent an arc from jumping between phases. This frequently consists of numerous steel chevron plates inside the crossover duct, cooling any plasma below conduction but not restricting cooling air flow between phases. Normally these are located between generator bushing housings and near the step-up transformer bushings.

# 7

# BUS COOLING CONSIDERATIONS

An isolated phase bus can be self-cooled, forced air-cooled, or water-cooled. Deionized water forced through copper conductors is used in some European bus designs (that is, Sweden, Germany, and the United Kingdom); however, very few of these designs are found in North American stations. Operating limits are very design-specific and should be provided by the manufacturer.

## 7.1 Self-Cooled Bus

A self-cooled bus relies on natural air circulation around the enclosures for cooling. Bus sections to the potential transformers (PTs) and auxiliary transformers are often self-cooled. Some air flow is desirable to reduce moisture accumulation. Small-screened air bleed holes are sometimes provided for this purpose if these bus runs are part of a forced air-cooled system.

When the entire bus is self-cooled, it is desirable to keep the system sealed, thereby keeping dirt and moisture out. Some self-cooled enclosures are kept slightly pressurized with 1–8 psig (0.00690–0.05515 MPa) of nitrogen gas or instrument air to help prevent in-leakage of contaminants. Care must be taken to keep the pressure feed lines electrically insulated at each bus enclosure.

Self-cooled buses can be supplied with more than a 20,000-ampere rating, but the physical size becomes very large—and this design is often more expensive to install than a forced air-cooled system. Below 10,000 amperes, the self-cooled bus is the norm.

## 7.2 Forced Air-Cooled Bus

Beyond 20,000 amperes, economic compromises between energy loss and capital investment usually result in forced air cooling of the center conductor and external enclosures. Air-to-water heat exchangers and fans are used to keep the bus below design temperature limits at the rated phase current and at an air-cooler outlet temperature of 104°F (40°C). Some safety factors to compensate for dirt, reduced air flow, and plugged cooler tubes are usually included in each design.

## 7.3 Air Flow

In most systems, all air enters the center phase enclosure, usually near the generator. It flows to the main transformer, passes through air crossover ducts, and returns through the two outside phases. Some ventilation around the generator bushings and transformer bushings is usually provided. Excessive pressure drop will result if air velocity in the center phase is high. A typical isophase bus forced air flow cooling system is illustrated in Figure 7-1.

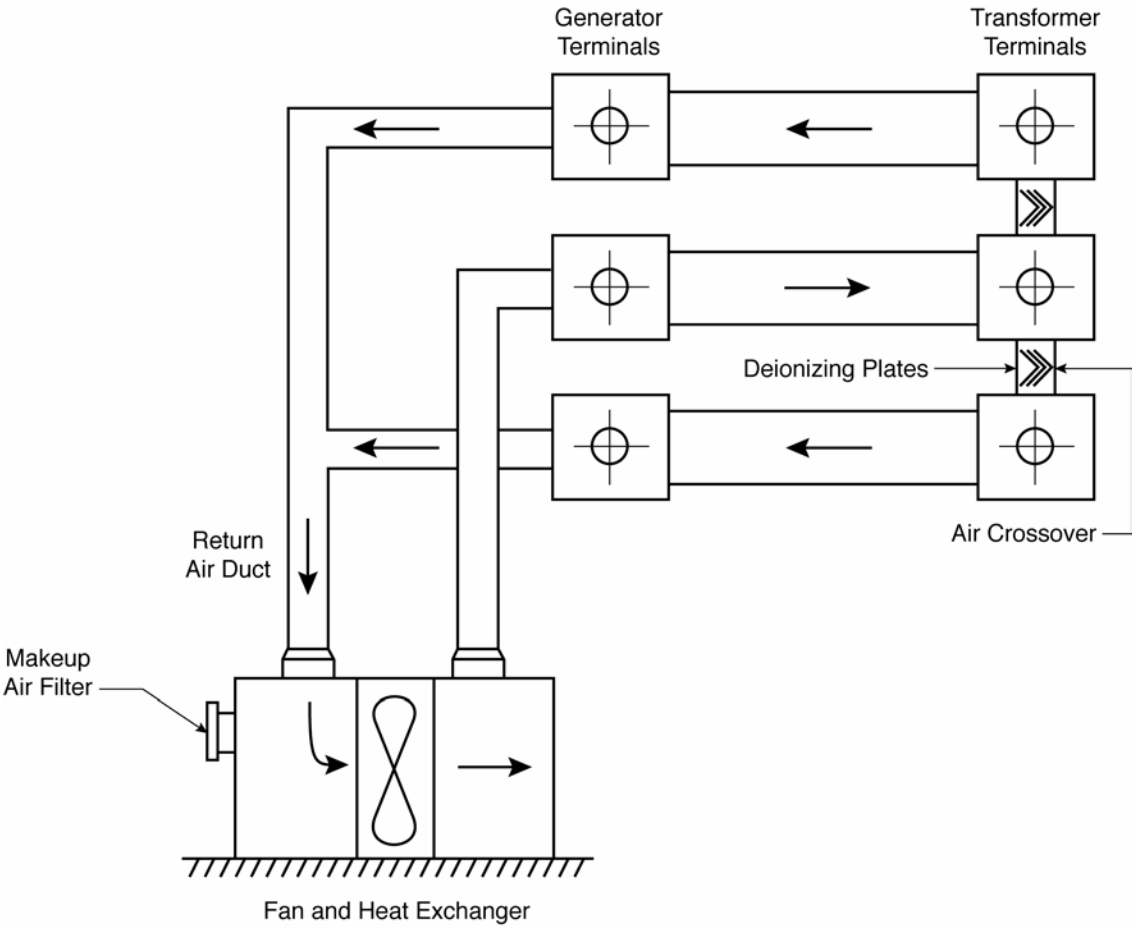

**Figure 7-1**
**Typical Isophase Bus Forced Air Flow Cooling System**

With long bus runs or high-capacity systems, some designs have cooling air enter the center phase at a point between the generator and main transformer. Here, air is divided to flow in both directions. Damper settings are critical for proper cooling of both circuits. The total required air flow remains constant, but back pressure is reduced with a dual-flow design.

Other air flow designs are also in service with all three phases carrying the same air flow. In others, cool air is supplied to the outside phases and returned through the center enclosure. In one design, the center phase is one of the two return air passages. Design calculations should be referred to if cooling problems develop. Air flow, cooler water flow, and pressure drops might require changes if any modification to the original system is implemented. Extended power uprates have resulted in modifications to bus cooling systems, generally increasing fan capacity to increase the heat removal capability of the system. Extended power uprates require a complete review and assessment of the isophase bus, including enclosure, electrical bus, insulation system, heat sink, forced ventilation, and interconnections including links and flexible connectors.

Isophase bus cooling system designs vary depending on manufacturer and generator rating. Optimum designs have two, 100% capacity cooler fan/motor trains with the standby train auto-starting on high discharge temperature or loss of cooling flow in the fan housing. Less optimal designs have dual 50% capacity cooler fan/motor trains or a single fan with two 100% capacity drive motors with one motor in standby.

The fans are mainly belt-driven. Fan discharge is directed through a damper and across a cooling coil. Cooling water is supplied by the plant service water system or by a turbine building closed cooling water system.

The loss of air flow for systems with forced-air bus cooling is a significant plant event. Operations must reduce generator load in as little as five minutes if this occurs because generator output without forced air cooling of the bus is limited to 40–60% of rated amperage.

Some forced-air systems include a sump pit near the base of the heat exchanger. The pit is equipped with liquid level detectors to detect and alarm upon a major water leak in the heat exchanger. A small tube leak in the heat exchanger is difficult to detect and may inject a fine water mist into the air stream, thus compromising bus and enclosure insulation integrity.

## 7.4 Seal-Off Bushings

Porcelain seal-off assemblies are supplied to prevent air flow into PT cabinets and to prevent air flow from forced-cooled into self-cooled sections. They are also installed to prevent air flow from inside to outside bus sections on self-cooled systems. Current transformers (CTs) can also be mounted on these insulating porcelain sleeves.

Wall baffles are typically located at the interface of the building interior/exterior wall and help to act as a fire barrier. The baffles minimize short-term transfer of undesirable airborne material such as smoke, particulates, or moisture while allowing normal transfer of cooling air. Baffles should be periodically inspected for damage, effective sealing to the wall interface, and overall cleanliness. Some wall baffles incorporate shorting plates in their design and should be grounded in a manner consistent with the other shorting plates in the system.

# 8

# OPERATING TEMPERATURE LIMITS

An isolated phase bus is usually constructed with few organic materials. The material creep and the differences in expansion rates therefore dictate the maximum continuous operating temperature. Each manufacturer has developed specific limits depending on the design and materials used. If this documentation is unavailable, the following general guidelines can usually be applied safely.

## 8.1 Enclosure

Temperatures of the three external enclosures can be measured directly. Thermostatic switches can be attached at expected hot spots to operate high-temperature annunciators. Several standards for metal-enclosed bus bars apply in setting a design temperature limit [3]. A 104°F (40°C) ambient temperature is the usual baseline. According to ANSI guidelines, the following applies (see Table 8-1).

**Table 8-1**
**Isolated Phase Bus Enclosure Temperature Limits**

| | Rise | Max |
|---|---|---|
| Inaccessible areas | 158°F (70°C) | 230°F (110°C) |
| Accessible areas | 104°F (40°C) | 176°F (80°C) |

Forced air flow cooling systems are custom-designed to keep temperature profiles within acceptable limits. The center enclosure produces the most heat and is usually provided the most air flow.

Enclosure hot spots can occur on the outside phase, near the cooling air return, at the generator bushings, or at the main transformer bushings. In-service, infrared (IR) inspection of an entire bus is a well-proven method of detecting enclosure hot spots and the heating of adjacent supports from stray circulating currents.

Changes in these patterns can indicate deterioration and warrant additional investigation. Enclosure color and thermal emissivity are important. Outside the plant, direct sunlight can easily add 27°F (15°C) to enclosure temperatures. Changing from a matte dark gray to glossy white paint has been successful in reducing summertime temperatures by 18°F (10°C). Paint discoloration or peeling can also indicate that temperatures exist that are higher than anticipated. All aluminum surfaces should be painted to reduce corrosion and provide the thermal emissivity desired.

## 8.2 Conductor

Coaxial construction with thick-wall aluminum pipe as a center conductor is the most common arrangement. A copper box beam or a pair of channels, either copper or aluminum, have also been successfully used as a center conductor. Most suppliers used the EC (a pure grade of aluminum with high electrical conductivity, Aluminum 1350) soft aluminum or a harder alloy with 60% conductivity, such as Alloy 6101. An ambient temperature of 104°F (40°C) is the normal starting point of most standards, such as ANSI C37.20, BS 159:1957 or International Electrotechnical Commission (IEC) Publication 694. In the ANSI guidelines, the temperature limits in Table 8-2 apply.

**Table 8-2**
**Isolated Phase Bus Enclosure Temperature Limits**

| | Rise | Max |
|---|---|---|
| Aluminum-to-aluminum joints, plain | 86°F (30°C) | 158°F (70°C) |
| Aluminum-to-aluminum joints, plated | 149°F (65°C) | 221°F (105°C) |

Both tin and silver plating have been used for this application. Silver plating on all surfaces is the preferred treatment [4]. Both bolted joint surfaces must be plated for the higher temperature rating. If only one surface is plated, then the lower temperature limit is applicable.

## 8.3 Monitoring

Direct conductor temperature measurement is difficult because these surfaces operate from 8000 to 15,000 V above ground. Non-contact IR devices are available. However, some units are equipped with contact disk thermometers, which are attached to the bus conductors and viewable through inspection glass windows.

Thermal emissivity of the conductor surface can affect readings. A dull, flat black surface has an emissivity of 1.0 while a typical painted aluminum conductor ranges from 0.90 to 0.95. Polished aluminum can exhibit an emissivity as low as 0.14.

Non-contact IR devices are available. An IR transparent window to the conductor is also desired. Modern IR non-contact temperature devices can often compensate for both issues and provide acceptable accuracy.

Surface-mounted bimetal circular scale thermometers have been successfully applied at many locations. Vibration may limit service life to a few years, but some have been reported to be in service for 25 years or longer. Temperature-sensitive or color-changing paints and labels are very effective when a maximum in-service temperature is desired. Sophisticated systems operating through fiber-optics or other data transfer methods such as radio frequency (RF) and IR have been proposed and built, but few have been installed as permanent monitoring devices.

## 8.4 Insulators

Older designs use wet process porcelain post insulators. Newer designs can use organic-based materials such as a filled epoxy. A thermal limit for porcelain construction is around 257°F (125°C). Above this temperature, thermal expansion of the iron fittings can crack the portland cement grout or fracture the porcelain itself. Epoxy-based insulators would have an upper temperature limit specified by the manufacturer.

## 8.5 Loss of Cooling

The continuous current rating of a bus is increased with forced air cooling. Loss of bus cooling is a serious event. Over 75% of the heat generated in the system is removed by the forced air-cooling package. Without this energy dissipation, temperatures increase rapidly. Most bus designs have a self-cooled rating that could be as low as 40% of normal operation. Original design specifications can provide this value, or it can be calculated if design details are known [5].

Depending on operating temperature, ambient conditions, and phase current, there can be little time to compensate for total loss of cooling water or air flow. In the summer with full sun, high ambient temperature, and rated phase current, there can be five minutes or less to either reduce load to a self-cooled rating or trip the unit. With winter conditions, overcast sky, cold temperatures, and high winds, more time will be available before damage develops. Cracked insulators, flashover, and failure have occurred when a bus is permitted to operate without cooling.

Heat exchanger efficiency should be monitored. Design conditions for the heat sink (that is, the cooling water system) may require that the temperature of the water leaving the air-to-water heat exchangers not exceed a certain limit (that is, 115°F [46.1°C]) as shown by local temperature indicators). Loss of cooling water and loss of air or water flow must be monitored and alarmed to allow proper operator intervention.

# 9

# BOUNDARY COMPONENTS

The isophase bus has several important components on its boundary that are included here. The bus PTs, the bus CTs, the bus surge or lightning equipment, and the generator neutral bus grounding transformer are all included because there have been several failures, or lost generation attributed to failures, of these components. Transformer and generator bushings were also considered for inclusion, but because they are more intimately associated with the pressure boundary of the transformer and the generator they are not included as boundary components.

## 9.1 Potential Transformers

The metering and regulation PT banks are generally located in housing directly below the generator prior to the isophase fan housing. The PTs are in locked cabinets with sliding rack-out drawers. The connection point to the isophase bus is on the backside of the PT drawer as shown in Figure 9-1. The PT, its secondary wiring, fuses, insulators, and high-voltage or low-voltage sliding contact connections to the isophase bus can all lead to shutdowns or extended outages if not properly maintained. Improper operation or generator over-excitation may result from poor contact between PT fuses and fuse holders.

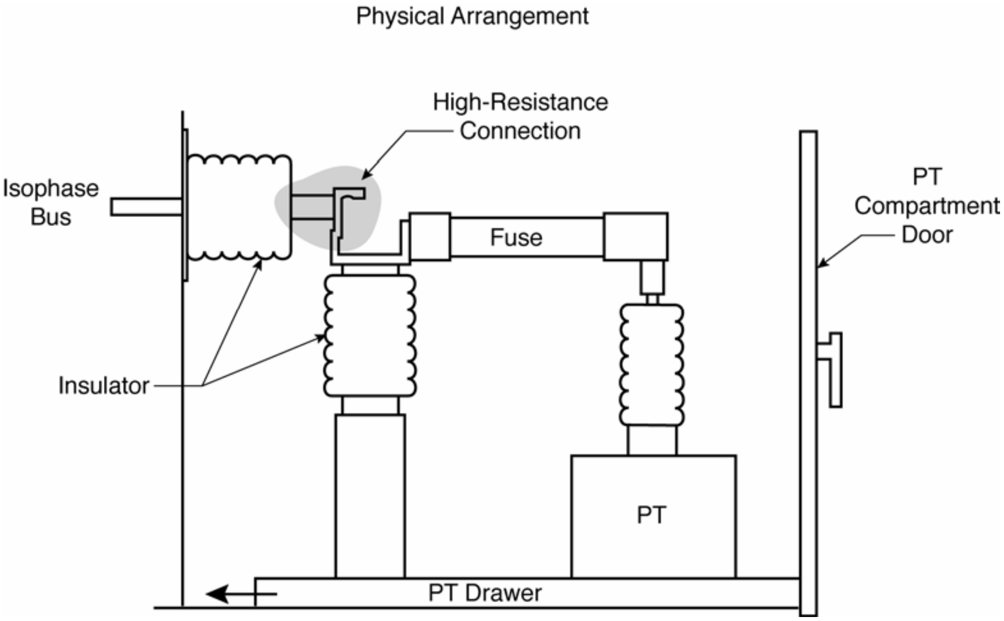

**Figure 9-1**
**Typical PT-to-Isophase Bus Connection**

### 9.1.1 Miscellaneous Components Typically Located Behind PT Cubicles

The PT housing may also include surge suppression and capacitor banks. Because of their static nature, little maintenance, if any, may be given to those components. Utilities should assess the condition and remaining life of the surge suppressors (lightning arresters) and capacitors in the bus and establish preventive maintenance (PM) based on OEM recommendations. Older isophase bus systems may still be equipped with silicon carbide surge arresters. Industry experience provides evidence that silicon carbide arresters can fail explosively. That presents a hazard to both adjacent equipment and personnel, aggravated by the shattering damage of their porcelain housing exposed to the internal fault.

The silicon carbide design uses varistors (nonlinear resistors) made of a bonded silicon carbide placed in series with gaps. The function of the gaps is to isolate the resistors from the normal steady-state system voltage. The unpredictable gap construction cannot guarantee consistency over time of spark-over level and positive clearing after a transient surge.

The silicon carbide lightning arresters typically do not exceed a 20-year life expectancy. Modern metal-oxide varistor (MOV) designs do not require series gaps to isolate the elements from steady-state voltages because the material (zinc oxide) is more nonlinear than silicon carbide, which has a more predictable and consistent non-linearity. Also, a shatterproof insulated housing made of polymer-based epoxy/fiberglass material protects the series disks of zinc oxide. The disks have a conducting layer (generally aluminum) applied to their flat faces to ensure a proper contact and uniform current distribution within the disk.

Older isophase buses may still be equipped with surge capacitors with polychlorinated biphenyls (PCB). PCB is very toxic and persistent in the environment and was banned in 1979. The presence of capacitors with PCB should be investigated, and users should plan for their disposal and replacement with modern components at the earliest convenience.

## 9.2 Current Transformers

CTs are located around the generator neutral bushings. Although they are passive devices, their close proximity to the isophase bus and neutral bus makes them candidates for inclusion. Consideration for operating experience, mechanical connections, and consequence of failure will be evaluated in the maintenance recommendations section (see Section 11).

## 9.3 Neutral Bus and Transformer

Like the isophase bus, the generator neutral connections are made of flexible links connected to make the wye connection of the generator. Because the boundary of the generator is considered to be the neutral bushings and because the operating experience for this equipment is similar in nature from a mechanical standpoint to the isophase bus, we will discuss those failure mechanisms and maintenance recommendations to preclude them in the maintenance recommendations section (see Section 11). The neutral bus may also be equipped with a grounding transformer and associated grounding resistor bank.

# 10

# OPERATING EXPERIENCE

A review of operating experience was performed for events within the last 10 years. Unfortunately, the industry continues to experience issues with many of the subcomponents within the isophase bus system. This is significant because these troubles have led either to plant scrams or to power de-rates to affect repairs. No single area has been a dominant source of the operating experience, but the many of the main issues are discussed in more detail in this section:

- Bus crossover and fan back-draft damper
- Bus terminations (generator, transformer, neutral bus) and inter-bus terminations
- Fan, motor, and cooler
- Ground strap, jumper cables, shorting rings
- Maintenance practices

## 10.1 Bus Crossover and Fan Back-Draft Damper

Forced air flow systems usually have a discharge back-draft damper(s) on the exhaust side of the fan(s), and there are crossover dampers between the center phase and the outside phases on the generator and transformer end. There are many documented operating experiences, recent and historical, attributed to the dampers in the isophase bus system either failing or being found out of position. Normally, the only indication of damper position is an external plate with an indicating arm that swings between the "open" and "closed" position. A synopsis of events associated with dampers is as follows:

- Damper vanes or linkage arm failure due to fatigue of the vane material/weld because of non-robust damper design: Another cause of damper vane failure is fatigue resulting from increased windage/turbulence as a result of a design modification to increase system heat removal for extended power uprate. Worst-case failures have resulted in generator trip on neutral/ground protection (fan and crossover dampers). Other times the dampers were found failed during routine inspection or due to increased bus duct air temperatures.
- Dampers installed incorrectly, providing opposite indication of open/closed direction: Damper indicated open, when really closed, resulting in cooling imbalance between return phases (fan and crossover dampers).
- Dampers vanes left open during outage in cold weather drawing in freezing air, especially in negative pressure plant environments: Water in isophase cooling coils that were not drained froze, resulting in pinhole cooler leaks upon pressurization.

- Dampers repositioned during maintenance/outage and not returned to correct position prior to startup.
- Deionizer grids found so dirty that they either restricted air flow, resulting in elevated temperature of one phase, or dislodged, allowing air to bypass the deionizer grid (which would likely have allowed phase to phase flashover if a fault had occurred in that area).

## 10.2 Bus Terminations (Generator, Transformer, Neutral Bus) and Inter-Bus Terminations

Issues have been identified from operating experience review for all of the flexible link connections in the isophase bus. There are links between the isophase bus and the generator phase lead bushings, isophase bus and the low-voltage transformer bushings, neutral bus connections, and between sections of the isophase bus itself. Issues include the following:

- A loose connection in the neutral bus flexible link resulted in a hot spot that required removal of the unit from service to repair.
- Cracked laminations of leaf-style flexible links attributed to fatigue, higher than normal generator vibration, age, and design have been identified during routine inspection and post-scram investigations.
- Cracked bronze bolts due to repetitive over-torque to stainless steel bolt values.
- Creep/cold flow of bolt holes due to repeated torquing.
- Over-torquing or under-torquing of electrical connections.
- Broken/damaged braided flexible links.
- Deterioration of silver or tin plating on bolted joints.
- Loose connections that cannot be easily inspected due to poor access.
- Loose connections due to improper hardware/mismatch of flat and Belleville washers.
- Loose connection due to change in orientation of the flexible link.
- Incorrect installation of insulating parts, or use of undersized insulating parts that results in burning/sparking damage inside the generator lead/neutral box.

These issues have resulted in generator trips or plant scrams on neutral/ground relay actuation, power reductions to repair high-resistance connections, and localized overheating of bus connections. In one case where the unit scrammed on neutral/ground relay actuation, the entire isophase bus duct was robotically inspected to identify any other foreign material present and ultimately the failed bus connector link that had delaminated.

## 10.3 Fan, Motor, and Coolers

The operating experience of the cooling supply units is not atypical of other duct-enclosed fans and coolers. These experiences include:

- Fan belts, which are made up of conductive material, sucked into the duct, creating a ground hazard
- Belt mismatch or misalignment, broken stiffeners, and broken motor mounts, creating vibration issues and bearing failures
- Cooler assembled without head gasket, causing high bypass flow and high duct temperatures during summer months
- Inadequate fan and/or bus heater run time to remove condensation from the bus duct, resulting in failed electrical testing or delaying plant startup

Broken fan belts have found their way into the bus ducts and caused neutral/ground relay actuations, generator trips, and reactor scrams. Load reductions have been required to swap motors, repair fan belts, and maintain bus temperature within thermal limits as a result of these issues.

## 10.4 Ground Straps, Jumper Cables, Insulating Gaskets, and Shorting Rings

The subject items play key roles in the proper operation of the bus design. Failure of any of these subcomponents often results in hot spots, localized heating, and, in the worst case, a fire. Recent problems and causes include:

- Current imbalance in the jumper cables due to unequal jumper length and torque issues with heli-coil inserts resulted in a variance in current distribution between 100 and 950 amperes (normal expected value is 340 amperes).
- Current imbalance in jumper cables caused by a high-resistance connection due to poor mechanical connection resulted in jumper cables failing and catching fire due to exceeding the current rating of cables.
- Ground strap on one phase of the generator end of the isophase bus melted due to a poor mechanical connection, which resulted in a high-resistance connection. Localized heating caused a loss of gasket seal and loss of pressure boundary for the isophase air flow.
- Localized heating due to the wrong size insulating board between the isophase bus and the low-voltage bushing flange at the generator step-up (GSU).
- Misalignment of the GSU bushing box to the isophase duct resulted in many mounting bolt insulated sleeve failures. The GSU sidewall acted as a shorting plate, resulting in melting of all affected mounting bolts.
- The duct aluminum leaf-type jumper bolted connection failed mechanically, resulting in jumpers melting and adjacent supporting steel beam overheating due to duct inter-phase duct shorting currents.

When dealing with parallel current paths, it is useful to remember that overheated sections are carrying higher load than the cooler sections (with higher resistance connections). The connections that appear to be cooler are the ones that require tightening.

