Lessons Learned from Exelon's Non-Segregated Bus Inspections

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REPORT SUMMARY

Background

In response to industry operating experience and a catastrophic failure of a non-segregated electrical bus at a U.S. nuclear power plant in 2009, Exelon's nuclear plants undertook an extensive multiyear program to inspect and test the non-segregated electrical buses at all of Exelon's nuclear plants.

The overall goal of Electric Power Research Institute (EPRI) activities in this area is to investigate bus maintenance techniques and determine whether the current recommended and/or accepted maintenance programs are sufficient for the world's existing fleet of nuclear plants, assuming long-term operation in excess of 40 years.

Objective

- To capture and document data and critical lessons learned from the inspections and testing of non-segregated buses within the Exelon fleet of nuclear power plants

Approach

This report was developed in close coordination with key individuals at Exelon who were instrumental in implementing the bus inspection program throughout the Exelon fleet. Test results, correspondence, photographs, and lessons learned were compiled to develop the information provided in this report. Exelon personnel reviewed this report for technical accuracy.

Results

This report introduces the reader to various industry events and documents pertaining to non-segregated bus maintenance. It also describes Exelon's non-segregated bus inspection strategy, and it documents critical lessons learned throughout Exelon's non-segregated bus inspection program.

Applications, Value, and Use

This report is valuable for licensees developing or enhancing a maintenance program for non-segregated electrical buses. EPRI's goal in producing this report is to help member utilities avoid bus failures—which can lead to significant damage, repair costs, plant shutdown, and plant transients—that can impact nuclear safety systems. The information in this report is based on results compiled by Exelon during fleetwide inspections. These inspections were performed on various buses of different manufacturers, designs, and materials. Consequently, the findings in this report are believed to be applicable for use throughout the worldwide fleet of nuclear power plants having non-segregated buses.

Keywords

Bus inspection
Bus maintenance
Electrical bus
Non-segregated bus
Preventive maintenance (PM)

ABSTRACT

In response to industry operating experience and a catastrophic failure of a non-segregated electrical bus at a U.S. nuclear power plant in 2009, Exelon's nuclear plants undertook an extensive multiyear program to inspect and test non-segregated electrical buses at all of Exelon's nuclear plants. The objective of the research project that is the subject of this report was to capture and document data and critical lessons learned from the inspections and testing of non-segregated buses within the Exelon fleet of nuclear power plants. This report was developed in close coordination with key individuals at Exelon who were instrumental in implementing the bus inspection program throughout the Exelon fleet. Test results, correspondence, photographs, and lessons learned were compiled to develop the information provided in this report.

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1.1 Background

In response to industry operating experience and a catastrophic failure of a non-segregated electrical bus at a U.S. nuclear power plant in August 2009, Exelon's nuclear plants undertook a multiyear program to inspect and test the non-segregated buses at all of Exelon's nuclear plants.

Also in response to industry operating experience and the catastrophic failure in 2009, the Electric Power Research institute (EPRI) has undertaken an investigation into current industry guidance and practices. A goal of EPRI activities in this area is to investigate bus maintenance techniques and determine whether the current recommended and/or accepted maintenance programs are sufficient for the world's existing fleet of nuclear plants, assuming long-term operation in excess of 40 years. In addition, EPRI's goal is to establish a sound technical basis for bus maintenance and provide more detailed and practical guidance. This report is a part of EPRI's overall initiative on the topic of bus maintenance.

The accepted maintenance program for electrical bus includes the following:

- Periodic visual inspections
- Verification of low-resistance connections
- Checking the torque of bolted connections
- Infrared thermography

Infrared thermography is used for monitoring and diagnostic purposes. Based on EPRI working group discussions, maintenance practices among plants vary considerably. Based on U.S. nuclear power industry surveys, a typical maintenance frequency is 10 years for an electrical bus. The frequencies adopted at some plants are more or less frequent. With taped joints, connection bolt torque checks are typically not performed. Access to the electrical bus is limited because of physical barriers and operational considerations. These access issues are significant challenges to industry personnel and equipment maintenance.

Opportunities for inspections of the bus are infrequent and sometimes not identified far enough in advance to capture the relevant data or lessons learned. In addition, some plants perform limited inspections and testing. Exelon's extensive testing and inspection program on electrical bus bars represents a unique and significant opportunity for EPRI and the industry to capture data, photographs, and lessons learned from Exelon's focused effort. A significant number of lessons have already been learned but have yet to be documented and communicated to EPRI-member utilities.