## 10.5 Maintenance Practices

Poor maintenance practices, human performance errors, and a lack of knowledgeable oversight have been the initiators of isophase bus-related events. The lack of sound bolting practices, peer checking, and understanding of the consequences of actions associated with working on and around the isophase bus has resulted in the following events:

- Arcing between scaffolding and the isophase bus during scaffold removal with the unit at power resulted in the unit being removed from service.
- Fan belts left behind after maintenance to replace the belts were sucked into the bus duct and caused a unit trip on neutral overcurrent because the fan belts were conductive material.
- Contractors without proper oversight made a poor ground strap connection using incorrect nuts, washers, and bolting that started arcing when in-service, requiring unit shutdown to repair.
- Worker received static discharge from isophase bus following electrical testing of the bus due to improper grounding practices.
- High bus duct temperature discovered during system engineer walkdown identified a crossover damper on the generator end of the machine that was fully closed, even though procedural guidance to verify damper position by maintenance during the previous outage had been signed off.
- Contractors installing cable tray during an outage attached the mounting brackets across the three isophase ducts, creating a shorting plate. Walkdowns before startup found the error.

## 10.6 Physical Deterioration

On early designs, insulation deterioration proved to be a significant maintenance problem. Materials available to designers 40 years ago were very limited in performance. Stray currents in adjacent structures and pipes and through floors can be expected. Very high temperatures result when two or more enclosures short together. There are often scores of insulating sleeves, washers, and bushings of cotton-based material used at the enclosure supports for electrical insulation. Voltages are low (30 V or less), so failure is usually thermal/mechanical in nature. Deterioration of bolted connections follows the same pattern.

Deterioration of a high current bus usually follows an exponential curve. Many years of slow decline are followed by months of rapid disintegration, culminating in failure. If periodic inspections and maintenance are performed, service life can be unlimited.

As with any system, some areas deteriorate faster than others. Each bus design is unique, depending on the voltage, current rating, cooling package, length, and manufacturer. The following list is generic and includes problem areas from various manufacturers. Some examples of physical deterioration include:

- Crumbling, cracking, and hardening of gaskets on inspection doors, permitting water to enter the bus and/or air to escape on forced air flow systems
- Deterioration of rubber expansion joints (boots) from heat and ultraviolet (UV) exposure
- Peeling and flaking of paint, exposing bare aluminum and resulting in higher temperatures
- Corrosion, loosening, and overheating of bolted connections
- Drain holes filling with dirt, permitting water accumulation

Understanding the causes of operating event experience and correcting those causes, combined with proper life cycle management refurbishments, will help to better ensure a more event-free future for this system.

# 11

# MAINTENANCE

The maintenance strategy for the isophase bus system must combine trending of key operating parameters, routine internal and external inspections, and consideration for age-related/life cycle management of subcomponents. This may require subcomponent refurbishment or replacement to meet the desired operating life of the plant (including license extensions up to 60 years). The review of operating experience indicates that the current conduct of maintenance has not been able to prevent numerous downpowers, removal of units from service, or generator trips due to problems with this system. The following sections will provide recommendations and guidance for improving and/or maintaining the reliability of the system.

## 11.1 Safety

Operating experience contains several significant near-misses for work being performed on and around the isophase bus while in service and out of service. While in service, the isophase bus carries upward of 30,000 amperes output from a nominal 20-kV generator. Electrical theory indicates that a conductor within the range of the magnetic field has the potential to become a lethal source of energy. Working in the vicinity of the isophase bus requires an understanding that personnel consider the isophase bus and the bus duct as a current-carrying conductor in a magnetic field. Any new conductor within close proximity to the bus has the potential to carry an induced current, and the use of personnel protective gear and proper grounding is required. At no time should a metal object or person be positioned between phases of the isophase bus because of the high magnetic field between phases.

The two safety areas of concern for off-line isophase bus work are grounding practices and energy injection. Prior to starting work, PTs should be isolated by pulling the fuses. Electrical testing is often required on either end of the isophase bus (generator and GSU transformer) and on the bus itself. Grounds are often repositioned to allow testing to occur and not interfere with other work. Workers need to diligently monitor for changes in safe work clearances and employ test before touch when working on the electrical portions of the system. Additionally, proper grounding of equipment following energy injection to the Institute of Electrical and Electronics Engineers (IEEE) recommended durations is required to remove any residual charge from the generator, transformer, or bus conductors themselves prior to moving grounds or reconnecting the bus links to prevent the chance of electrical shock.

Isophase bus grounds rarely have enough current-carrying capability to protect against inadvertent back-energization from the system. Proper isophase grounding will require that adequate grounds also be placed on the high-voltage side of the GSU transformer.

Finally, portions of the isophase duct enclosure can be defined as a confined space. Confined space entries must comply with approved procedures.

## 11.2 On-Line Visual Inspection, Predictive Maintenance, and Performance Monitoring

The routine, periodic collection of visual observations by operators, predictive maintenance data collectors, maintenance, and system engineers, as well as the collection of vibration data, thermography rounds, bus temperatures, and discharge air temperature, are the key inputs into a robust system monitoring plan.

### *11.2.1 Visual Inspections*

Visual inspection by operations should include in-plant and outside-plant inspections. In-plant inspections should focus on recording available performance data (air temperatures, bus temperatures and duct temperatures) for trending by the system engineer. Visual inspection of the fan plenum should include changes in audible noise levels, water leaks, change in structural vibration, blistering or peeling of paint, and any signs of overheating. Operator rounds should be performed optimally once per shift and daily at a minimum.

System engineer walkdowns should be performed at a minimum of once per month but more frequently during peak operating periods and periods of high ambient temperature. Engineering walkdowns are done with more of a focus on long-term system health and configuration management. Key performance parameters and physical conditions should be checked, but the overall material condition, presence of temporary structures (such as scaffolding) that could cause an operating or safety hazard, and recording and verification of all equipment deficiency tags should also be included. If accessible, crossover damper position should be verified.

Predictive maintenance data collectors should be sure to include visual observations and related performance parameters while collecting vibration and thermography data. Items such as plant output, equipment line-up, local ambient temperature, operating temperatures (bus, duct, and air) may be required to properly diagnose anomalies.

Outside-plant inspections should be performed, and the use of binoculars is highly recommended. Operator rounds should be used to collect and record bus temperatures for trending by the system engineer. Visual inspection of the bus duct should include support structures, expansion gasket/bellows, flexible bus jumpers and split covers (as applicable), the isophase bus to GSU transformer low-voltage bushing compartment, and ground connections. Conditions that should be noted are peeling/blistering paint, crumbling/cracking of gaskets (from age or UV light exposure), corrosion/rust or other signs of water intrusion, indications of overheating of flexible conductors, overheating of gasket for corrosion (external signs of water intrusion), damage to structural supports, and bird nesting. Outside operator rounds should be performed optimally daily and weekly at a minimum.

### 11.2.2 Performance Monitoring

The system engineer should create a system monitoring plan in accordance with the guidance set forth in *Guideline for System Monitoring by System Engineers* (EPRI report TR-107668) if a plan does not already exist. Trending of bus temperatures, duct temperatures, and fan discharge temperature can provide indications of problems, including position change or failure of a damper, cooler fouling or bypass, or bus overheating. System instrumentation is somewhat basic and can be supplemented by use of data loggers to record temperatures in areas not originally instrumented.

### 11.2.3 Vibration

Predictive maintenance technologies applied to the system are vibration thermography and partial discharge. Access to the fans and motors may be an issue on some designs, but operating experience indicates that sufficient industry-related problems (downpowers or unplanned shutdowns) could justify using permanently installed probes or the use of wireless technology to gather vibration data. Routine vibration data should be collected between 60 and 90 days. Based on the failure history over the last 10 years, vibration severity criteria should not rely on overall values but should assign alert and alarm levels for bearing fault frequencies, fan belt and sheave fault frequencies, and structural bands. Fan run time should be equalized by operations to assist in data collection and to ensure reliability of both trains.

### 11.2.4 Thermography

IR scanning should be performed twice a year, once with a high ambient temperature and once with a low ambient temperature. In addition, following an outage after the unit has reached full electric output, a survey should be performed to ensure that there are no air cooling issues that resulted from work performed or system realignment during the outage.

Inside, the plant IR thermography can be performed at any time. Outside inspections should not be done if there is direct sunlight on the bus. Solar radiation will result in false indications. Data collection is best performed at dawn, at dusk, or during an overcast day to obtain accurate data.

These surveys are best performed when bus current is at a maximum. Overheating is increased as a square of the current. Usually maximum megawatt and megavar loading coincide with both ambient temperature extremes.

Severity criteria should be established for alert and alarm value. These values should be based on temperature rise of the material involved. For example, if the design maximum temperature for the bus duct is 230°F (110°C), a reading above that value should be considered the alarm point and marked for a detailed visual inspection and possible repairs. Internal areas that have overheated connections (heating that is not a direct measurement of the heated surface, but heating of the air and materials around the actual source of heat) must be carefully evaluated because the measured heating is often a fraction of the source temperature.

Burnt or chalked paint is always a positive sign that operating temperatures are too high and a corrective action is needed. Differential heating on the air return path or between the generator side and the unit step-up transformer side is an indication of improper damper position, which can be caused by crossover damper position movement or crossover damper failure. Inspection of crossover dampers and changes to damper position are best performed off-line. Crossover damper position changes made on-line must be performed with contingency actions to reduce load quickly if cooling is lost due to damper closure and being unable to restore cooling within the timeframe allowed by the manufacturer to operate without forced air cooling.

Some examples of items identified by thermography on the isophase bus follow.

Figure 11-1 shows a thermal image of a GSU transformer that highlights an area of the transformer surface where a temperature of 250ºF (121°C) is measured. The corresponding visual image is shown. This specific area is where the isolated phase bus duct enters the low-voltage bushing compartment of the transformer. The 250ºF (121°C) temperature is excessive, especially considering the ambient air temperature of 45ºF (7.2°C). Another thermal image of the same location, taken from a different angle, is presented in Figure 11-2. This image was taken from directly below the isophase. A careful inspection of the visual image reveals oil stains on the flanges of the compartment that are probably caused by oil leakage from within. The low-side transformer bushing would have to be generating a significant amount of heat in order to cause the compartment surface to reach this extreme temperature on such a cool day.

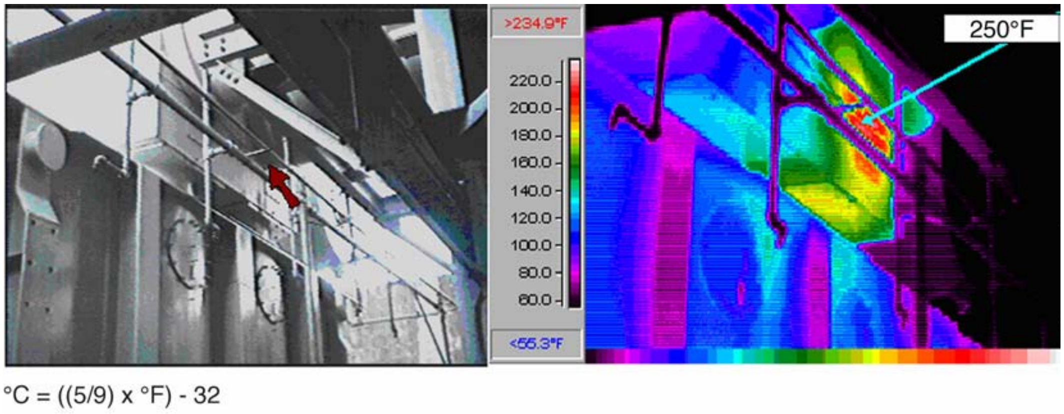

**Figure 11-1**
**Visual and Thermal IR Images of the Isophase/GSU Transformer Connection Area**

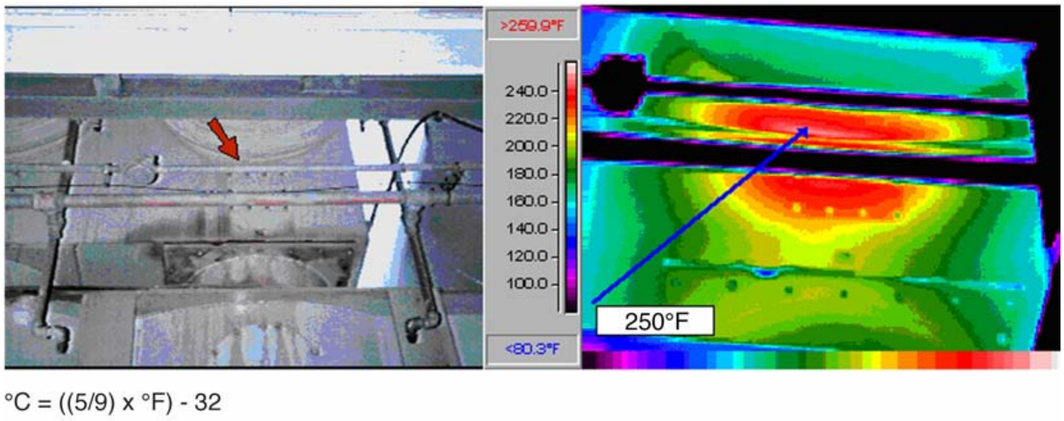

**Figure 11-2**
**Images Captured from Directly Below the Anomaly (Note the oil leakage in the visual image.)**

A decision was made to remove the unit from service in an effort to avoid a catastrophic failure of the transformer. An investigation of the bushing compartment revealed that the bushing and the surrounding components had sustained significant damage. Temperatures within the compartment had been hot enough to cause the component to begin to melt. Pictures of pieces of the damaged components are shown in Figure 11-3.

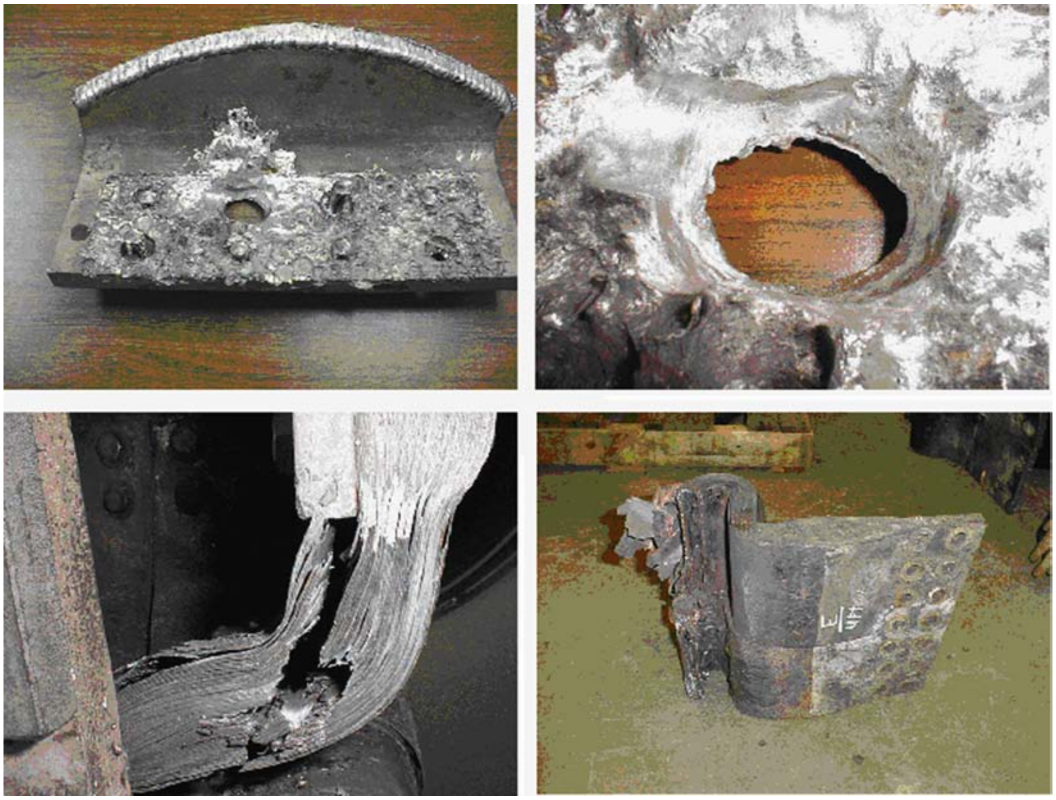

**Figure 11-3**
**Damage to Connections Between the Isophase Bus and Low-Voltage Bushing**

Many connection and insulation issues can be readily identified using IR thermography (see Figures 11-4 through 11-6).

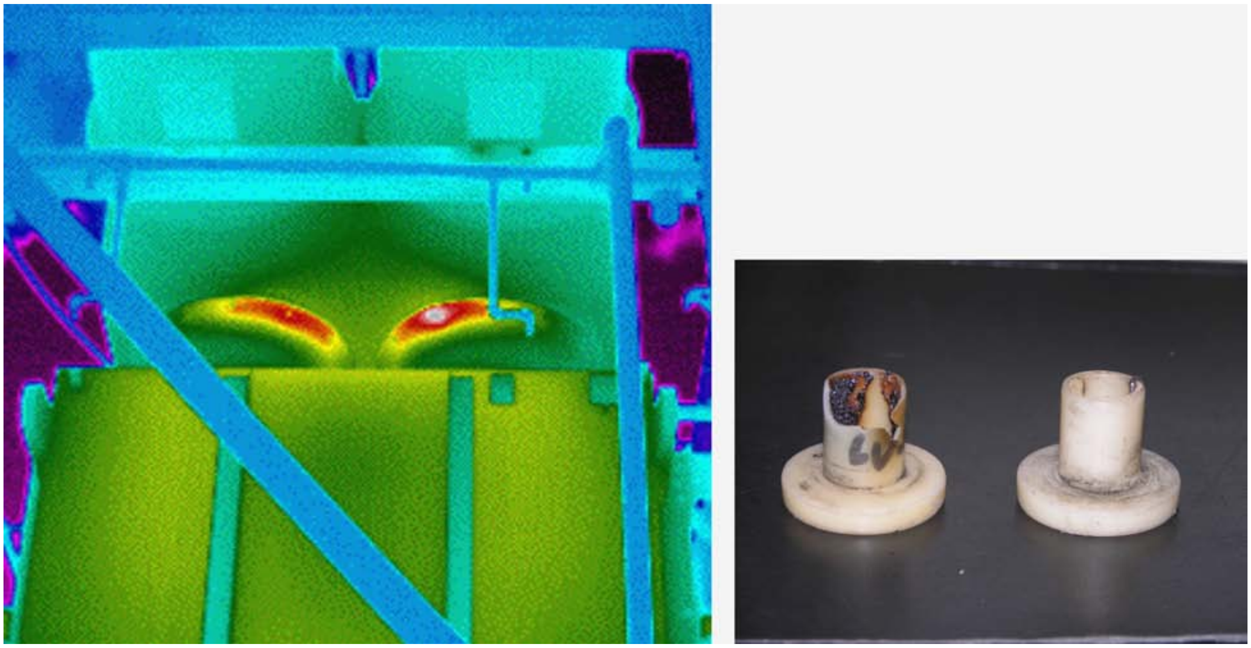

**Figure 11-4**
**Inductive Heating Between Low-Voltage Bushings on One Phase of the GSU Transformer (Note the bolt heating on the right side of the enclosure and damaged insulator found during the next outage.)**

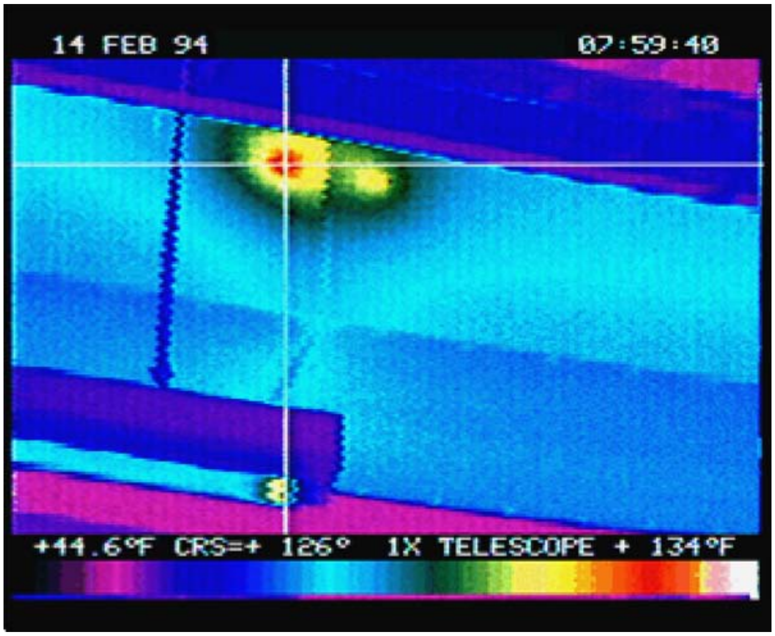

**Figure 11-5**
**Overheating Caused by a Loose Ground Strap**

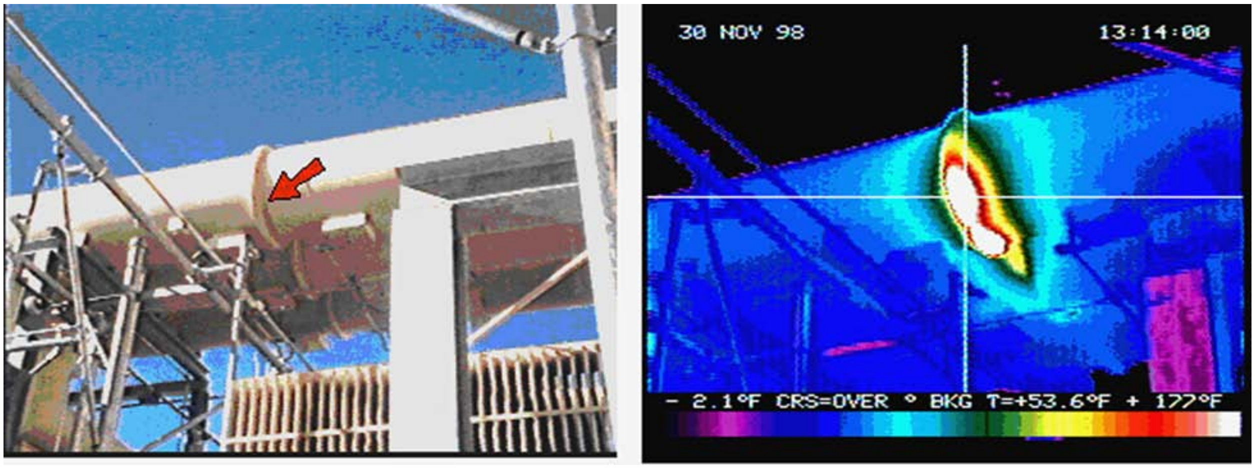

**Figure 11-6**
**Overheating at the Bus Section Joint**

As can be seen by Figures 11-4 through 11-6, thermography is an effective tool for finding various degradation mechanisms that can occur on the isophase bus duct. Whether the problem is caused by inductive heating, insulation breakdown, or loose connections, it can be readily identified. Even connections within the bus duct that are indirect indications of overheating can be picked up. Therefore, the need for costly IR windows is not required or recommended. Additionally, IR windows are not weather resistant and would not hold up well in outside environments. The use of IR windows to gather bus temperatures or monitor the bolted connections of the links between the bus and the transformer bushings, while providing valuable data, would become an expensive, high-maintenance item.

### *11.2.5 Partial Discharge*

Isolated phase, air-insulated buses are a notorious source of partial discharge activity. Contaminated or cracked insulators, loose hardware, and slip-fit bus supports can generate high levels of electromagnetic interference (EMI) over a wide range of frequencies above 50 MHz. Progress has been made in the application of partial discharge monitoring with high-voltage, gas-insulated substations over the past decade in Canada, Japan, and Switzerland.

There has been very little activity in developing a continuous monitor for the air-insulated bus. One reason is that most partial discharge activity in the isolated phase bus does not always result in additional deterioration. Active sources can be trended for many years. No bus is free of EMI, but a strong source indicates that a problem has developed that should be investigated. The on-line EMI spectrum analysis of a generator has been effective in detecting partial discharge sources in the adjacent isolated phase bus.

### *11.2.6 Acoustics*

Acoustics has been used primarily as a troubleshooting tool, but it can also be used for periodic monitoring. In regard to the isophase bus, acoustics can be used to locate tracking or arcing that is occurring. Filtering for frequencies greater than 25 MHz is recommended for this type of discharge. Due to the thickness of the bus enclosure, it is likely that the contact probe will be required; thus some locations may be inaccessible without a scaffold, ladder, or man-lift of some type. Of course, proper grounding and other safety precautions must be considered when placing conductive materials in proximity to the bus. Figure 11-7 shows the proper technique for acoustic monitoring on the bus.

**Figure 11-7**
**Proper Technique for Monitoring Isophase Bus with an Acoustic Contact Probe**

In addition to electrical discharges, acoustic monitoring of the fan enclosure in the low-frequency range may be useful in identifying mechanical damage such as back draft damper degradation.

## 11.3 Off-Line Periodic Inspections

Many external areas can be inspected during operation. Internal components, however, must be inspected when a bus is out of service. These inspections are the most difficult to schedule due to a high demand for resources during scheduled outages. The entire bus, inside and out, should be visually inspected every 7 to 10 years. Even if no bus problems have been noted in the past, there is no assurance that trouble-free operation can be expected in the future.

Internal inspections are critical but must be scheduled to coincide with other important activities during those brief periods when a bus is out of service, such as GSU transformer and generator testing. With ever-increasing pressure to shorten outages and reduce resources, a limited internal inspection, occurring every few years, might be all that can be scheduled. Performing an inspection on different sections can be scheduled during every outage so that the entire bus is inspected within the recommended timeframe.

### 11.3.1 Foreign Material Exclusion

After safety, the next important consideration of maintenance of the isophase bus is foreign material exclusion (FME). FME has been cited as a cause of numerous operating experiences. Therefore, finding FME and preventing FME issues from being generated by poor maintenance controls are keys to success. Control of tools and material that is taken in or brought out of the bus should be logged. Unexpected FME items found in the bus during inspection shall be removed and evaluated in the corrective action program. The time that inspection covers are open should be minimized to prevent exposure to dirt and moisture. The generator bushing box, transformer doghouse (low-voltage bushing box), and fan cooler housing should all be covered under the FME controls.

### 11.3.2 Use of Robotics for Internal Bus Inspections

Poor access to the internal bus duct to perform adequate visual inspections has been problematic. Access covers are often too small to allow for direct visual observation of a given bus section. The current state of small robotic roving devices, as shown in Figure 11-8, with high-quality optics provides a means to perform much better visual inspections than are possible by use of direct observation, telescopic mirrors, or flexible borescopes. It is also possible to record the inspection to allow review at a later date if needed.

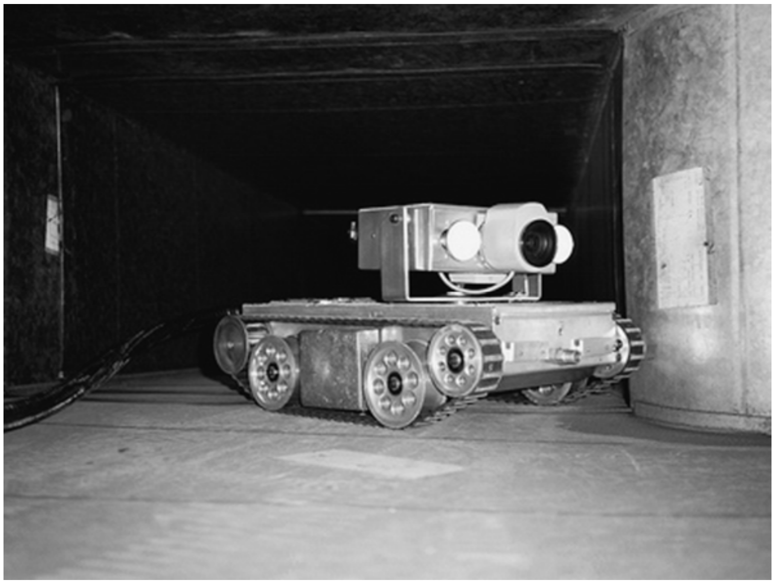

**Figure 11-8**
**Robotic Walkers Are Ideal for Performing and Recording Visual Inspections in Isophase Buses with Limited-Sized Inspection Covers**

### *11.3.3 Maintenance Task and Frequencies*

The routine and regular maintenance activities shown in Tables 11-1 through 11-5 identify an effective maintenance program that considers bus stressors and degradation mechanisms that deteriorate the bus components. These maintenance tasks can be used or modified according to specific equipment installations, site operating experience, and maintenance history.

**Table 11-1**
**Maintenance Recommendations for Isophase Bus Duct and Bus Enclosure**

| Equipment | Visual Inspection | Inspection Frequencies | Tests |
|---|---|---|---|
| Bus duct (general) | General appearance of the non-segregated bus duct and its associated systems (preservation, cleaning, and debris). | Every major maintenance outage | As a general guideline, micro-ohm test all ground connections using a 100-amperes tester. Disassemble and clean any connection greater than 200 micro-ohms. Other test acceptance criteria may be used based on in-house experience or OEM recommendation. |
| | Proper clearance from all adjacent structures and equipment (permanent and temporary). | | |
| | Proper connection between the bus duct enclosure and ground contact assembly and ground. | | |
| | Proper bracing, suspension alignment, and evidence of damage to any of the bus duct structural supports. | | |
| | Make-up air filter integrity and cleanliness. | Monthly | Clean/replace as needed. |
| Bus enclosure | Exterior general cleanliness and wildlife intrusion and/or nesting. | Whenever disturbed for other maintenance, one-third of bus every major maintenance outage, or every 7 to 10 years | Consider the use of a robotic device to inspect the bus. Robotics have proved helpful in locating FME items that may be difficult to observe directly due to space limitations of inspection hatches.<br>Micro-ohm test all ground connections using a 100-amperes tester. Disassemble and clean any connection greater than 200 micro-ohms. Other test acceptance criteria may be used based on in-house practice or OEM recommendation. |
| | Interior cleanliness (free from moisture, dust, or foreign materials). | | |
| | Proper mounting of the bus enclosure inspection covers, including fastener/fastener sealing washer arrangement and tightness. | | |
| | Evidence of moisture/water coming from the inspection cover gasket area or standing water. | | |
| | Degradation of the inspection cover gasket. | | |
| | Proper mounting of all duct flange boiling assemblies, including fastener, gasket, and fastener tightness. | | |
| | Proper installation and alignment of bus duct drain connections. | | |
| | Proper posting of the requirements to access the bus duct through each inspection cover. | | |
| | Cracking of the enclosure walls. | | |
| | Damaged and/or missing nut retainers. | | |
| | Inspection of the bus crossover deionizer screens (clean/repair/replace as required). | | |
| | Inspection of the bus crossover damper louvers, actuator arm, and linkages for overall integrity (repair/replace as required). | | |
| | Micro-ohm testing of all ground connections (disassemble, clean, and retest as required). | | |

**Table 11-2**
**Maintenance Recommendations for Isophase Bus Stand-Off Insulators**

| Equipment | Visual Inspection | Frequency | Test |
|---|---|---|---|
| Stand-off insulators | Evidence of porcelain chipping, cracking, arcing, flaking, missing hardware, cleanliness, or other physical damage. | Whenever disturbed for other maintenance, one-third of bus every major maintenance outage, or every 7 to 10 years | Perform insulation resistance tests during major maintenance outages or every 7 to 10 years. Perform tests before returning equipment to service.<br>High-potential tests may be necessary when repair or replacement of parts/components has been performed. Consult vendor manuals or vendor for high-potential test values. High-potential values after initial installation and during maintenance tests should be at reduced voltages from acceptance tests. |
| | Evidence of shearing or twisting of insulators that supports the bus at or near 90-degree bends due to thermal expansion and torsional stress. | | |
| | Evidence of corrosion or discoloration due to heating. | | |
| | Proper tightness of stand-off insulator electrical connections. | | |
| | Proper tightness of stand-off insulator mounting hardware. | | |
| | Proper operation of sliding-type bus supports and integrity of associated ground/bleed wires. | | |
| | Proper stand-off insulator washer compression. | | |
| | Inspection and recording of serial numbers of all stand-off insulators. | | |

**Table 11-3**
**Maintenance Recommendations for Isophase Bus Conductors**

| Equipment | Visual Inspection | Frequency | Test |
|---|---|---|---|
| Bus conductors<br>(includes neutral bus) | Evidence of blistering, peeling, wear, or damage of silver plating on rigid and flexible connections. | Whenever disturbed for other maintenance, one-third of bus every major maintenance outage, or every 7 to 10 years | Perform insulation resistance tests during major maintenance outages or every 7 to 10 years. Perform tests before returning equipment to service.<br>High-potential tests may be necessary when repair or replacement of parts/components has been performed. Consult vendor manuals or vendor for high-potential test values. High-potential values after initial installation and during maintenance tests should be at reduced voltages from acceptance tests.<br>Consider the use of a robotic device to inspect the bus. Robotics have proved helpful assisting in visual inspection of insulators, flexible links, and so on that may be difficult to observe directly due to space limitations of inspection hatches.<br>Laminate-type flexible links should be dye-penetrant-tested for cracks. |
| | Evidence of corrosion (typically as greenish deposit on copper) or discoloration (typically from overheating) at each of the following:<br>• Bus work-to-bus work connections<br>• Bus work-to-transformer bushing connections<br>• Bus work-to-disconnect link connections<br>• Bus work-to-metering and relaying connections<br>• Bus work-to-stand-off insulator connections | | |
| | Evidence of cracking at tab welds of laminated links, if used. | | |
| | Evidence of fraying (small barbs of wire or “fish hooks”) at the bend areas of the flexible connectors. | | |
| | Evidence of material fatigue (that is, broken, cracked, or deformed hardware). | | |
| | Proper alignment at all bus connections. | | |
| | Evidence of contamination (that is, dust, oil, and water). | | |
| | Proper tightness of bus work electrical connections, including washer compression and development of severe cold flow and creep at bolted aluminum joints at each of the following:<br>• Bus work-to-bus work connections<br>• Bus work-to-transformer connections<br>• Bus work-to-disconnect link connections<br>• Bus work-to-metering and relaying connections | | |
| | Proper clearance between the bus work and the bus enclosure. | | |
| | Main power transformer low-voltage bushing compartment crossover duct mounting bolts exhibiting discoloration due to overheating from carrying magnetic shielding currents. | | |
| | Proper installation of bus section flash band taping. | | |

**Table 11-4**
**Maintenance Recommendations for Expansion Joints, Boots, and Auxiliary Power Transformer Secondary Side Bushings**

| Equipment | Visual Inspection | Frequency | Test |
|---|---|---|---|
| Auxiliary power transformer secondary bushing enclosure | Inspect secondary bushing connections to segregated or non-segregated bus duct for evidence of oil leakage from gasket deterioration or excessive transformer vibration. | Whenever disturbed for other maintenance or every 7 to 10 years<br>Replace bushing gaskets as required | Perform a power factor test. Trend results (threshold below 1%). |
| Current transformers | Inspect CT and housing for signs of overheating, such as cracks, blisters, or discoloration.<br>Verify that the conduit connecting the CT secondary lead boxes is either non-metallic or non-magnetic. Magnetic conduit may overheat due to induced currents and degrade the wiring insulation. | Every major maintenance outage, if accessible | Perform an insulation resistance test, turns ratio test, and excitation test not to exceed every 5 years. |
| | Verify turns ratio. | Every 7 to 10 years | Perform a turns ratio test. |
| Rubber expansion boots | Inspect for material condition, dryness, cracks, or signs of air leakage. | Whenever disturbed for other maintenance or every 7 to 10 years | N/A |
| Expansion joints | Inspect for material condition.<br>Inspect welded connections for cracking of flexible metal leaves or welds.<br>Inspect bolted connections for overheating, corrosion, and proper torque values. | One-third of bus every major maintenance outage or every 7 to 10 years | N/A |

**Table 11-5**
**Maintenance Recommendations for Isophase Cooling System and Fire Barriers**

| Equipment | Visual Inspection | Frequency | Test |
|---|---|---|---|
| Cooling system | Inspect cooling equipment for the following:<br>• Water leaks from cooling coils and standing water<br>• Condition of backdraft damper and position arm locking mechanism<br>• Corrosion or other deterioration, including debris in the tubes or fins<br>• Fan impeller for proper operation, alignment, and belt wear, including cracking, fraying, or looseness and material condition<br>• Fan/motor bearing condition<br>• Temperature instrument calibration and loop checks and alarm functional checks<br>• Sump-well-level switch operation<br>• Cooler isolation valve tightness<br>• Make-up air filter condition/signs of air in-leakage or out-leakage<br>• NDE heat exchangers | Every major maintenance outage<br>Review vendor recommendations for cooling coil maintenance | Perform an air or hydro pressure test. |
| Fire barriers and wall/floor | Inspect for material condition, dryness, or cracks. | During major maintenance outage or every 7 to 10 years; replace every 15 years | N/A |
| Generator PTs | Check PT connection to isophase bus for signs of corrosion and overheating.<br>Inspect fuse clip and secondary contact alignment and silvered connections.<br>Inspect sliding ground contact and bus.<br>Inspect all mechanical and electrical connections. | Every major maintenance outage<br>OEM recommendation for periodic replacement | Check the secondary burden resistance "PT continuity check" with fuses removed.<br>Take voltage readings at the secondary side while on-line. |
| | Inspect/replace PT fuses. | | Check tightness between fuse and fuse holders. |
| | Verify turns ratio. | Every 7 to 10 years | Perform a turns ratio test. |

## 11.4 Testing

Evaluation of an isophase bus system to determine suitability for service is performed both on-line and while out of service. Partial discharge tests can be applied only during operation. Most other tests must be scheduled for off-line application. A few, such as an overpotential test (HI-POT), are infrequently used. Others, such as an insulation resistance test, are often applied before a bus is returned to service at the end of each outage.

### *11.4.1 Insulation Resistance*

An insulation resistance or Megger test should be a routine evaluation applied before a bus is returned to service. If a bus is isolated from the generator, a 2500-Vdc applied voltage will develop readings of over 1000 megohms when insulators are dry and clean. When a bus is long (over 328 ft [100 m]) or insulators are dirty and moisture is present, readings can be much lower.

A typical criterion for deciding if a bus is safe to energize is an insulation resistance between bus and ground of “1 megohm per rated kV plus 1 megohm” or greater. For instance, a 22-kV installation will have an acceptance criteria of 23 megohms or greater during a 2500-V Megger test. Insulation values below this value should be carefully investigated. If a generator is connected to the bus, the machine insulation resistance will determine readings. With water-cooled stators, resistance values will be very low due to the numerous paths to ground through stator bar water hoses. Values below 10,000 ohms have been measured on 26-kV systems when all three phases were parallel and bus, transformers, and generators were connected.

The polarization index (PI) is a useful indicator of the integrity of the bus insulation system. It is defined as the ratio between a 1-minute and a 10-minute Megger reading. Typically, a PI value close to unity suggests the presence of a heavily dirty or wet bus while values closer to (or greater than) 2.0 are suggestive of dry and clean bus insulation system. The use of dehumidifiers in isophase buses during scheduled outages will minimize the probability of unsatisfactory Megger and/or PI readings prior to unit restart.

### *11.4.2 Continuity*

Low-resistance connections are required with a high-current bus. Measuring these micro-ohm joints is possible but difficult. Trending joint resistance is a good method to track deterioration. Many areas are silver-plated, and contact resistance is, therefore, not directly related to bolting pressure. If an increase in joint resistance is measured, corrective action should be taken during that outage and not be postponed. Continuity of the inner conductor, outer tube, and all expansion joints can be compromised by cracks in the material or at welds. A detailed visual inspection should uncover these defects.

### 11.4.3 Overpotential

ANSI C37.20 provides information on overpotential testing of metal enclosed buses. Due to the use of porcelain insulators, only ac test voltages are recommended: dc tests will not damage the bus, but information provided has little practical significance in determining suitability for service. Most insulators have long creep distance designs and will withstand rated impulse voltage wet or dry.

Maintenance overpotential testing is not generally performed. If a bus fault had occurred or major repairs were completed, an ac overpotential test would be needed. These test values could be either the shop test value or field test value, depending on the extent of repairs and confidence level desired. Table 11-6 provides typical values for the manufacturer and in the field overpotential voltage test values.

**Table 11-6**
**Typical Values Supplied by One Manufacturer**

| Basic Impulse Level (in kV) | Rated Bus (in kV) | Shop Test Value (in kV) | Field Test Value (in kV) |
|---|---|---|---|
| 110 | 14.4 | 50 | 37.5 |
| 150 | 23 | 60 | 45 |

**Note:**
All voltages are root-mean-square (rms) at 60 Hz applied for 1 minute.

If no information is available on the original factory or field-test voltages, twice the rate voltage, applied for 1 minute, can be used to prove suitability for service.

### 11.4.4 Doble Testing

Another widely accepted test is a Doble® test taken at 10 kVac to measure watts loss and power factor. This test is useful in trending, but ambient humidity and temperature may affect results. However, a cracked insulator or general insulator contamination will usually show a significant change in trend results. A significant change from past readings may indicate that cleaning or further visual inspection is required.

# 12
# DETERIORATION AND REPAIRS

## 12.1 Bolting Considerations

### *12.1.1 Internal Bolted Joints*

As stated in Section 10.2, operational experiences due to bolting practices have been a significant contributor to lost megawatts and costly maintenance repairs for this system. High-resistance connections in a high-current-carrying system create thermally damaging overheating conditions. Electromechanical joints, often of dissimilar metals, require special consideration to ensure reliable long-term operation. Causes identified by operating experience point to over-torque of silicon bronze bolting, connections made with inconsistent hardware, not using Belleville washers, severe creep/cold flow of bolt holes, lack of tin or silver plating on mating surfaces, improper use of antioxidants on mating surfaces, restricted access at inspection covers, thermal cycling, high generator vibration, and lack of space to properly torque connections.

Much has been published on the design of high-current bolted joints. Reference [4] in Section 15 of the report provides good basic information. A variety of bolt materials, terminal surfaces, and washer types are employed on bolted joints. Specifics were determined by the experience and test data available to each manufacturer when the original order was placed. When most designs were implemented in the 1970s and 1980s, there was very little operating history with 20,000- to 30,000-ampere bolted joints.

Some designs required modification much sooner than others. Time-related cold flow (creep) of aluminum terminals is a material problem that is developing with some systems after 20 or more years of service. If a copper center conductor is used, creep is not a problem. The terminals are usually silver plated, but in some cases are only cleaned and greased. Bolts, washers, and nuts are frequently made of copper or copper alloy. Thermal expansion is very similar and, once properly torqued, these joints usually need no further attention. Steel bolts have been employed with some designs. The bolts are stretched during assembly. This maintains pressure on the joint during temperature cycling. This technique is successful because the copper does not cold flow away from the source of pressure.

Aluminum is the material of choice for most high-current bus designs. A very pure material is used to have maximum conductivity. For given current-carrying capacity, aluminum bus weighs much less and costs less than copper bus.

Aluminum bolted joints, however, are more prone to problems than bolted copper joints. Aluminum oxide is a good insulator and forms as soon as bare aluminum is exposed to air. Galvanic action is also a problem if other metals and moisture are present at the joint. Silver plating an aluminum conductor at a joint is the common technique to reduce these problems. Contact resistance at a silver-to-silver joint is not as sensitive to pressure as at other junctions. This is very important because the high-conductivity aluminum used for the center conductor is soft and will creep from under the pressure points.

A balance is therefore required that allows enough pressure to keep resistance low but not high enough to result in rapid cold flow of the conductor. High-strength magnetic and non-magnetic bolts are employed along with various types of flat and locking washers. Belleville washers are also used with some designs. Each system is designed to apply pressure to a joint and compensate for temperature changes and short-circuit stress.

Elongation of the bolt or compression of spring washers is calculated to absorb the differential expansion between components. Cold flow or creep of the aluminum is to be expected. Welding on new terminal pads might be necessary when severe distortion has occurred.

One of the most common mistakes is to over-torque bolts on aluminum connections because, in this case, cold flow from under the bolts is rapid. The bolts seem to be loose and are tightened again, repeating the cycle. Manufacturer recommendations for joint assembly and bolt torque values must be followed unless problems develop. Redesign of these bolted joints is not uncommon; however, great care must be given to the selection of the new hardware if additional problems are to be avoided.

Appendix A provides valuable insight into understanding the nature of the isophase bus connections and practical considerations for improving the integrity of these important connections. Use of stainless steel bolting is recommended due to minimum effects from thermal cycling. Belleville washers are also recommended for this reason. Use of a stainless steel flat bar backing plate with tack-welded nuts is recommended for ease of installation. Additionally, the more uniform compression of the current-carrying surfaces will maximize the area available to conduct current. It is important to note that Belleville washers should not be reused.

### 12.1.2 External Bolted Joints

With a minimum flux design, phase current is present in the continuous enclosures. One major bus supplier welded all external joints between the enclosure tubes and shorting plates. Another major manufacturer chose to use an array of bolted jumpers from one enclosure to the next. These jumpers are prone to overheating, as shown in Figures 12-1 and 12-2, if the original design is marginal or not properly maintained.

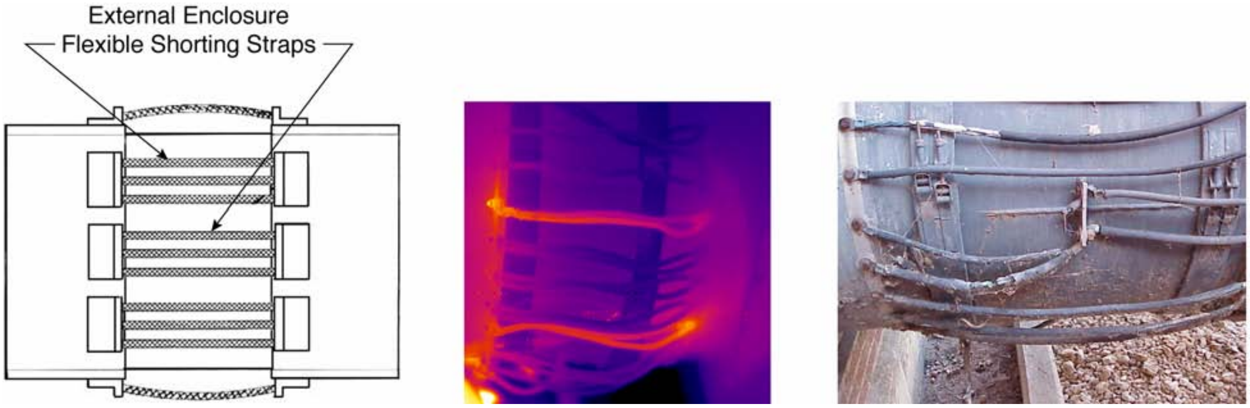

**Figure 12-1**
**Bus Duct with Bolted Jumpers, Thermography Showing a High-Resistance Joint, and a Visual Image of Jumper Cables**

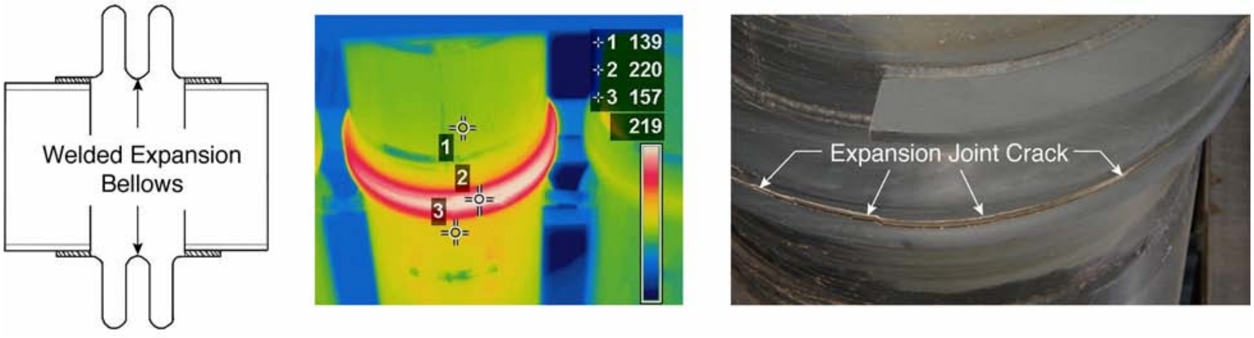

**Figure 12-2**
**Bus Duct with Welded Expansion Bellows, Thermography Indicating a Problem, and a Visual Image of the Cracked Joint**

In one case, a 20,000-ampere bus overheated at the expansion joints after less than 10 years of service. The steam rising during a light rain was the first indication of serious deterioration at the bolted joints. Thermography found a wide variation in jumper temperature; some jumpers were at the enclosure temperature while others were more than 212°F (100°C) hotter. An investigation and repair was scheduled for the next unit outage. As follows, the visual inspection and design review found a system that violated almost every guideline for a successful bolted joint:

- Steel bolts held copper lugs to the aluminum enclosure.
- No silver plating was used.
- No spring washers were used.
- No compound was used to seal the bolted joints.
- The ampacity of the jumper cables was less than the bus rating.
- Jumper cables were insulated with a low-temperature-class rubber.
- Jumper cable insulation had deteriorated due to sunlight.

A complete redesign was implemented by a distribution engineer familiar with bolted joints for outdoor service in substations. This new design has operated for over 10 years with no additional attention. External bolted joints are prone to all of the problems found with internal joints, but they also face rain and sunlight, which causes additional deterioration.

When overheating occurs, a root cause analysis can point to the features that need corrections. As stated earlier, a complete thermography inspection of the external bolted joints should be conducted twice a year. Jumpers that operate at a lower temperature than adjacent jumpers are the ones with highly resistant joints. There is very little potential across these enclosures, and a slight increase in resistance lowers current flow, reducing jumper temperature. Warm jumpers are working, and cold jumpers are not.

A recent operating experience saw unbalanced current flow between jumpers. Current varied from 100–950 amperes. The cause was that new jumpers were not cut to equal lengths. The variances in resistance of the jumper leads were sufficient to cause the current imbalances. Bolting issues with heli-coil inserts were also cited as contributors.

With some designs, there are small braces between the phases for mechanical bracing during bus faults. They also carry a small (100-ampere) current during normal operation. The original joint construction did not address this condition. Steel bolts were used to fix each aluminum brace to both aluminum ears on the phase enclosures, and overheating resulted. When redesigned as an outdoor aluminum-to-aluminum joint, the high temperatures are eliminated.

## 12.2 Flexible Links

The use of the laminar-style flexible links connecting the bus sections, bus to bushing, and neutral bus have been problematic. Cyclic vibration, increased air flow, and/or age-related thermal cycling has resulted in cracking of laminations, as shown in Figure 12-3. Cracked laminations have been found to be the cause of unit trips on neutral/ground overcurrent relay actuation.