Key Technical Point

Exelon’s extensive testing and inspection program on electrical bus bars represents a unique and significant opportunity for EPRI and the industry to capture data, photographs, and lessons learned from Exelon’s focused effort.

1.2 Objectives

The primary objective of the research project that is the subject of this report was to capture and document data and critical lessons learned from the inspections and testing of the non-segregated buses within the Exelon fleet of nuclear power plants. Specific objectives included the following:

- Introducing the reader to various industry events and documents pertaining to non-segregated bus maintenance
- Describing Exelon’s non-segregated bus inspection strategy
- Documenting critical lessons learned throughout Exelon’s non-segregated bus inspection program

1.3 Scope

The scope of this report covers the results of Exelon’s comprehensive condition assessments of the bolted connections in more than 20 non-segregated buses in use throughout its fleet. The Exelon strategy separated the different designs of non-segregated buses into the following four categories:

- Non-segregated buses with aluminum bus conductors
- Non-segregated buses with copper bus conductors using stainless steel bolting hardware
- Non-segregated buses with copper bus conductors using galvanized carbon steel bolting hardware
- Non-segregated buses with aluminum bus conductors having louvered openings at the locations of the bolted connections

1.4 Definitions of Key Terms and Acronyms

A *non-segregated phase bus* is a bus in which all phase conductors are in a common metal enclosure without barriers between the phases [1].

The following is a list of acronyms that are used in the report:

DLRO	digital low-resistance ohmmeter
EPRI	Electric Power Research Institute
FME	foreign material exclusion
GALL	generic aging lessons learned
IN	Information Notice

IR	incident report
MEB	metal-enclosed bus
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Commission regulation
OEM	original equipment manufacturer
PM	preventive maintenance

1.5 Listing of Key Points

Appendix A of this report contains a listing of all Key Points in each category. The listing restates each Key Point and provides a reference to its location in the body of the report. By reviewing this listing, users of this report can determine whether they have taken advantage of key information that the writers of this report believe will benefit their plants.

Throughout this report, key information is summarized in Key Points. Key Points are bold-lettered boxes that succinctly restate information covered in detail in the surrounding text, making the Key Point easier to locate.

The primary intent of a Key Point is to emphasize information that will allow individuals to act for the benefit of their plant. EPRI personnel who reviewed this report assisted in the selection of the information included in these Key Points.

The Key Points are organized into two categories: Human Performance and Technical. Each category has an identifying icon to draw attention to it for the benefit of readers who are quickly reviewing the report. The Key Points are shown in the following way:

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent personal injury, prevent equipment damage, and/or improve the efficiency and effectiveness of the task.

Key Technical Point

Targets information that will lead to improved equipment reliability.

2

INDUSTRY DOCUMENTS PERTAINING TO BUS MAINTENANCE

The purpose of this section is to provide a listing of industry documents pertaining to or related to bus maintenance practices in the nuclear power industry. The listing is comprehensive of documents available at the time this report was published. This section will familiarize the reader with the industry documents associated with bus inspection and testing and with what prompted Exelon to undertake its fleetwide inspection program.

One objective of this report was to introduce the reader to various industry documents pertaining to non-segregated bus maintenance. It is recognized that the technical recommendations in these various industry documents are not in alignment. By identifying these discrepancies, EPRI and the industry can focus future efforts on resolving any discrepancies within the industry guidance.

2.1 Catastrophic Failure of a 6.9-kV Bus at a U.S. Nuclear Power Plant

In August 2009, a U.S. nuclear power plant experienced a reactor scram and main turbine trip. This nuclear plant trip was partially caused by an electrical fault in the 6.9-kV electrical distribution system. The non-segregated bus's flex connections overheated and failed catastrophically. All three bus conductors melted and resulted in a fire and significant damage. Figures 2-1 and 2-2 illustrate the effects of the electrical fault and resulting fire.

Figure 2-1
The catastrophic failure of a 6.9-kV non-segregated phase bus at a U.S. nuclear power plant

Figure 2-2
Debris from the catastrophic failure of a 6.9-kV non-segregated phase bus

The most likely cause of the failure was a combination of overheating of the flex connection and torque relaxation because of thermal cycling over time. Contributing causes to the failure included a lack of torque checks on the connection bolting and insufficient temperature monitoring.