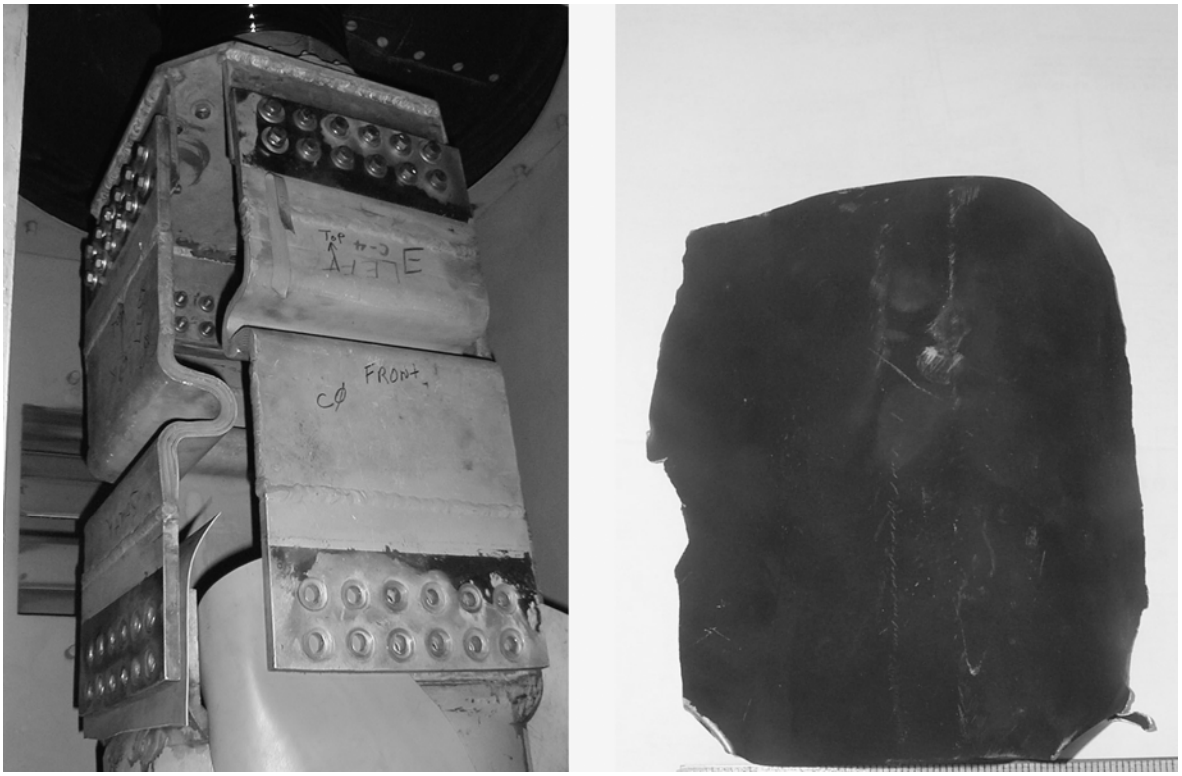

**Figure 12-3**
**Main Generator Flexible Link Lamination Style and Delaminated Piece That Caused a Unit Trip**

The recommended replacement for the laminar-style links is the use of a flexible braid-style link. Flexible braid-style links can also be damaged by improper maintenance techniques. Electricians need to be careful not to overstress the braids by bending them backward during removal and installation. Repeated flexing or bending, as illustrated in Figures 12-4 and 12-5, could result in breaking of strands and greatly reduced life.

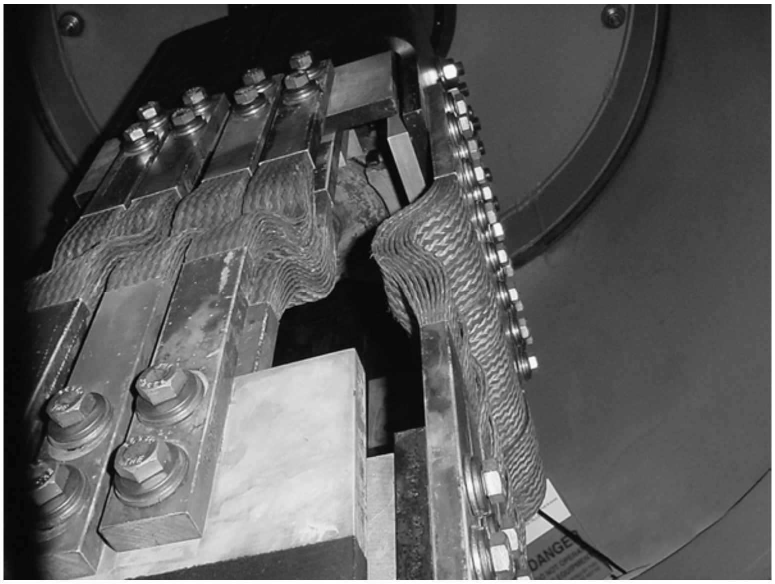

**Figure 12-4**
**Flexible Braid-Style Main Generator Links**

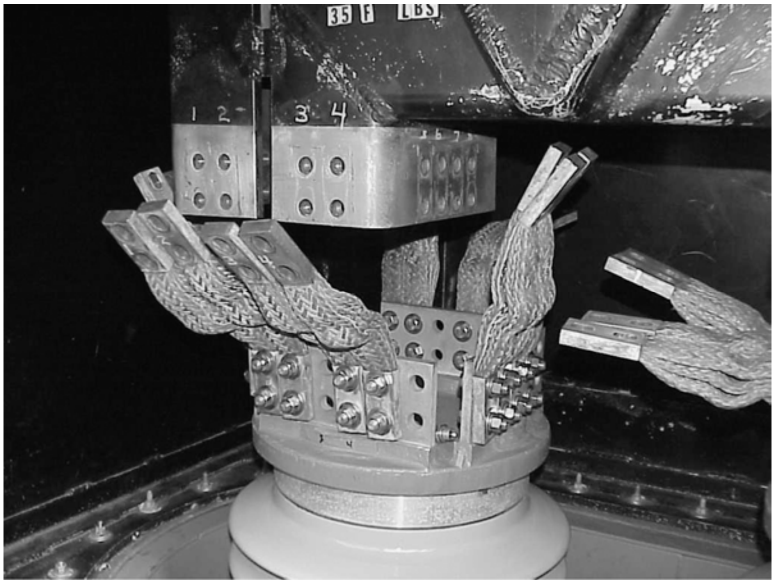

**Figure 12-5**
**Flexible Links at Transformer End Improperly Bent Back (This practice could lead to broken strands and shortened link life.)**

## 12.3 Crossover Dampers

Forced-air cooled bus sections must have air crossovers for cooling air to circulate through the enclosures. These are often located under the generators and at the main transformer. There are three common features:

- Air crossovers are usually insulated with single-point grounding to prevent stray circulating currents.
- Air control dampers might be provided in the form of a vane assembly or sliding aluminum plates.
- Metal chevron plates are installed as a deionizer grid between phases.

Depending on the design location, air crossovers can be small or quite large. Small ducts are used to provide air flow around bushings. Large ducts carry total enclosure air flow as described in Section 6.

Crossover dampers have catastrophically fallen apart, and pieces have fallen onto the bus and flashed over to ground. Damper position locking devices have loosened, allowing the dampers to swing closed. Dampers have been repositioned during maintenance and left closed or accidentally closed because the damper was installed upside-down. Closed dampers resulted in differential cooling between phases in operation.

These operating experiences identify key issues. The initial design of some dampers may not be robust enough to ensure event-free operation for a 40-year life, let alone a 60-year life. At least one manufacturer developed a more robust damper that had much thicker vanes and connecting arm. Maintenance or operations needs to validate that the as-found damper position is correct, the damper position is returned to the correct as-left position, or the damper is installed correctly if removed/replaced so that the external position indication is correct. If the system design flow is increased, the windage/turbulence effect on the dampers (and any other items in the duct that could be affected) must be evaluated. Periodic inspection and cleaning of deionizer grids is also recommended.

## 12.4 Split Covers

The ends of continuous enclosure bus are fitted with thick shorting plates welded to two or all three of the outer tubes. Beyond this shorting plate, a very strong magnetic field exists. This is often the case at transformers; however, near the generator bushings, split covers are sometimes used (as shown in Figure 12-6) to eliminate the external magnetic field and reduce mechanical forces on the generator bushings during a bus fault. This assembly has all of the features of the main bus except that it is insulated from adjacent structures and grounded at only one location. Failure of this thin insulation gasket is a common problem. Secondary grounds can result in unwanted circulating currents and overheating of adjacent structures or the split covers.

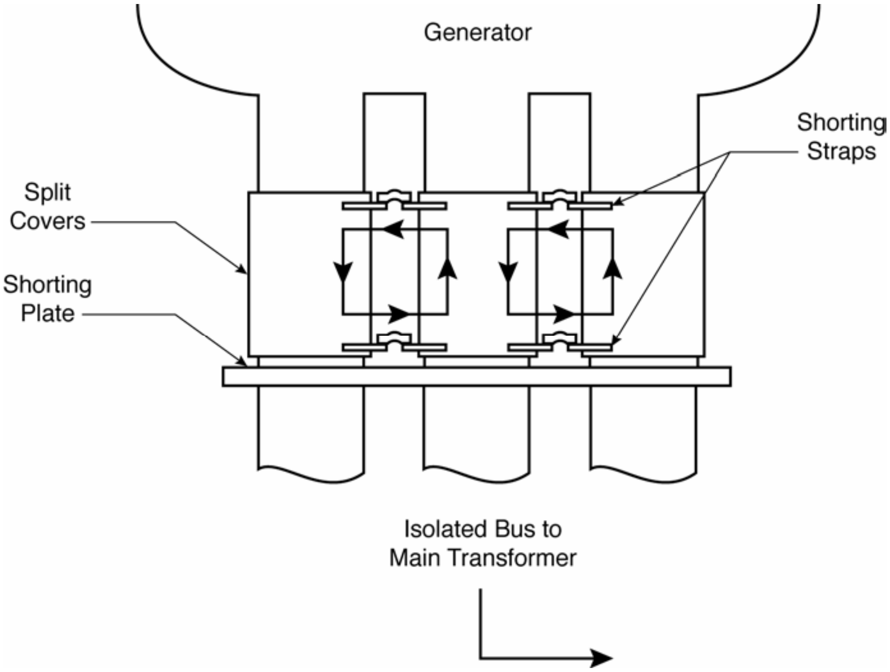

**Figure 12-6**
**Typical Arrangement of Split Covers**

Another source of higher temperatures is a lack of ventilation. Fans to increase air flow under a machine have proven effective in reducing split cover operating temperatures. Replacement of all original gasket material with insulation rated for Class H, 356°F (180°C) operation has proven to be a long-term solution to deterioration.

Heavy shorting straps are fitted at both ends of the split covers to carry the circulation current. Mechanical misadjustment is a frequent problem. All three split covers must be positioned correctly to properly attach the shorting straps. Distortion of components results when final alignment is forced. Bolted joints at the split covers are prone to all of the problems of internal bolted joints as discussed in Section 11.1. Operating temperatures can approach the limits for silver-plated aluminum. Conductor creep and loss of plating are common problems. Shorting strap replacement can be expected when design margins are small or the covers have been frequently removed.

## 12.5 Inspection Covers

Removable hatches or inspection covers are often provided along the enclosure to permit access to center conductor support insulators, expansion joints, and other internal components. These covers should be both air- and water-tight to keep contamination out of the bus. Gasket material often hardens and cracks, as shown in Figure 12-7, because of fluctuation in operating temperatures. Replacement can be expected. The use of closed-cell silicone rubber sponge per aerospace material specification (AMS) 3195, medium or soft, has been found to be a long-term solution to inspection cover gasket deterioration.

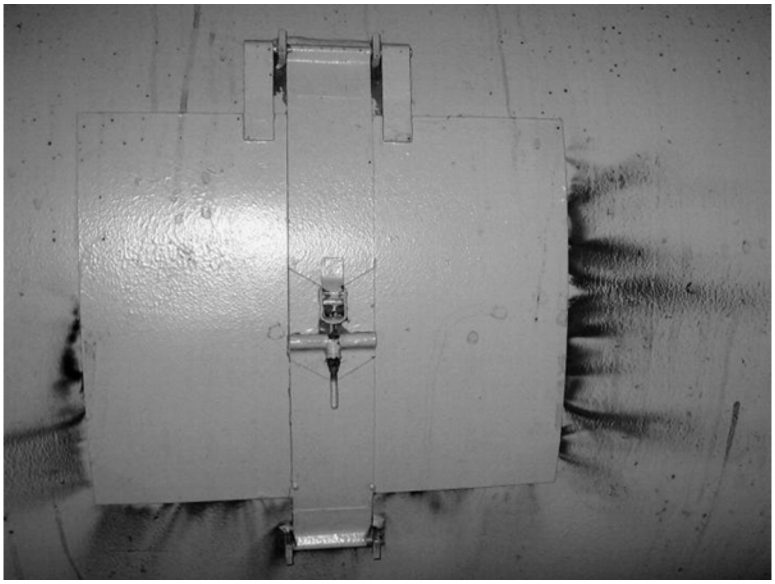

**Figure 12-7**
**Inspection Cover with Failed Gasket, Noting Evidence of Gasket Breakdown on the Surface of the Bus Duct**

## 12.6 Rubber Expansion Boots

With many designs, each enclosure is fitted with a rubber expansion joint between the end shorting plate and transformer bushing, as illustrated in Figure 12-8. These “boots” keep rain and dirt out and keep bus-cooling air in. An insulating material is necessary to eliminate stray currents in this non-shielded area. Usually, the original material deteriorates from heat and sunlight in 15–20 years. Replacements can be ordered from the original supplier or fabricated by a ventilation contractor. If non-OEM boots are installed, no wire-reinforced material can be used and only high-temperature (Thermal Class F, 311°F [155°C]) components will provide long life. Low-temperature material was the downfall of many OEM designs.

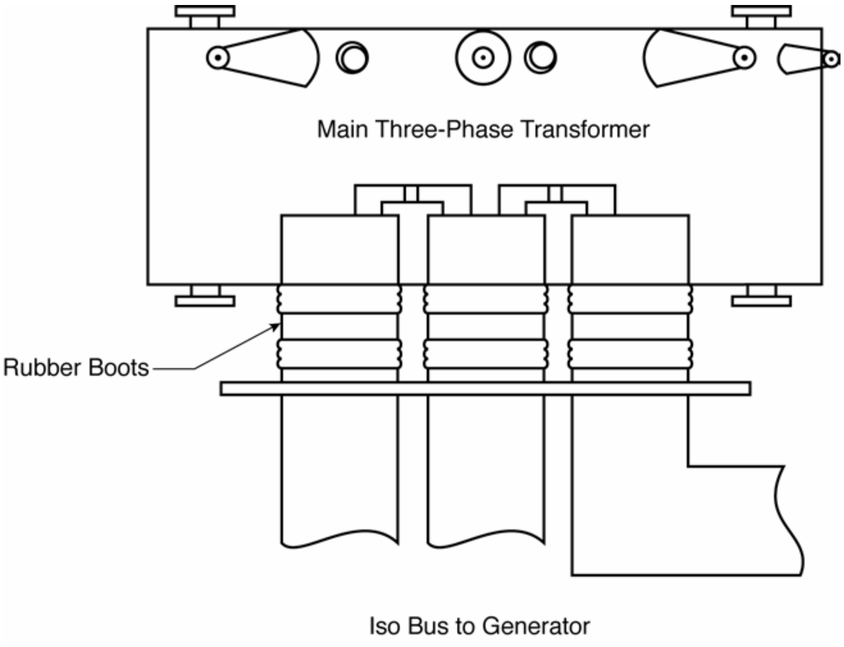

**Figure 12-8**
**Typical Location of Enclosure Boots**

Many generators also have a rubber seal or boot, as shown in Figure 12-9, between the bushings and the neutral or high-voltage bushing box penetrations. These seals serve a similar function in keeping dirt out and cooling air in on forced-air isophase systems. These seals may fail from thermal degradation over time and must be replaced.


Rubber seal may fail, resulting in in-leakage of dirt and out-leakage of isophase cooling air.

**Figure 12-9**
**24-kV Generator Bushing with a Rubber Seal**

## 12.7 Air-to-Water Heat Exchangers

Usually the only moving component in a high-current bus is the fan for forced-air circulation. As with any rotating machine, bearings, belts, and motor windings fail and must eventually be replaced. A visual inspection should be conducted during each outage to look for cooler leaks, damper movement, dirt accumulation, cracked belts, loose hardware, stuck valves, and plugged filters. Rubber air seals around the air-to-water heat exchanger and the primary air ducts should be inspected for cracks and misadjustment. Air flow switches must be checked to verify that an alarm or trip is given if air flow is reduced. This is vital because there is very little reaction time to reduce load after a cooling failure. If the flow switches are not working, melted bus and flashover will be the first signs of cooling fan failure.

# 13

# DEFINITIONS

*Isolated Phase* (ANSI definition 20-2.1.4.3)

One in which each phase conductor is enclosed by an individual metal housing separated from adjacent conductor housings by an air space. (The bus may be self-cooled or force-cooled by means of circulating air, gas or liquid.) There are two design variations of isolated phase bus, continuous enclosure and non-continuous enclosure. The external magnetic field is greatly limited by the continuous enclosure type.

*Metal Enclosed Bus* (ANSI definition 20-2.1.4)

An assembly of rigid conductors with associated connections, joints and insulating supports with a grounded metal enclosure.

*Non-Segregated Phase Bus* (ANSI definition 20-2.1.4.1)

One in which all phase conductors are in a common metal enclosure without barriers between phases. (When associated with metal-clad switchgear the primary bus conductors and connections are covered with insulating material throughout.)

*Segregated Phase Bus* (ANSI definition 20-2.1.4.2)

One in which all phase conductors are in a common metal enclosure, but are segregated by metal barriers between phases.

# 14
# STANDARDS

The following standards were used in the development of this technical report:

American National Standards Institute (ANSI) C37.20c-1974 and C37.20d-1978 (IEEE Std. 27-1974).

ANSI C37.20 d. 1978: “Switchgear Assemblies Including Metal-Enclosed Bus.”

British Standard 159:1957, “Busbars and Busbar Connection.”

IEC Publ. 694/1980: “Common Clauses for High-Voltage Switchgear and Control Gear Standards.”

IEC Publ. 71.2/1976: “Insulation Coordination Part 2: Application Guide,” Appendix E, table VI/A.

International Electrotechnical Commission (IEC) Publ. 298/1981: “AC Metal-Enclosed Switchgear and Control Gear for Rated Voltage Above 1 kV and up to and Including 72.5 kV.”

VDE 0101/11.80: “Specifications for the Construction of Power Installations with Rated Voltage Above 1 kV.”

VDE 0103 2.82 (DIN 57 103): Recommendations for mechanical and thermal short-circuit strength of electrical power installations.

VDE 0111 part 1/10.79 (DIN 57 111): Installations coordination of equipment for three-phase ac systems above 1 kV.

VDE 0141/7.76 (DIN 57 141): “Specifications for earthing installations for rated voltages above 1 kV ac.”

Verband Deutscher Elektrotechniker (VDE) 0102/Part 2/11.75 (Deutsches Institut fur Normung [DIN] 57 102) VDE: Recommendation for the calculation of short-circuit currents. Three-phase installations with rated voltages up to 1000 V.

# 15

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2. E. J. Casey and N. Swerdlow, "Application of Aluminum Channel Conductors for Station Bus," *AIEE Transactions*, Vol. 71, Pt. III, 1952, pp. 1004–1009.
3. H. Haneke, "High-Current Technique for Installations in Power Plants, Isolated Phase Metal-Enclosed Generator Busbars, High-Current Isolated Phase Busbars," CIGRE Symposium 06-85 Brussels 1985, Section 230-03.
4. T. J. Connor and W. R. Wilson, "Performance of Electrical Joints Utilizing New Silver Coating on Aluminum Conductors," *AIEE Transactions,* August 1953, pp. 702–712.
5. R. H. Albright, A. Conangla, A. C. Bates, and J. B. Owens, "Isolated Phase Metal Enclosed Conductors for Large Electric Generators," *IEEE Transactions, Power Apparatus and Systems*, February 1963, pp. 655–667.

# 16

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Edith Clarke, *Circuit Analysis of AC Power Systems,* Volume 1. John Wiley and Sons, New York, 1943.

N. Swerdlow and M. A. Buchta, “Practical Solution of Inductive-Heating Problems Resulting from High-Current Buses,” *AIEE Transactions,* Volume 79, Pt. III, February 1960, pp. 1736–1746.

R. H. Rehder and L. Doucet, “Maintenance Considerations on Isolated Phase Bus Duct,” Proceedings of the Sixty-Second Annual International Conference of Doble Clients, pp. 2-7.1 through 2-7A.2, 1995.

W. R. Wilson and L. L. Mankoff, “Short-Circuit Forces in Isolated-Phase Buses,” *AIEE Transactions,* Volume 73, Pt. IIIA, April 1954, pp. 382–396.

W. Richter, “An Instrument for the Measurement of Large Alternating Currents,” *AIEE Transactions,* Volume 63, 1944, pp. 38–40.

# A

# GENERATOR MAIN AND NEUTRAL LEADS – GOOD PRACTICES

Inadequate or poor electrical connections on generator main and neutral leads have caused excessive heating that led to massive failures. The same electrical connection philosophy applies to generator main and neutral leads as to every other electrical connection. The same problems and approach apply to all electrical connections throughout the plant.

## A.1 Basic Philosophy and Facts

- All voltage and current are meant to pass between the contact surfaces of the conductors and not through the bolting.
- Maximum contact surface between the conductors is essential to a good electrical connection.
- Conductors are generally copper, brass, or aluminum, while bolting is generally steel.
- Steel bolting is stretched slightly by tightening the nut on the bolt.
- Copper, brass, and aluminum will “creep,” “conform,” “expand,” or “move away” from stress imposed by steel bolting being stretched.
- Silicone-bronze bolting loses its resilience when heated.
- The bolting attaching the neutral bus segments to the neutral lead bushings probably has not been checked since the original installation.
- The bolting attaching the isophase connection plate to the main lead bushings probably has not been checked since the original installation.
- The flexible links between neutral bus segments are removed and replaced periodically to facilitate electrical testing of the generator.
- The flexible links between the isophase connection plate and the isophase are removed and replaced periodically to facilitate electrical testing of the generator.
- The solid-appearing ends of flexible links are not solid; rather, they are the flexible link squeezed into a rectangular shape with a copper wrap around the outside.
- Dimples or concave shapes occur in the ends of flexible links or copper or aluminum conductors because of “creep” of the relatively soft material as compared to the steel bolting material.

- Unbolting 4-in. (101-mm) bus work at a 90-degree corner provides evidence of “creep” and the consequential loss of contact surface. There will be circles around the four bolt holes where the conductors were still making contact due to the force imposed by the bolts. The other area of the connection surface has crept apart and created a void between the surfaces of the conductors.
- Neutral bus segments “creep” away from neutral lead bushings so that contact between the bus segment and the neutral lead bushing is limited to the area around the bolts.
- Isophase connection plates “creep” away from main lead bushings so that contact between the isophase connection plate and the main lead bushing is limited to the area around the bolts.
- A flexible link that is darkened due to high current is the best conductor. The other flexible links have poor electrical connections and thus high resistance at the connection point, which causes the current to pass through the flexible link with the good electrical connection.
- An electrical circuit can “ring” or light a bulb to ensure continuity, but this is not an indication of the current-carrying capabilities of the connection. A poor electrical connection heats up, which causes a worse connection that produces more heat. Micro-ohm testing is recommended to ensure that quality connections have been made.
- Silver oxide is a good conductor, so Tar-X or any type of abrasive cleaning technique should not be used on silver contact surfaces.
- Cleaning of plated areas should be performed with denatured alcohol and clean, dry, lint-free cloths or pressurized air. The use of Scotch-Brite® pads should be discouraged.
- The use of dehumidifiers on the isophase bus work at the start of an outage will minimize the probability of unsatisfactory Megger and/or polarization index (PI) readings prior to unit restart.
- Plating/replating shall be done in a well-ventilated area.
- Some utilities have the plating/replating work sent out. The silver-plating process can be greatly simplified by maintaining a silver-electroplating machine and associated chemicals, leads, and applicator in-house.

## A.2 Solutions to “Creep” of Electrical Components

- Replace all silicone-bronze bolting with 316 stainless steel bolting.
- Fabricate and install stainless steel plates on the backside of conductors to spread out the compression imposed by the bolting.
- Use Belleville washers on bolting to spread load and provide compression that will accommodate “creep” of conductors. Never reuse Belleville washers.
- Check all large electrical connections with a 0.002-in. (0.05-mm) feeler gauge to ensure surface contact.
- Improving electrical connections should be an ongoing process that is carried out on a routine basis and not a massive changeout. Whatever the job or task, the condition of the electrical connection should be examined and improved if possible.

Examples of typical components, configurations, problem areas, and solutions are presented in Figures A-1 through A-11.

**Figure A-1**
**Typical Neutral Connection Point on the 13.8-kV Segregated Bus**

**Figure A-2**
**Improved Neutral Connection Using Stainless Steel Plates on Both Sides of the Bus Bar, Stainless Steel Bolting, and Belleville Washers (The electrician is making a cursory examination of the connection point with a 0.002-in. [0.051-mm] feeler gauge.)**

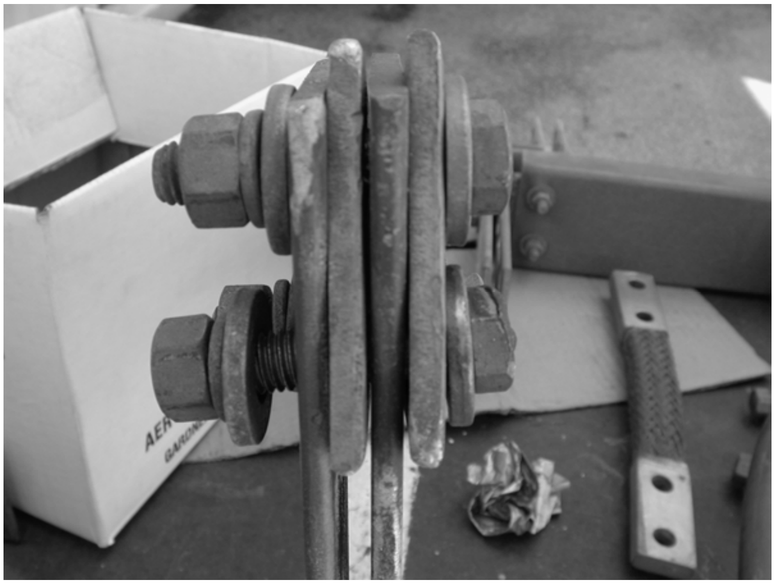


**Figure A-3**
**Typical As-Found Bolted Bus Bar Connection Using Steel Bolts and Flat Washers**

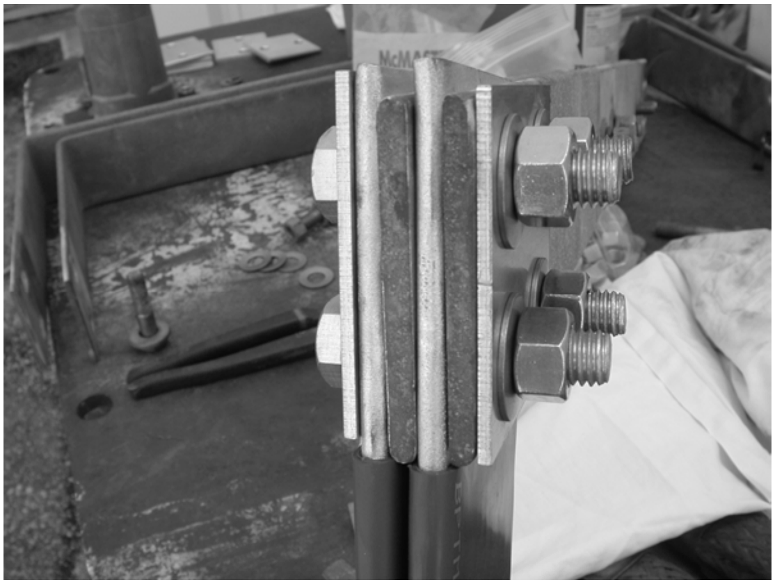


**Figure A-4**
**Improved Connection with Stainless Steel Plates on the Outside of the Bus Bars to Spread the Compressive Load of the Bolts, Stainless Steel Bolts, and Belleville Washers**

**Figure A-5**
**Flexible Strap Ends That Have Been Overtorqued into Concave Condition**

**Figure A-6**
**Typical Electrical Connection Pattern on Flexible Strap Ends; Design Is for the Entire Surface to Be in Contact with the Bus or Neutral Bus Segment (Poor electrical connections have caused the bus and the strap ends to be heated.)**

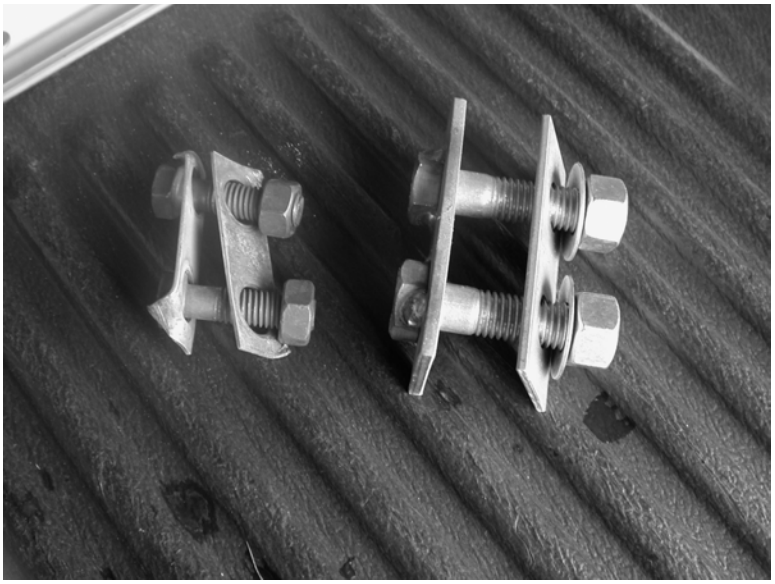


**Figure A-7**
**Before and After Flexible Strap End Bolting (The plate with the stainless steel bolts tack-welded in place provides technicians with a much easier to use bolting configuration.)**

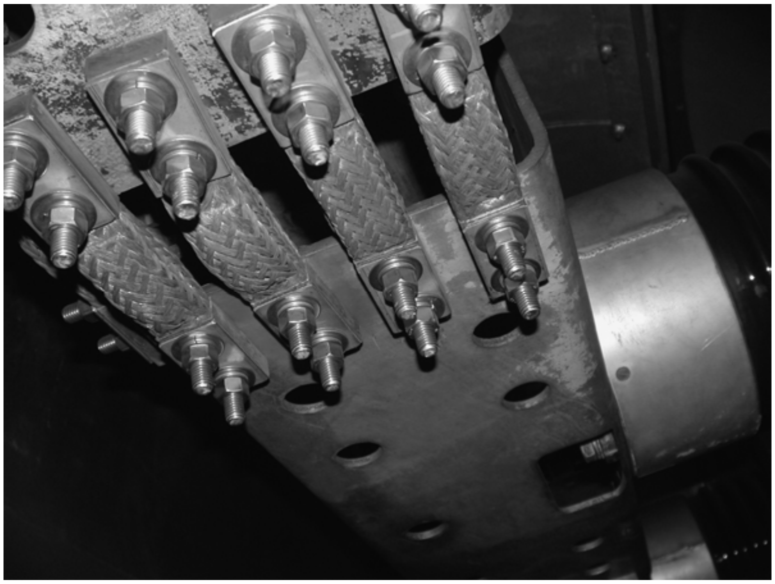


**Figure A-8**
**Flexible Straps Between Neutral Bus Segments with Improved Stainless Steel Plates, Bolting, and Belleville Washers (The bracket with two bolts tack-welded in place drops into the holes in the bus segments. Tightening the nuts on the outside does not require holding the bolt head on the inside.)**

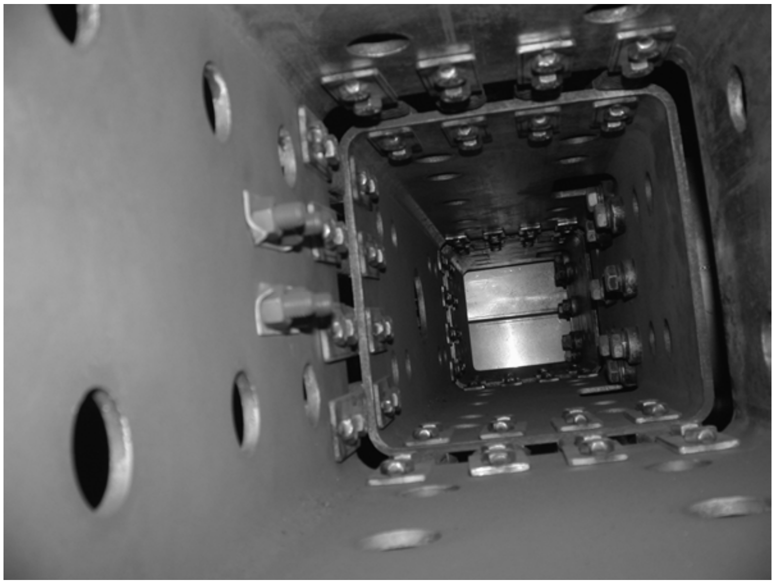


**Figure A-9**
**Neutral Bus Segments from the Inside (The plates with the bolts tack-welded in place make assembly much easier. The four silicone-bronze bolts and existing bend-up tabs on the left are the neutral grounding transformer connection point. They were changed to stainless steel bolts and Belleville washers after this picture was taken.)**

**Figure A-10**
**Typical Main Lead Connection Plate to Isophase Bus Work Flexible Links**

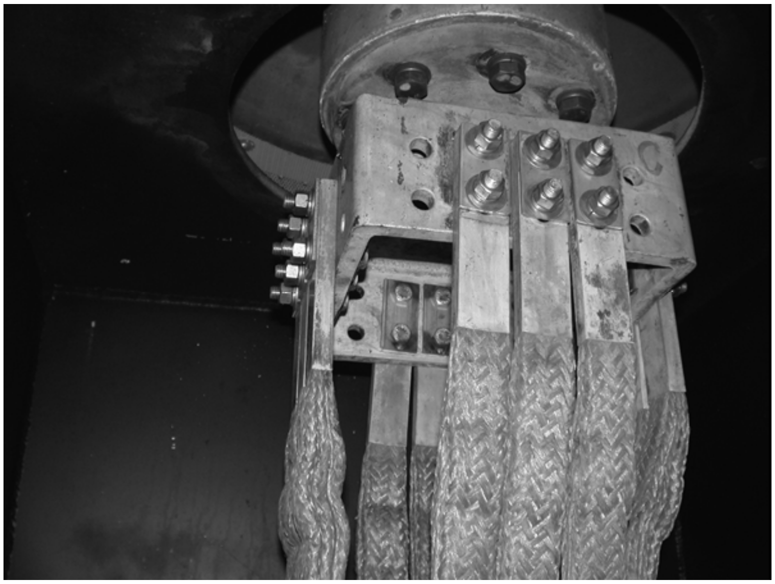


**Figure A-11**
**Improved Main Lead Connection Plate to Isophase Bus Work Flexible Links (The plates with the bolts tack-welded in place are on the inside. Stainless steel plates, Belleville washers, and nuts are on the outside. Again, this arrangement is easy to work while significantly improving the electrical connections.)**

## A.3 Case Histories

### *A.3.1 Case A*

On a 200-MW unit, a 0.002-in. (0.05-mm) feeler gauge could be slid between the center or B-phase main lead bushing and the connection plate for the isophase bus work. Upon closer examination, it was possible to see light across the connection between the B-phase main lead bushing and the connection plate. It appears that the electrical connection between the main lead bushing and the heavy connection plate had deteriorated over the years. As the connection became worse, the current passed through the steel bolting, which caused the bolts to heat and allowed the bolts to stretch and make the electrical connection worse. The unit was in startup when the problem was discovered, so the bolts were tightened to pull the connection plate up against the main lead bushing. Removal of the connectors, cleaning, and reassembly with appropriate backing plates was scheduled for later.

Returning to the electrical shop, we learned that the same unit had experienced some kind of major failure at the A-phase main lead some time in the past. We had noted that there was paint of a slightly different shade on the A-phase connection enclosure. Apparently, the failed main lead bushing had been repaired but the other two main lead bushings were not checked.

### A.3.2 Case B

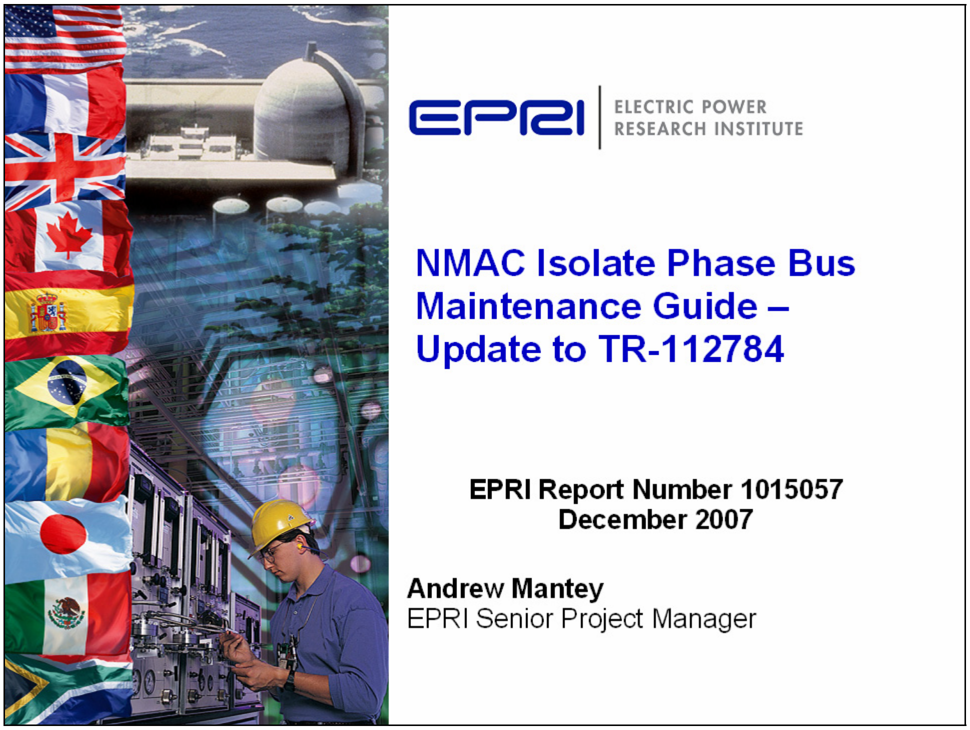
It is almost routine to be able to slide a 0.002-in. (0.05-mm) feeler gauge between some of the flexible strap ends and the neutral lead bushings on any given unit. On many units, the bolting used on the straps is silicone-bronze. The silicone-bronze bolts lose their resilience when heated, so a poor electrical connection between the flexible strap end and the neutral bus segments causes current to flow through the silicone-bronze bolts, which heats the bolts and loosens the connection. At one nuclear unit, the silicone-bronze bolting is checked for tightness every refueling outage. Loose bolts, which are generally more than 50% of the bolts, are replaced. At another nuclear unit, all silicone-bronze bolting with 316 stainless were replaced, stainless steel plates on the bolt head side of the connection were added, and Bellville washers were used on the bolting. Plant personnel later explained that their procedures required the installation of flexible straps between the neutral bus segments up to a certain torque value. They were also required to go back 24 hours later and check the torque on the bolts and retorque as necessary. Generally about 20% to 30% were found to be loose and require retorquing. After the installation of the stainless steel plates and the usage of stainless steel bolting and Belleville washers, 100% of the bolts were found to be tight and did not require retorquing. The neutral bus flexible strap installation procedure was immediately modified to eliminate retorquing.

### A.3.3 Case C

One nuclear facility experienced heating of the flexible straps closest to the neutral lead bushings. The shortest distance the current had to travel was through the closest flexible strap. Therefore, this was the path the current followed. Plant personnel removed the closest flexible straps, forcing the current to travel to the other straps. The connections of the other straps could have been improved and stainless steel plates, bolting, and Belleville washers could have been installed.

# B

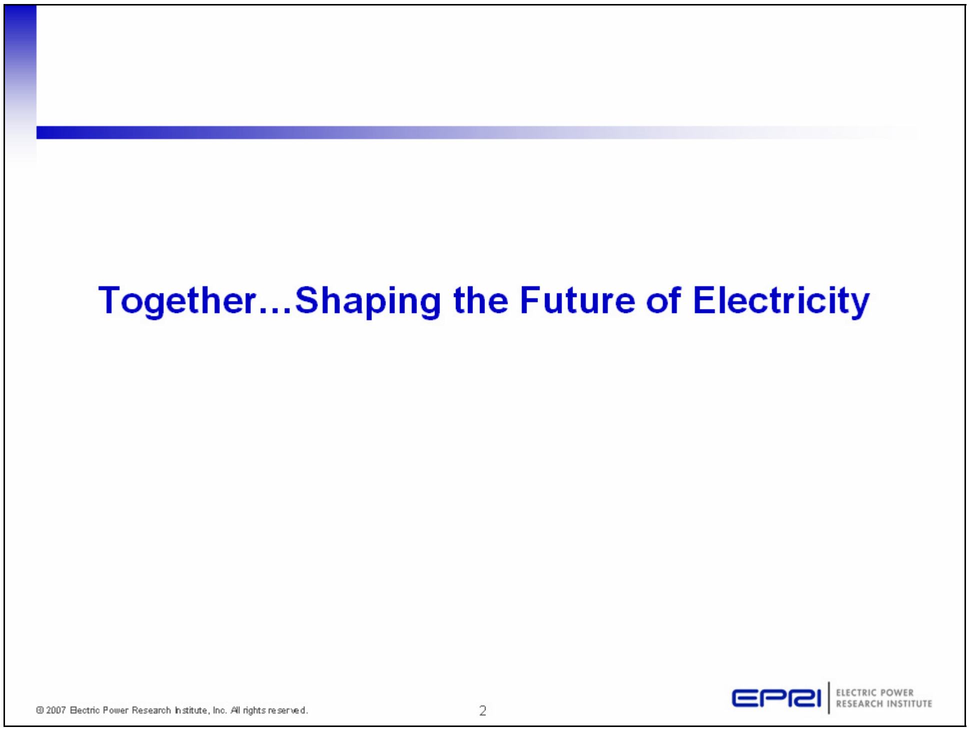
# TRAINING SLIDES



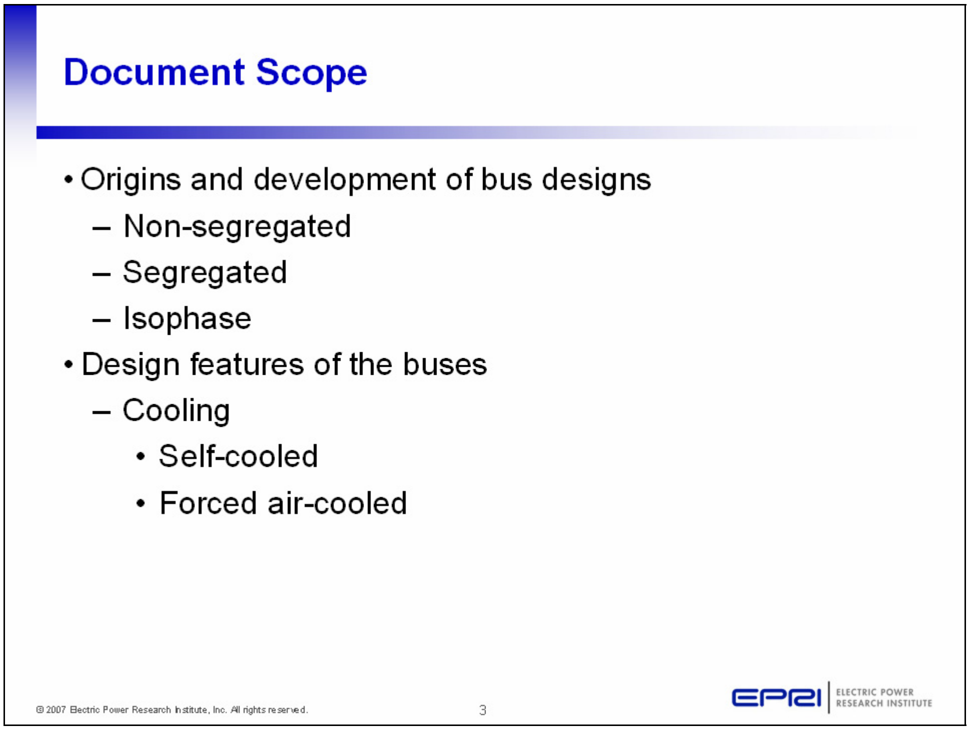
# NMAC Isolate Phase Bus Maintenance Guide – Update to TR-112784

**EPRI Report Number 1015057**
**December 2007**

**Andrew Mantey**
EPRI Senior Project Manager

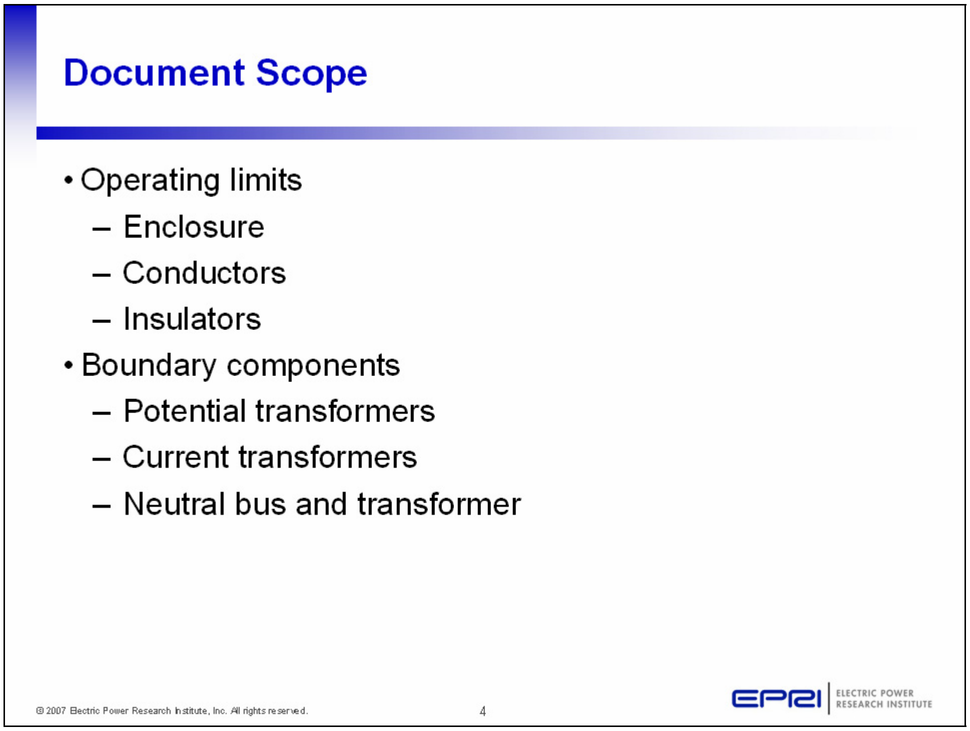


## Together…Shaping the Future of Electricity



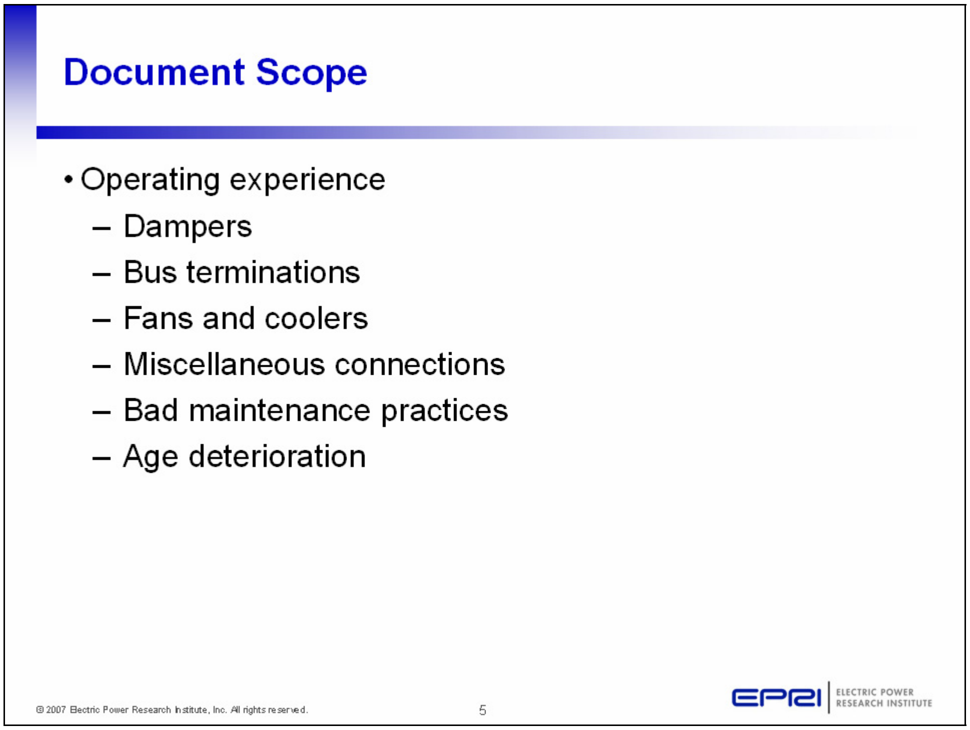
## Document Scope

- Origins and development of bus designs
  - Non-segregated
  - Segregated
  - Isophase
- Design features of the buses
  - Cooling
    - Self-cooled
    - Forced air-cooled



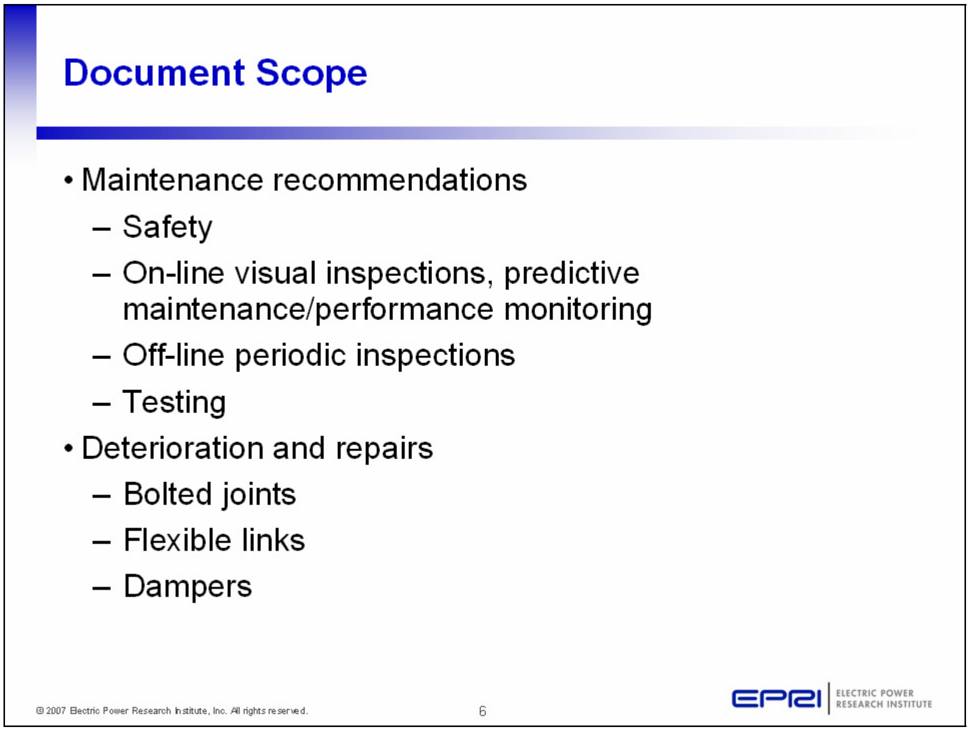
## Document Scope

- Operating limits
  - Enclosure
  - Conductors
  - Insulators
- Boundary components
  - Potential transformers
  - Current transformers
  - Neutral bus and transformer



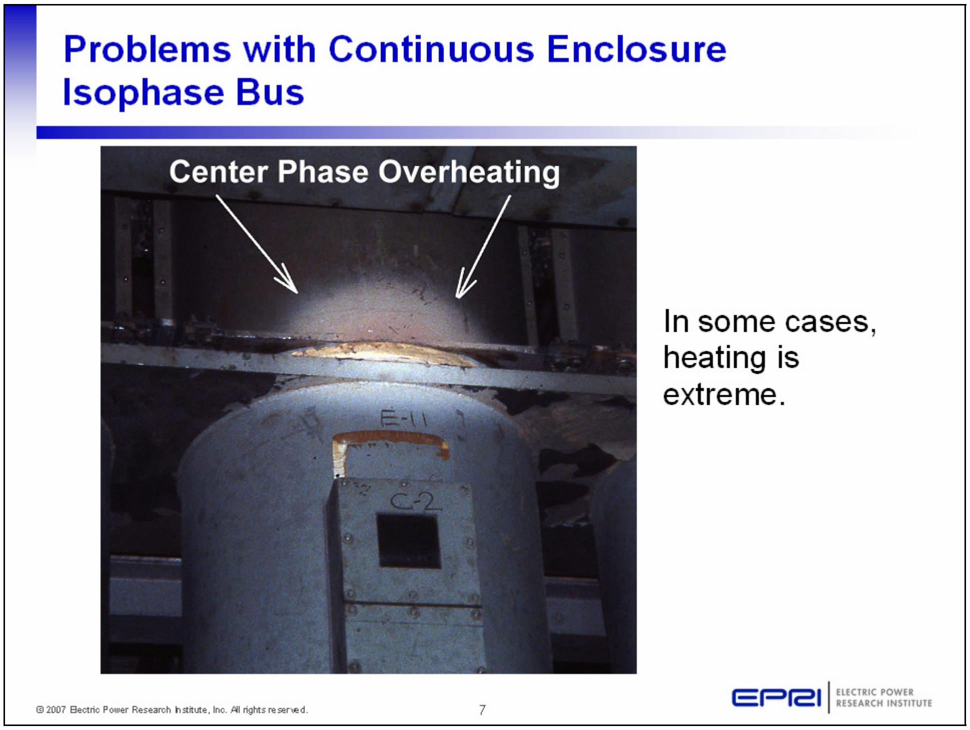
## Document Scope

- Operating experience
  - Dampers
  - Bus terminations
  - Fans and coolers
  - Miscellaneous connections
  - Bad maintenance practices
  - Age deterioration



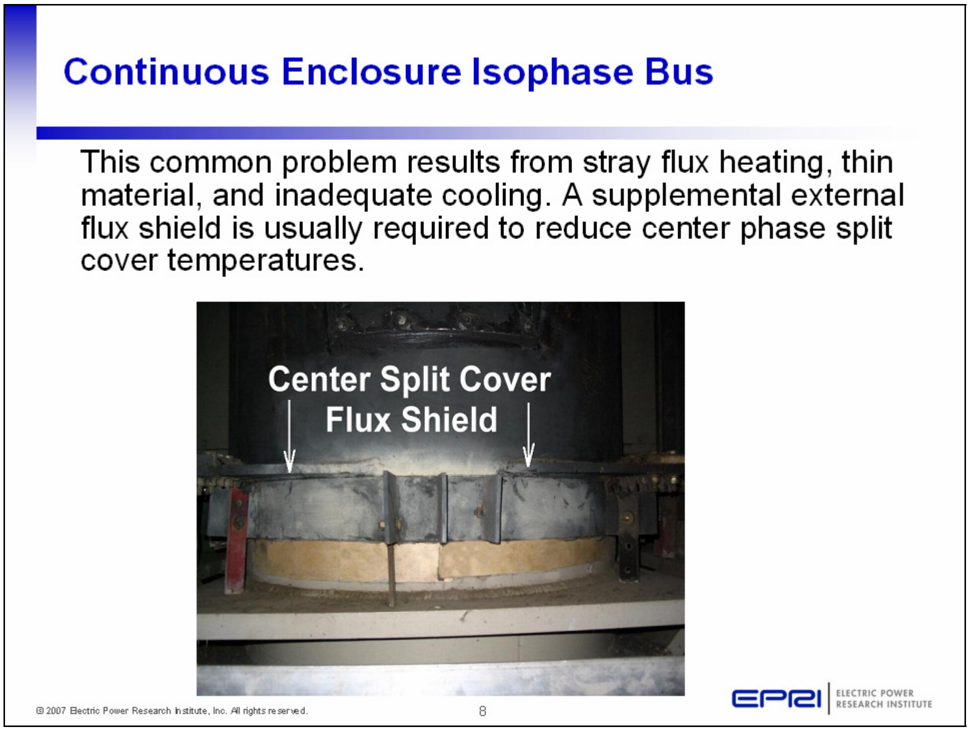
## Document Scope

- Maintenance recommendations
  - Safety
  - On-line visual inspections, predictive maintenance/performance monitoring
  - Off-line periodic inspections
  - Testing
- Deterioration and repairs
  - Bolted joints
  - Flexible links
  - Dampers



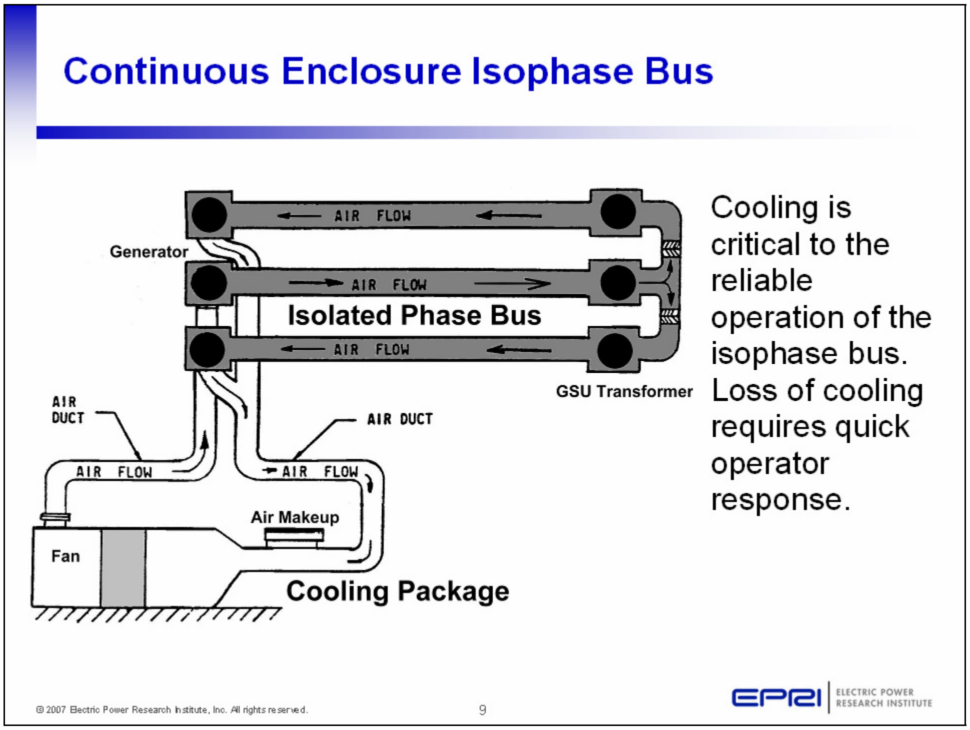
## Problems with Continuous Enclosure Isophase Bus

In some cases, heating is extreme.



## Continuous Enclosure Isophase Bus

This common problem results from stray flux heating, thin material, and inadequate cooling. A supplemental external flux shield is usually required to reduce center phase split cover temperatures.



## Continuous Enclosure Isophase Bus

Cooling is critical to the reliable operation of the isophase bus. Loss of cooling requires quick operator response.

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## Operating Limits

Loss of cooling will result in:

- Rapid temperature rise
- Required load reduction, sometimes in <4 minutes

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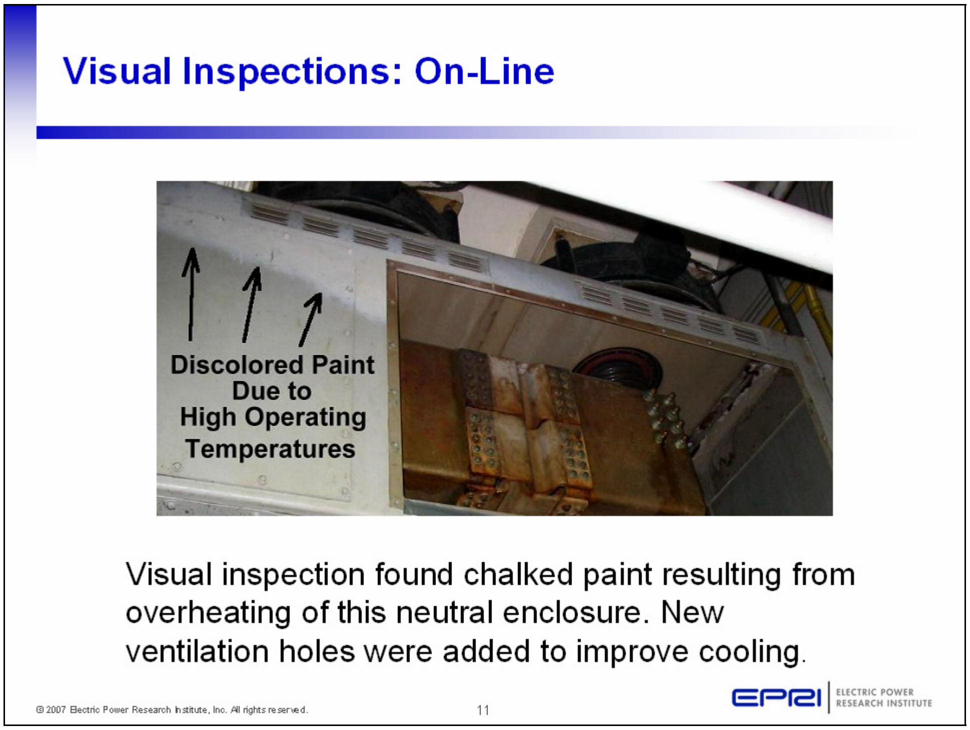
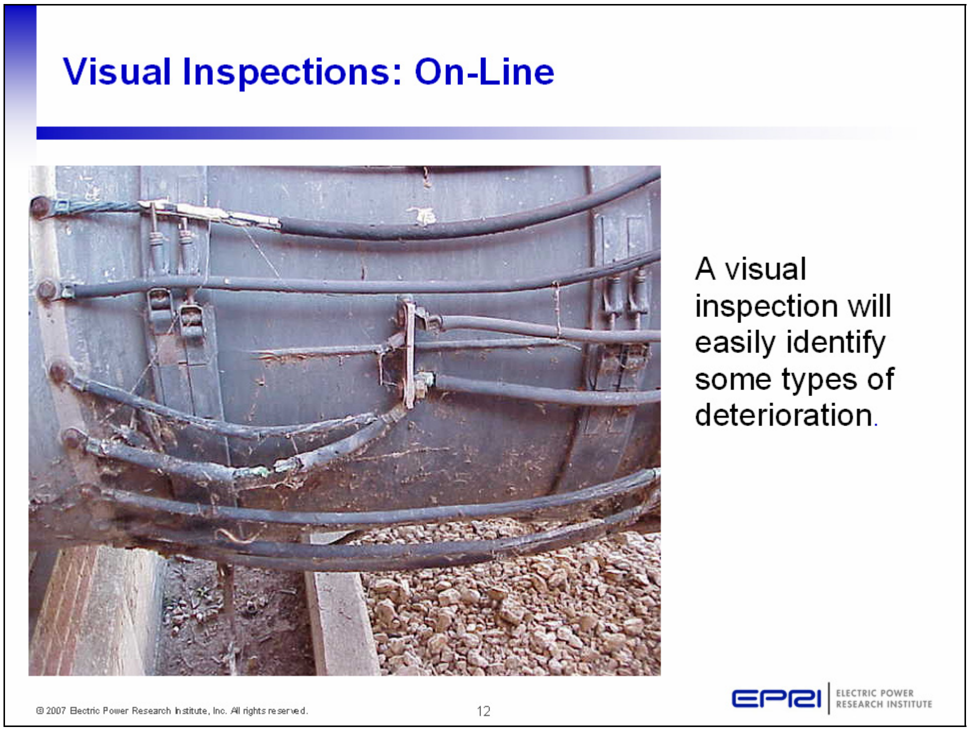


## Visual Inspections: On-Line

Discolored Paint
Due to
High Operating
Temperatures

Visual inspection found chalked paint resulting from overheating of this neutral enclosure. New ventilation holes were added to improve cooling.

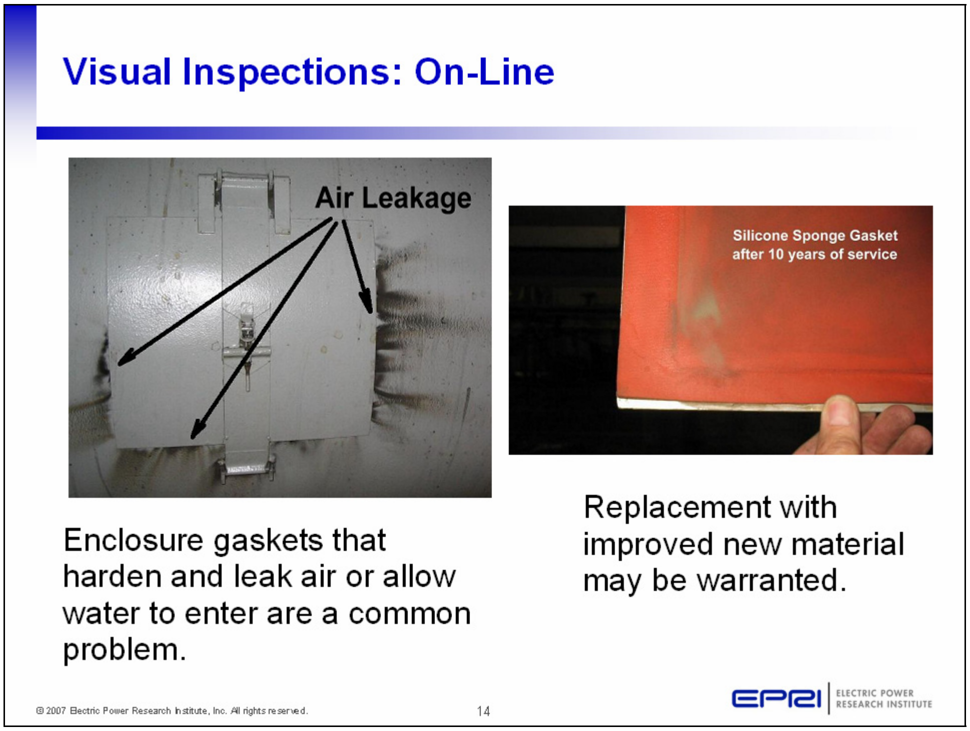


## Visual Inspections: On-Line

A visual inspection will easily identify some types of deterioration.

## Visual Inspections: On-Line

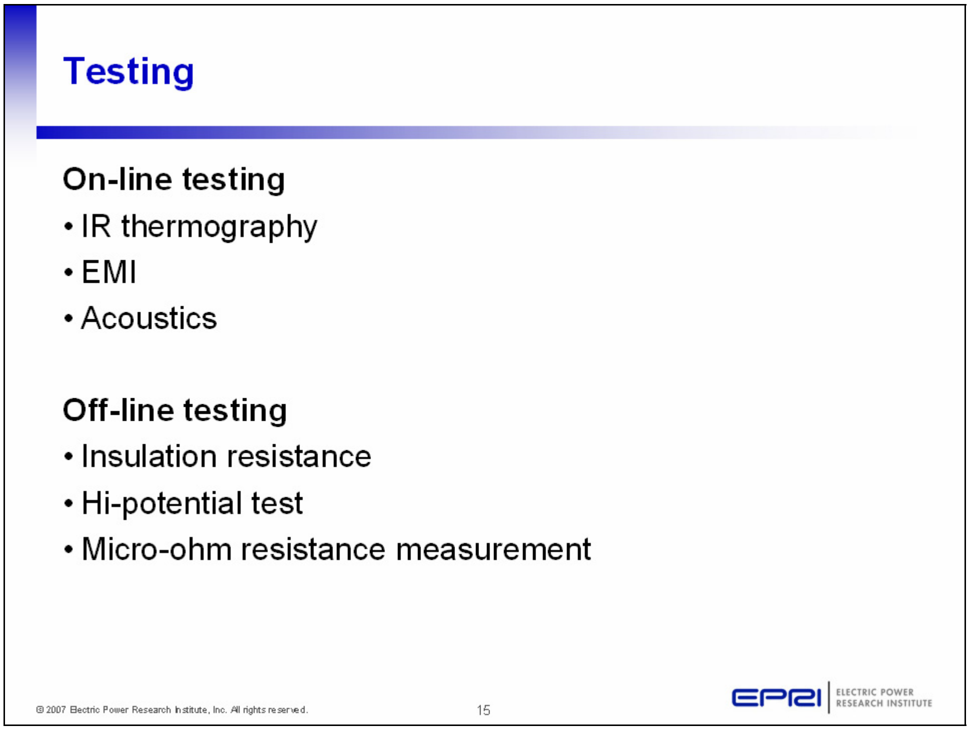
Forced air-cooled systems often develop air leaks around the inspection hatches due to hardening of the original gasket material.



## Visual Inspections: On-Line

Enclosure gaskets that harden and leak air or allow water to enter are a common problem.

Replacement with improved new material may be warranted.



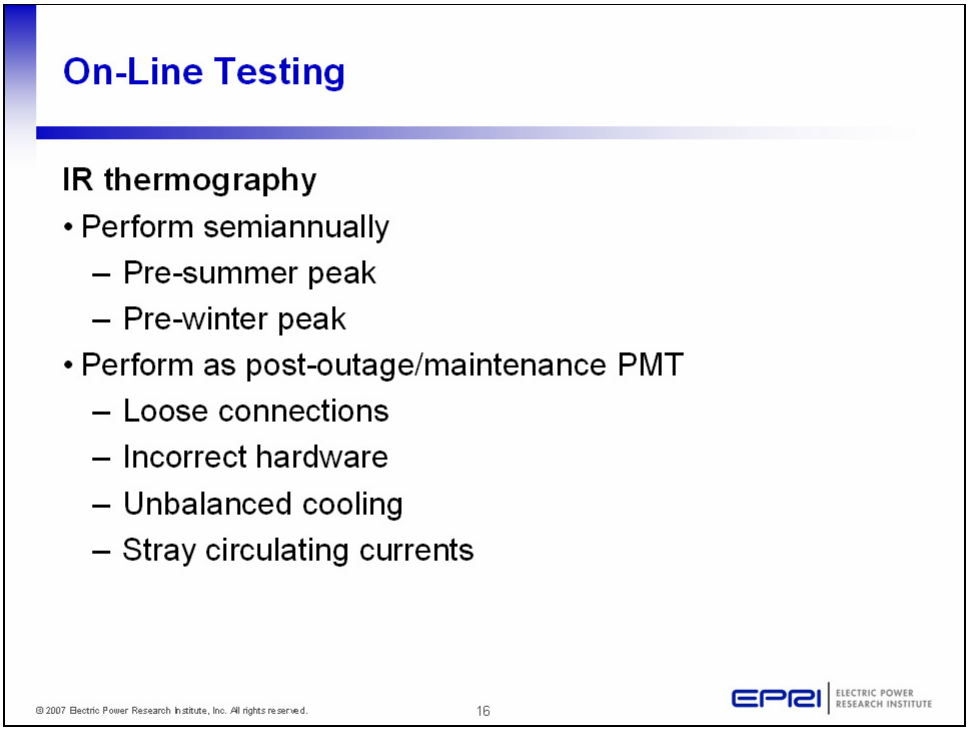
## Testing

**On-line testing**

- IR thermography
- EMI
- Acoustics

**Off-line testing**

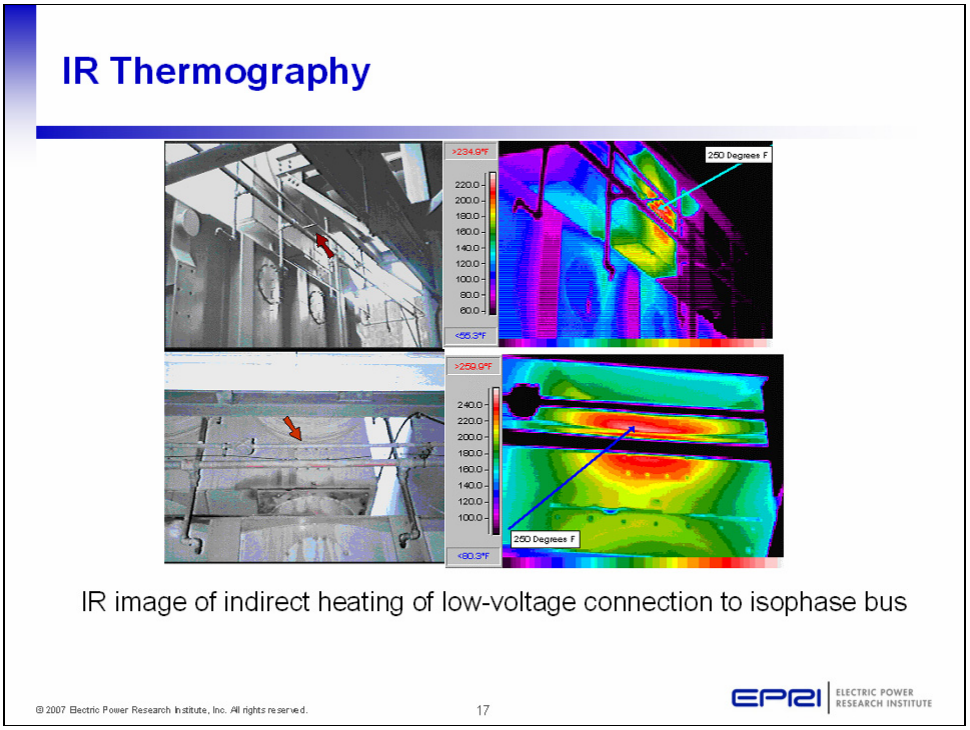
- Insulation resistance
- Hi-potential test
- Micro-ohm resistance measurement



## On-Line Testing

**IR thermography**

- Perform semiannually
  - Pre-summer peak
  - Pre-winter peak
- Perform as post-outage/maintenance PMT
  - Loose connections
  - Incorrect hardware
  - Unbalanced cooling
  - Stray circulating currents



## IR Thermography

IR image of indirect heating of low-voltage connection to isophase bus

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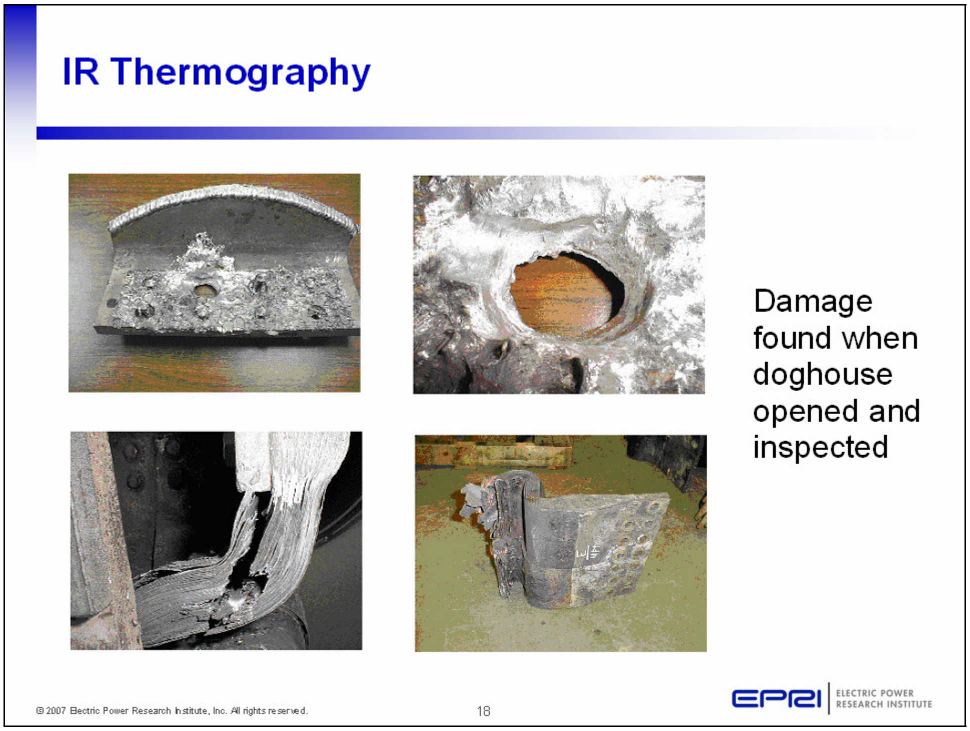

## IR Thermography

Damage found when doghouse opened and inspected

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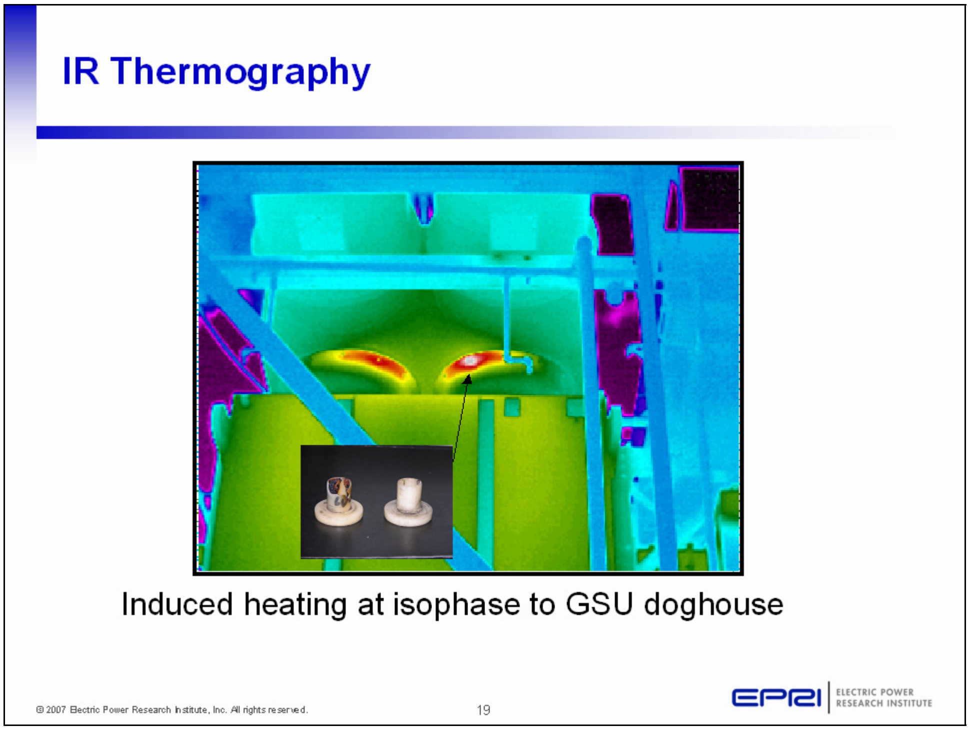
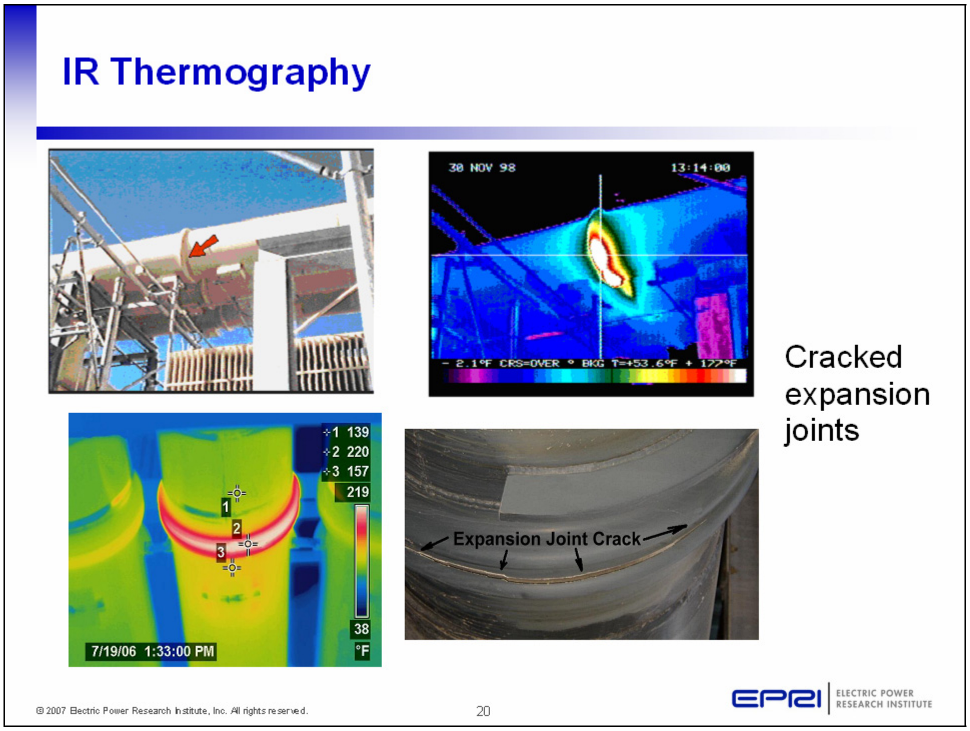


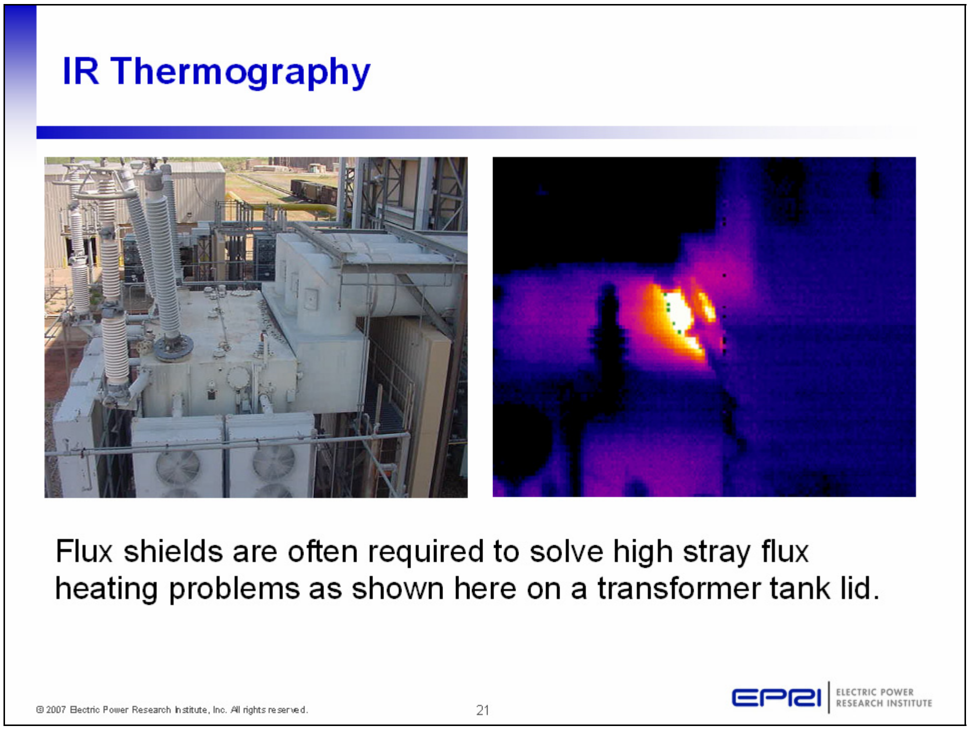
## IR Thermography

Induced heating at isophase to GSU doghouse



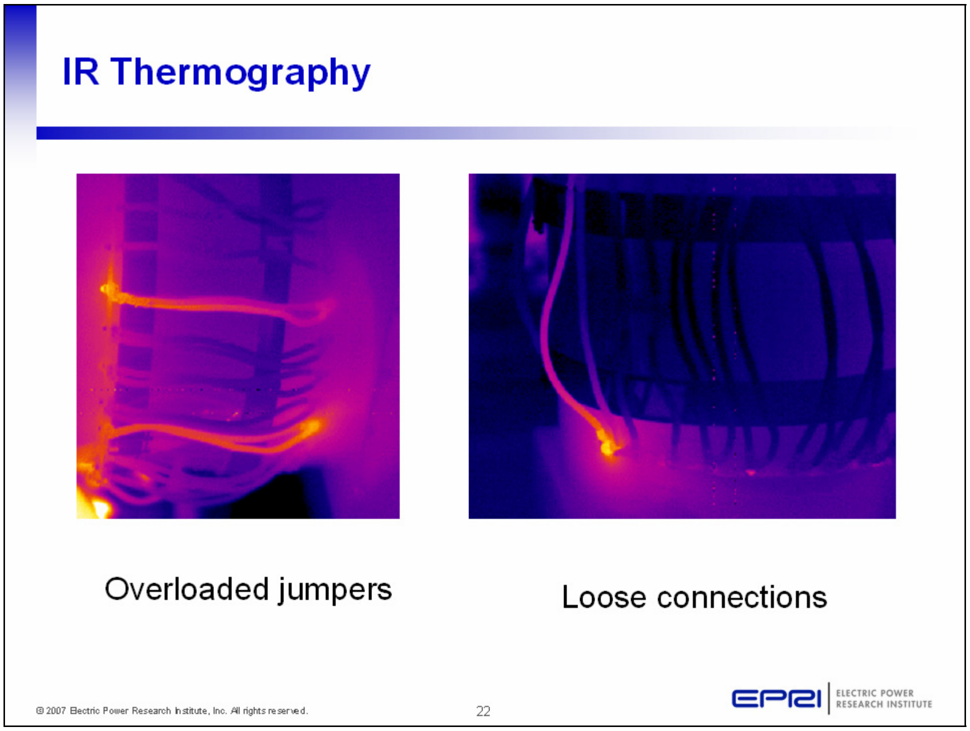
## IR Thermography

Cracked expansion joints



## IR Thermography

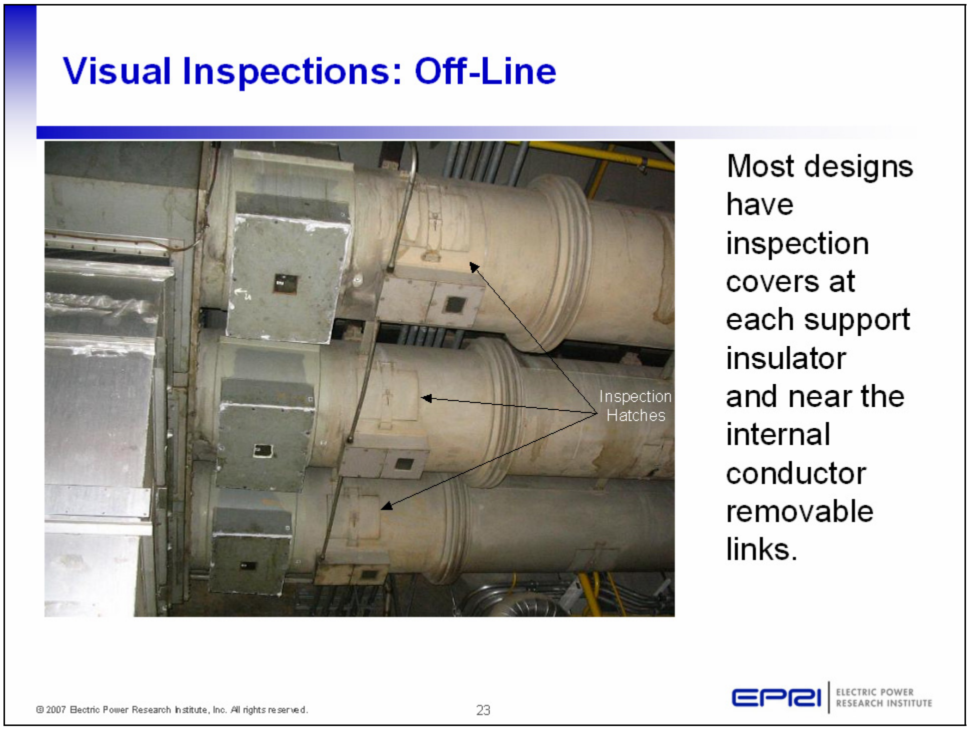
Flux shields are often required to solve high stray flux heating problems as shown here on a transformer tank lid.



## IR Thermography

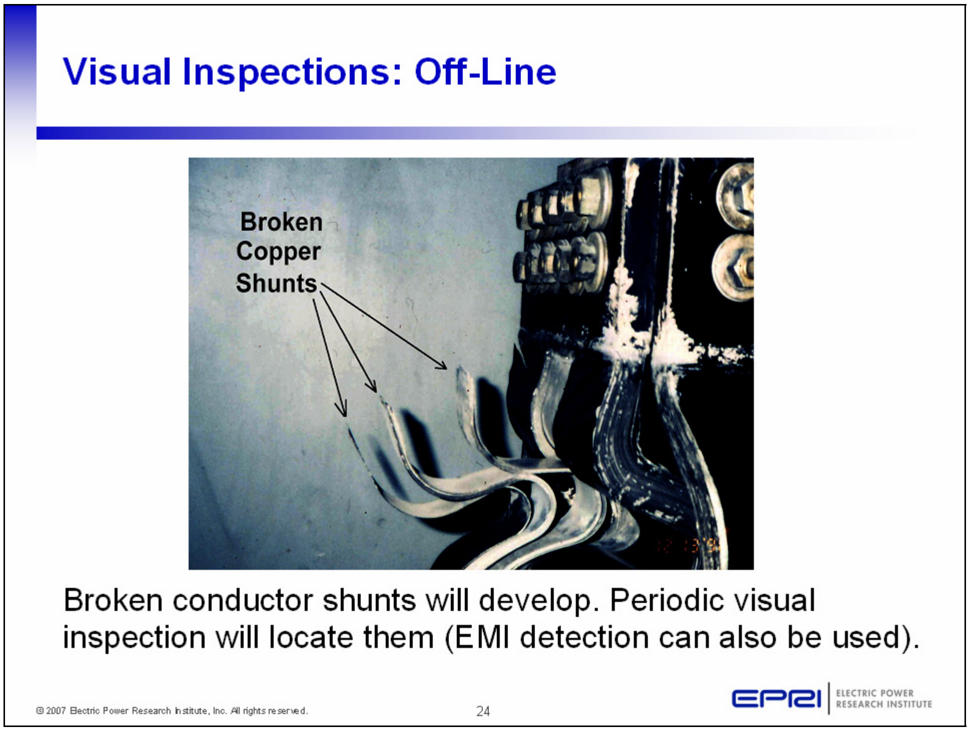
Overloaded jumpers

Loose connections



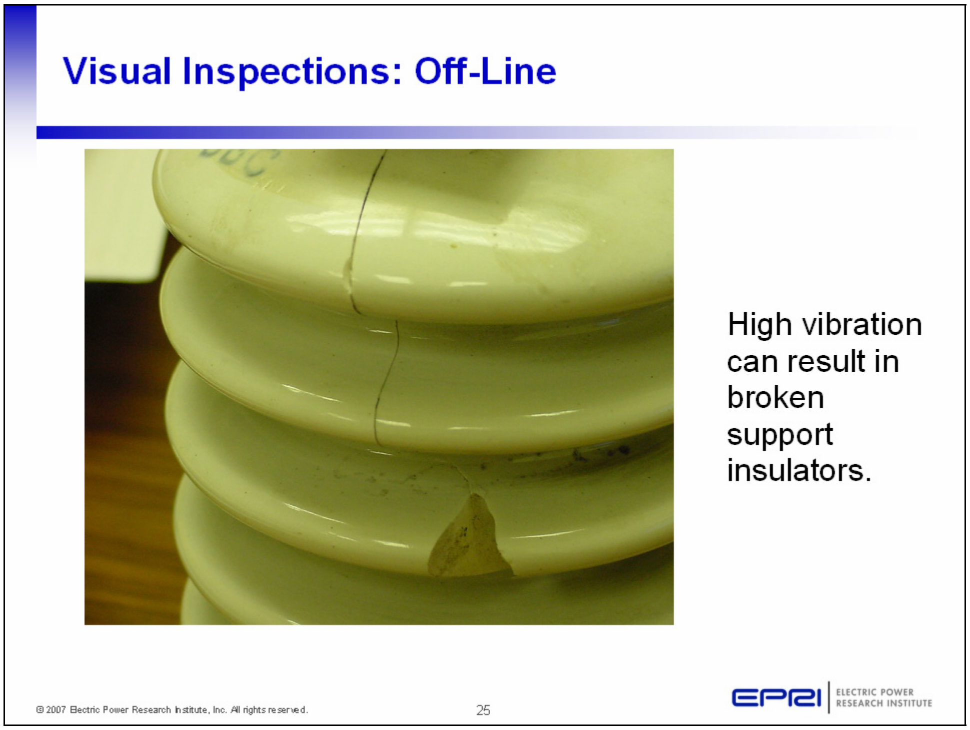
## Visual Inspections: Off-Line

Most designs have inspection covers at each support insulator and near the internal conductor removable links.



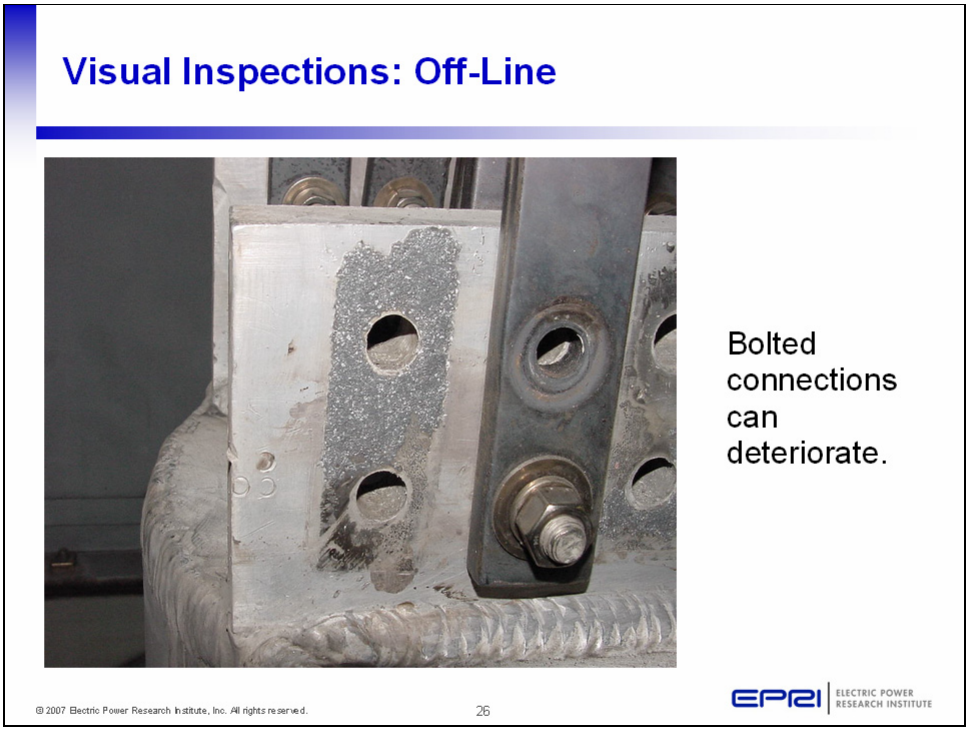
## Visual Inspections: Off-Line

Broken conductor shunts will develop. Periodic visual inspection will locate them (EMI detection can also be used).



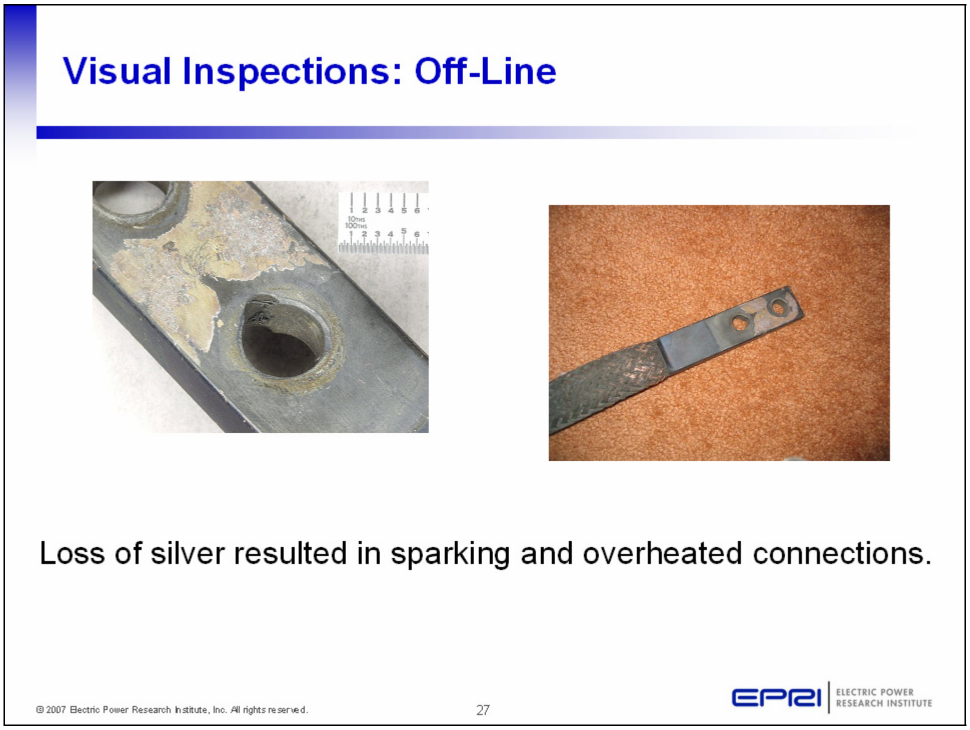
## Visual Inspections: Off-Line

High vibration can result in broken support insulators.



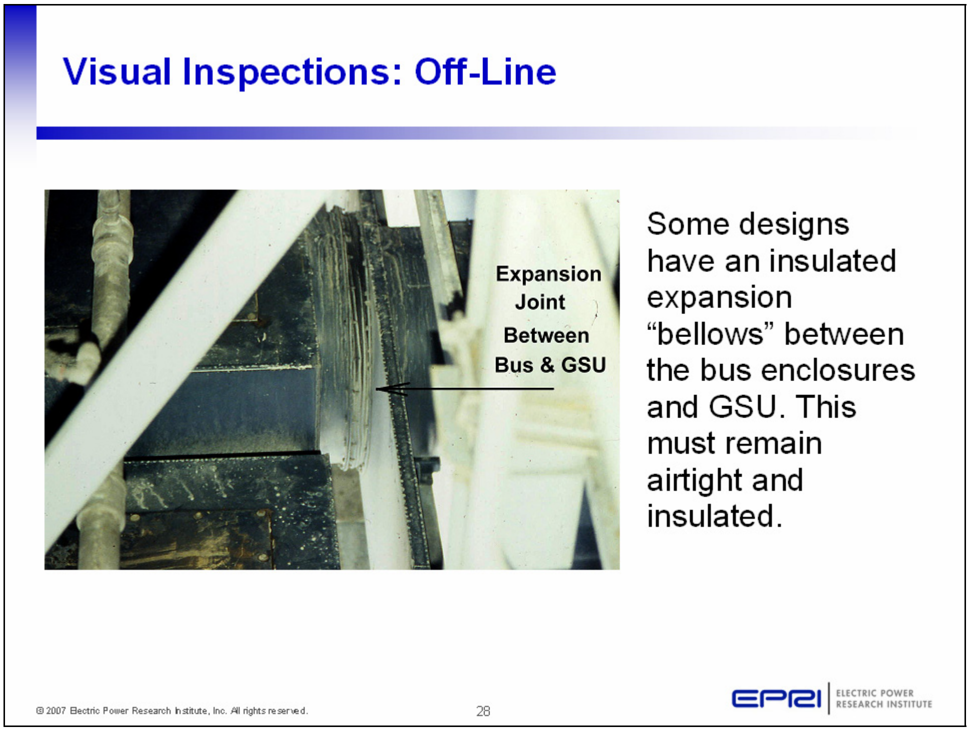
## Visual Inspections: Off-Line

Bolted connections can deteriorate.



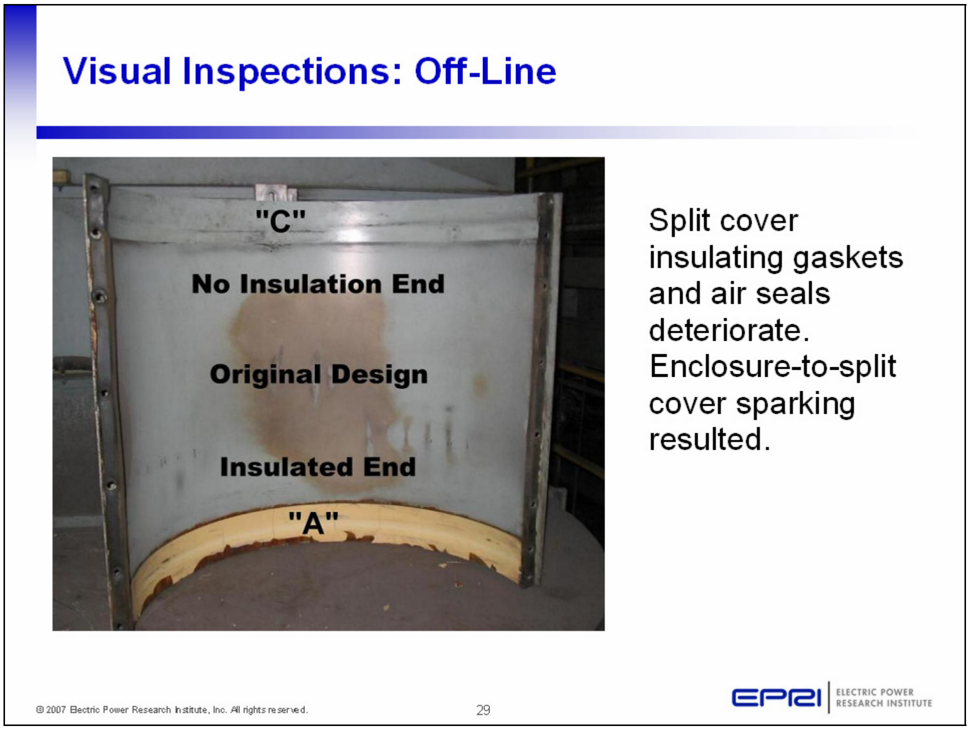
## Visual Inspections: Off-Line

Loss of silver resulted in sparking and overheated connections.



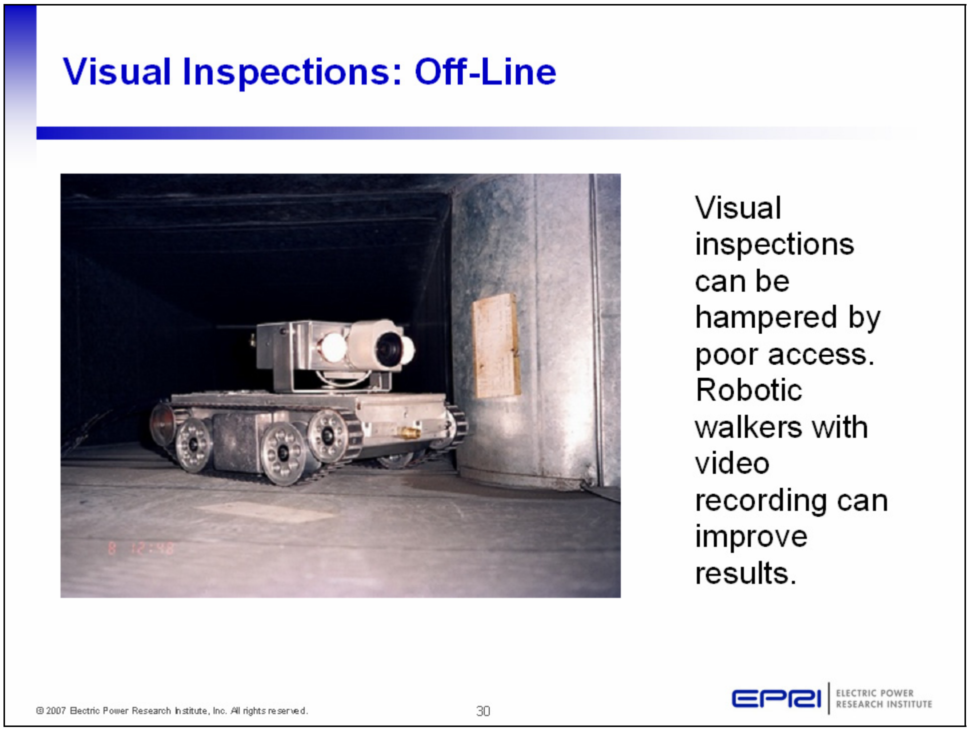
## Visual Inspections: Off-Line

Some designs have an insulated expansion “bellows” between the bus enclosures and GSU. This must remain airtight and insulated.



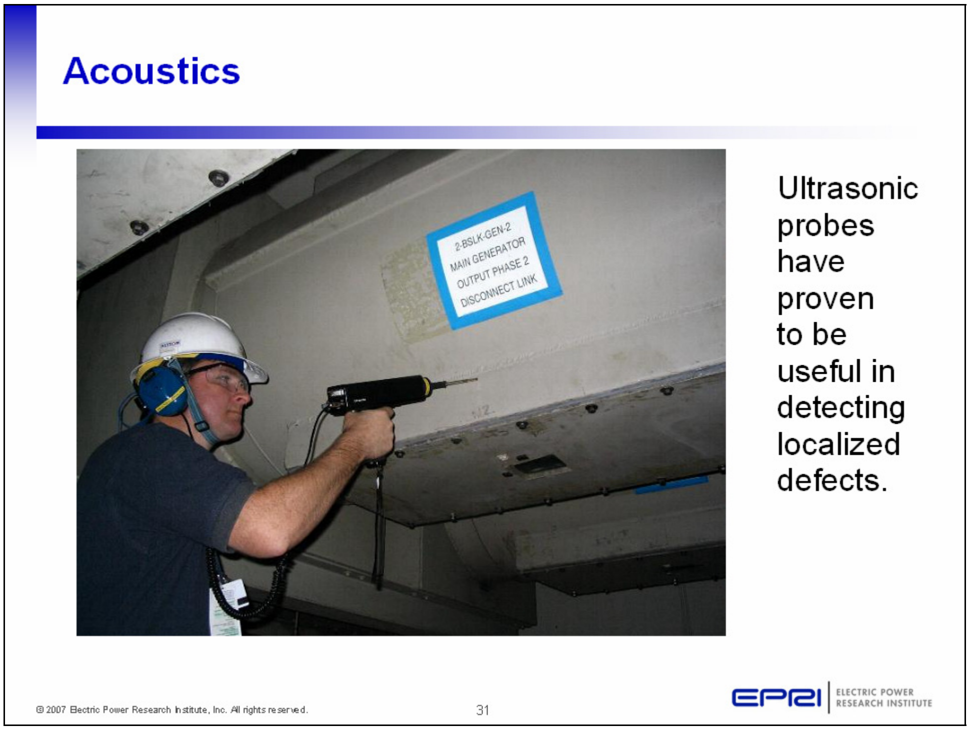
## Visual Inspections: Off-Line

Split cover insulating gaskets and air seals deteriorate. Enclosure-to-split cover sparking resulted.



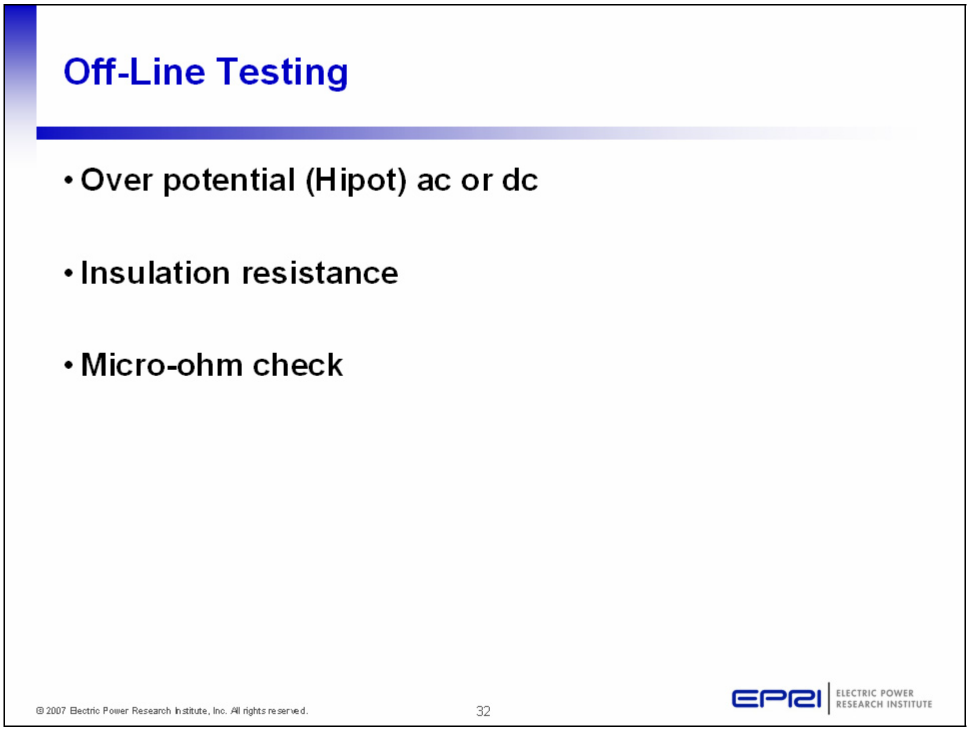
## Visual Inspections: Off-Line

Visual inspections can be hampered by poor access. Robotic walkers with video recording can improve results.



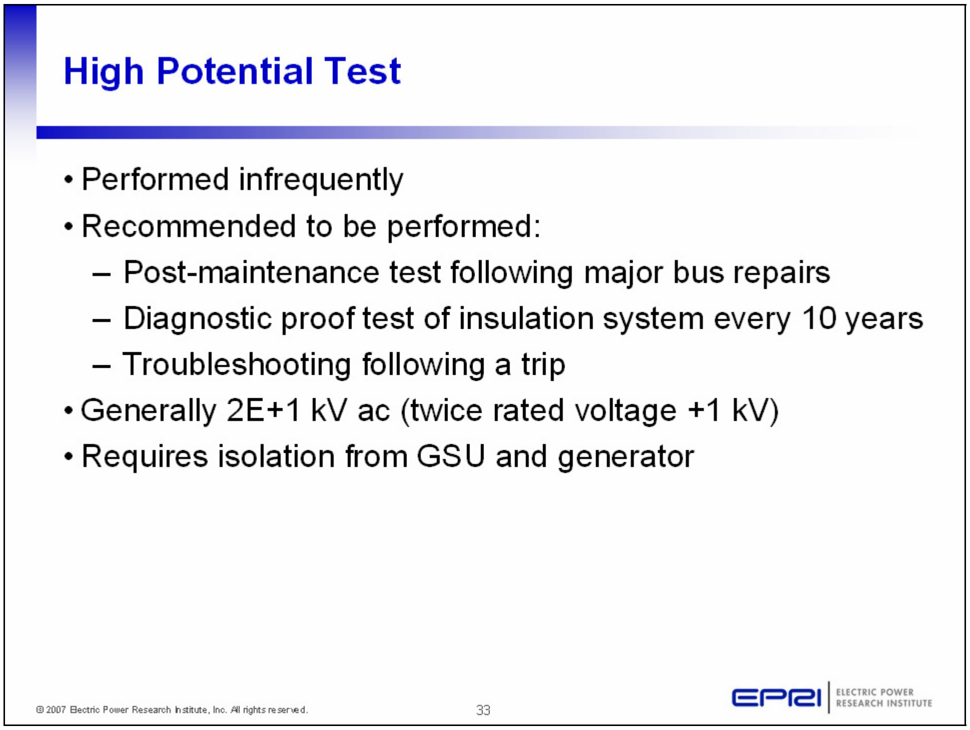
## Acoustics

Ultrasonic probes have proven to be useful in detecting localized defects.



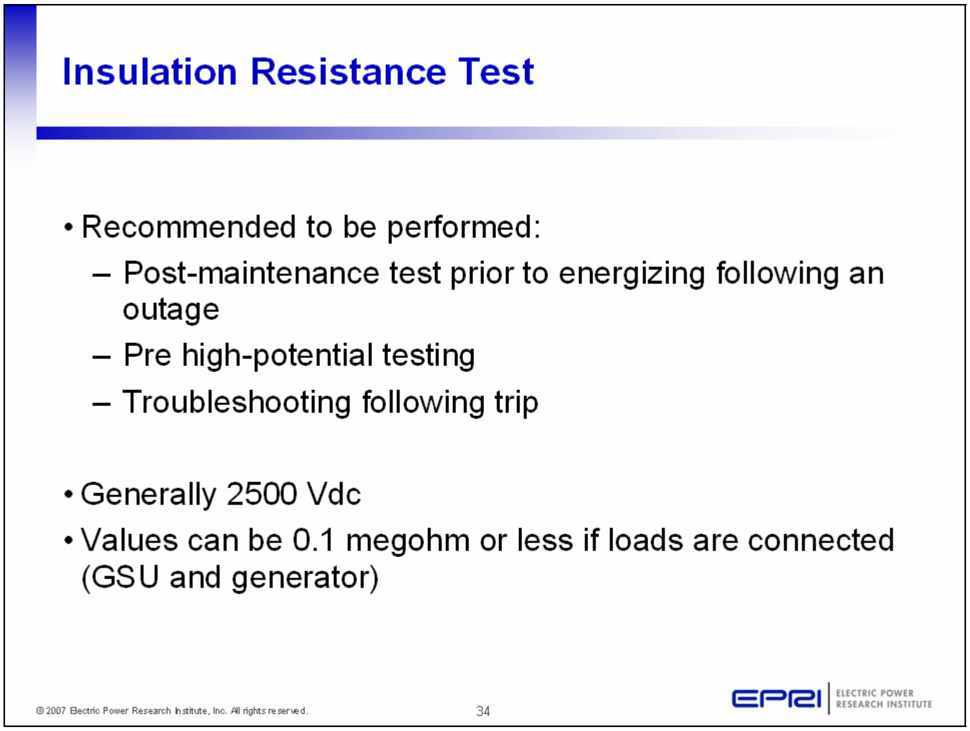
## Off-Line Testing

- Over potential (Hipot) ac or dc
- Insulation resistance
- Micro-ohm check



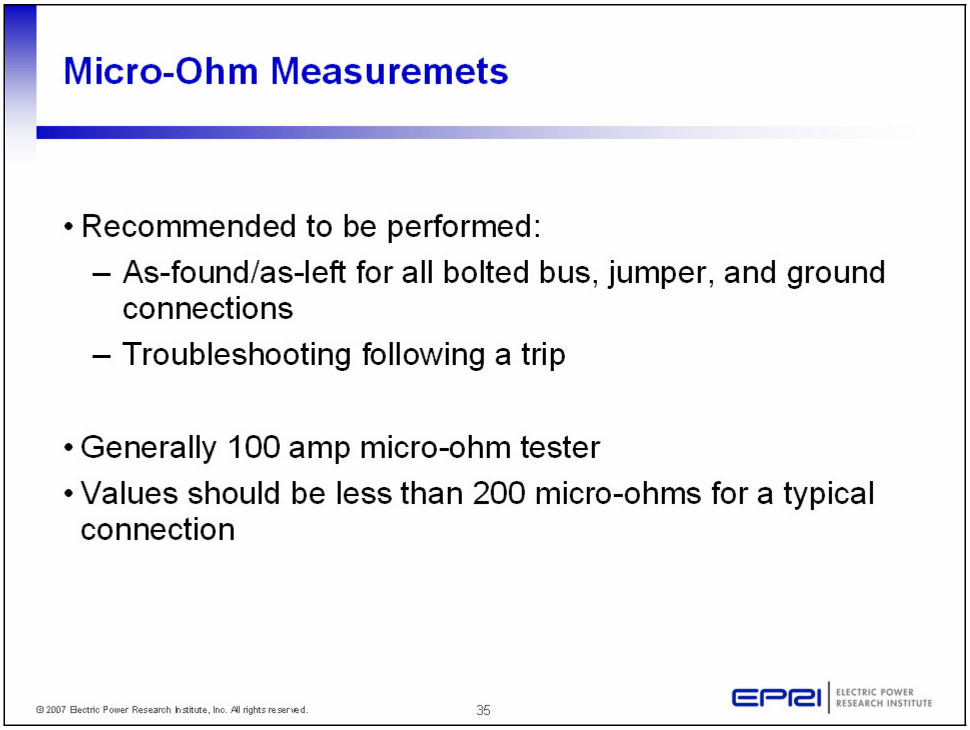
## High Potential Test

- Performed infrequently
- Recommended to be performed:
  - Post-maintenance test following major bus repairs
  - Diagnostic proof test of insulation system every 10 years
  - Troubleshooting following a trip
- Generally 2E+1 kV ac (twice rated voltage +1 kV)
- Requires isolation from GSU and generator



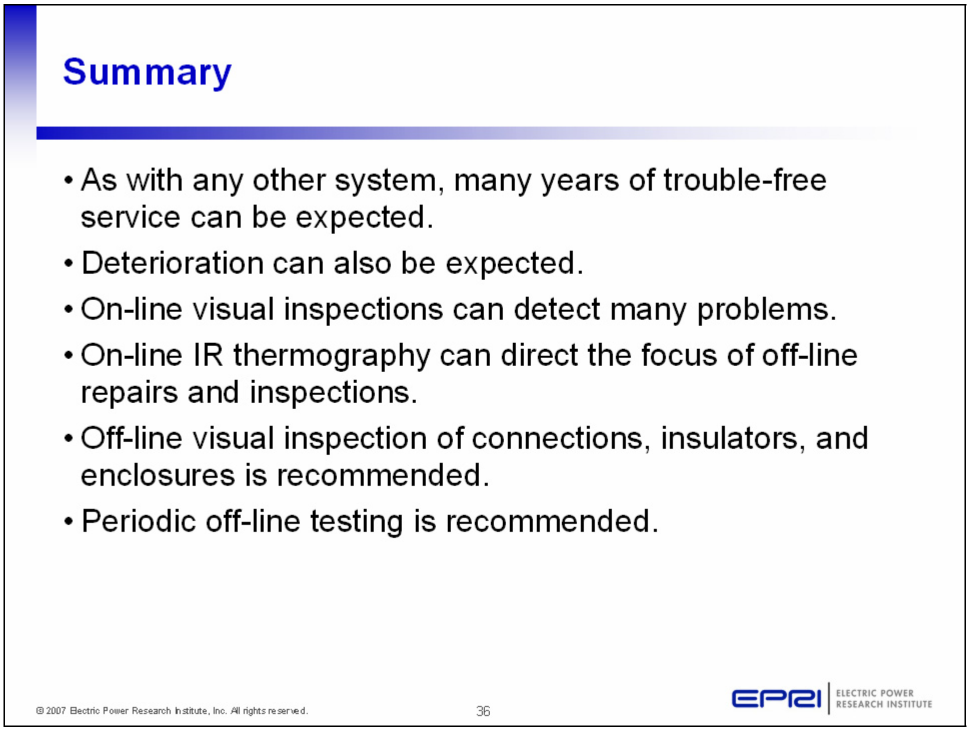
## Insulation Resistance Test

- Recommended to be performed:
  - Post-maintenance test prior to energizing following an outage
  - Pre high-potential testing
  - Troubleshooting following trip
- Generally 2500 Vdc
- Values can be 0.1 megohm or less if loads are connected (GSU and generator)



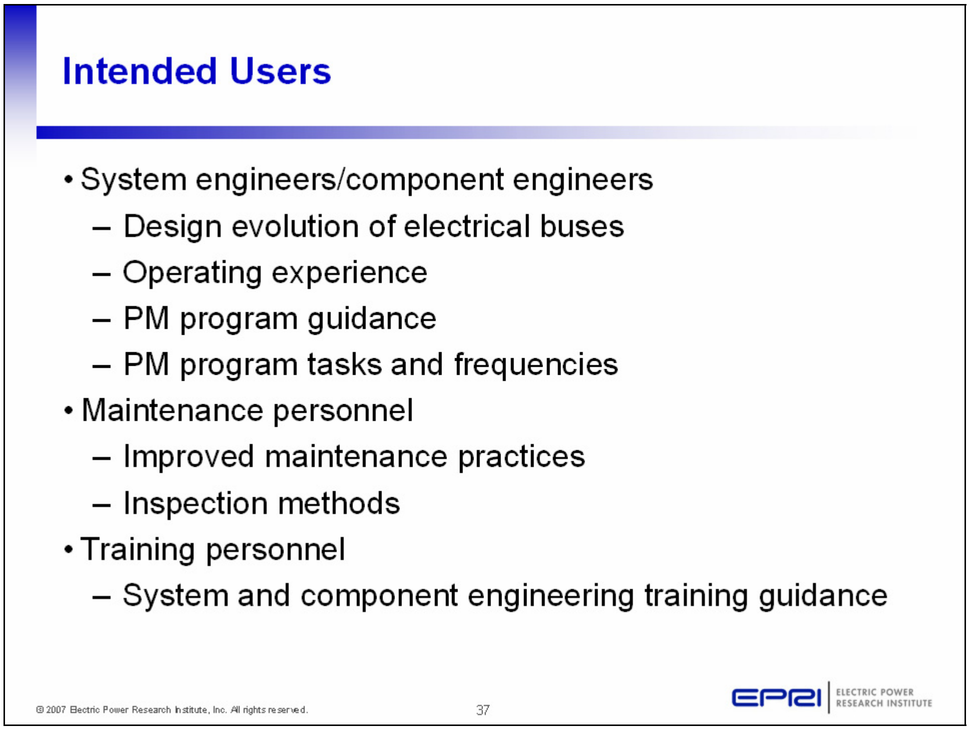
## Micro-Ohm Measuremets

- Recommended to be performed:
  - As-found/as-left for all bolted bus, jumper, and ground connections
  - Troubleshooting following a trip
- Generally 100 amp micro-ohm tester
- Values should be less than 200 micro-ohms for a typical connection



## Summary

- As with any other system, many years of trouble-free service can be expected.
- Deterioration can also be expected.
- On-line visual inspections can detect many problems.
- On-line IR thermography can direct the focus of off-line repairs and inspections.
- Off-line visual inspection of connections, insulators, and enclosures is recommended.
- Periodic off-line testing is recommended.



## Intended Users

- System engineers/component engineers
  - Design evolution of electrical buses
  - Operating experience
  - PM program guidance
  - PM program tasks and frequencies
- Maintenance personnel
  - Improved maintenance practices
  - Inspection methods
- Training personnel
  - System and component engineering training guidance

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# 產品說明

### 挑戰和宗旨

此報告讀者為對等相母線系統設計和影響系統可靠性的運行經驗不熟悉的系統或元器件工程師。本文對進行評估系統預測和預防性維修計畫工作的系統工程師也有幫助。檢修人員應當加深對通過恰當的電氣節點的栓接技術，減少出現高阻連接和重複維修的理解。本文對提高系統/元器件工程師及檢修人員對系統故障檢修的理解也有幫助。

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# 产品说明

## 挑战和宗旨

此报告读者为对等相母线系统设计和影响系统可靠性的运行经验不熟悉的系统或元器件工程师。本文对进行评估系统预测和预防性维修计划工作的系统工程师也有帮助。检修人员应当加深对通过恰当的电气节点的栓接技术，减少出现高阻连接和重复维修的理解。本文对提高系统/元器件工程师及检修人员对系统故障检修的理解也有帮助。

# 内容

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# DESCRIPTION DU PRODUIT

## Défis et objectifs

Ce rapport devrait être utile aux ingénieurs de systèmes/composants qui ne sont pas familiers avec la conception des systèmes de barres omnibus isophasées et les expériences d’exploitation qui ont affecté la fiabilité du système. Ce document est également utile aux ingénieurs de systèmes lors de l'évaluation des activités correctes de maintenance prédictive et préventive du système. Le personnel de maintenance trouvera des informations importantes sur les techniques correctes et améliorées de boulonnage des connexions électriques permettant de réduire l'apparition de connexions à résistances élevées et la répétition de leur maintenance. Ce document fournit également des informations aux ingénieurs systèmes/composants et au personnel de maintenance sur le dépannage de ce système.

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# 相分離ブス保全ガイド

### 課題と目的

本レポートは、相分離ブスシステムの設計及び運転経験情報をよく知らないシステム / 機器エンジニアに有用なレポートである。本図書はまた、システムを正しく予知保全および予防保全評価するうえで、システムエンジニアの役に立つものである。保全技術者は、高抵抗接続および繰り返し保全の発生低減に役立つ、電気的接続部のボルト改善および適切な締め付け技術ついて見識を得るであろう。さらに本レポートでは、システム / 構成部品エンジニアおよび保全技術者に、本システムのトラブルシューティングについての見識を提供する。

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# DESCRIPCIÓN DEL PRODUCTO

## Retos y objetivos

Este informe debería resultar útil para los ingenieros de componentes/sistemas que no estén familiarizados con el diseño del sistema de barra de fase aislada y las experiencias operativas que han influido en la fiabilidad del sistema. Este informe también resultará útil para los ingenieros de sistemas al determinar qué actividades de mantenimiento correctivo, preventivo y predictivo del sistema son las más adecuadas. El personal de mantenimiento debería encontrar la información sobre técnicas mejoradas y adecuadas de empernado de conexiones eléctricas útil para reducir los casos de conexiones de alta resistencia y evitar la repetición de tareas de mantenimiento en ellas. El documento también ofrece información para que los ingenieros de componentes/sistemas y el personal de mantenimiento puedan identificar y solucionar problemas en este sistema.

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