One of the more significant lessons learned from this event was that the torque (tightness) of bolted connections on a non-segregated bus should be periodically checked. This lesson learned was one of the primary reasons that Exelon was driven to establish a program for assessing and restoring the torque on the connection bolts.

It should be noted that, to better monitor the connection temperatures, the plant installed thermography windows to allow for periodic infrared thermography inspections.

2.2 Nuclear Regulatory Commission Information Notice 2010-25

The U.S. Nuclear Regulatory Commission (NRC) issued Information Notice (IN) 2010-25 [2] to inform addressees about operating experience involving electrical connections. The IN summarizes events relating to electrical connections that occurred at four U.S. nuclear power plants.

The NRC concluded that inadequate electrical connections could lead to failure or unavailability of safety-related equipment. Inadequately maintained connections could challenge safety-related equipment or could adversely affect equipment important to safety.

After a review of operating experience, the NRC determined that torque verification, visual inspections, periodic infrared thermography inspections, the use of proper lubricants, and resistance measurements were important to ensuring the integrity of electrical connections.

2.3 Exelon's Fleetwide Inspections

In response to industry operating experience and the catastrophic failure in 2009, Exelon embarked on a strategy in 2010 to assess the condition of the bolted connections in non-segregated buses at stations within the Exelon nuclear fleet. This strategy included separating the several different designs of non-segregated buses in use across the fleet into four bins based on the approach that would be used to perform the assessment on those designs of buses. With this report, Exelon is sharing with the industry the results of the comprehensive inspections performed. These results encompass measurement data taken from more than 20 non-segregated buses of voltage ratings ranging from 2.3 kV to 6.9 kV between 2010 and 2012. Nine different stations within the Exelon nuclear fleet—seven of which are dual-unit plants—participated in the inspection program and contributed information to the Exelon knowledge base on non-segregated bus connections.

It should be noted that when this report was published, the Exelon inspections were not complete. Because of bus availability and other factors, the inspection process will continue for several years. This EPRI report captures the data and lessons learned to date. If additional lessons learned or conclusions are identified, EPRI will consider updating this report to reflect these conclusions.

Performing comprehensive condition assessments of the bolted connections in more than 20 non-segregated buses of several different designs in use across the Exelon Nuclear fleet has yielded a large amount of data from which conclusions can be drawn as to the condition of those electrical connections. Based on data taken to date, preventive maintenance (PM) strategies for future inspections on some designs of non-segregated buses were subsequently adjusted to obtain assurance of continued reliability. PM strategies were also optimized by limiting the time and resources expended during inspections of those same buses.

Key Technical Point

It should be noted that when this report was published, the Exelon inspections were not complete. As a result of bus availability and other factors, the inspection process will continue for several years. This report captures the data and lessons learned to date.

2.4 NUREG 1801

The NRC Office of Nuclear Reactor Regulations published Nuclear Regulatory Commission regulation (NUREG) 1801, Revision 2 (a generic aging lessons learned [GALL] report), in December 2010 [3]. Section XI.E4 pertains to metal-enclosed buses (MEBs). This report recommends inspections and testing on MEBs prior to the end of a utility's licensing period (or prior to a period of extended operation) and periodically thereafter. The subsequent inspection and testing frequency is based upon the method by which the inspections and testing are performed.

The report covers the inspection of internal surfaces, insulating materials (supports), bus insulating materials, and elastomers. Inspection criteria are provided in the report. The report recommends testing of a sample of bus connections as opposed to testing all connections. The report recommends a representative sample of 20% of the connection population with a maximum sample of 25.

Testing could be either by means of a low-resistance ohmmeter or infrared thermography. In some cases, bus connections can be covered with tape or other insulating materials. For these cases, an alternative to testing by means of thermography or low-resistance measurements is provided. The report suggests that visual inspections be performed. If thermography or low-resistance measurements are used for testing, the recommended subsequent testing frequency is 10 years. If visual inspection is performed without testing, the recommended subsequent inspection and testing frequency is five years.

The report does note that the ability to trend inspection results is limited. What is interesting about Revision 2 of the GALL report is not what is recommended but what is not recommended. No mention is made of retorquing of bolted connections that have loosened because of thermal cycling. The report does note that repeated thermal cycling can result in the loosening of bolted bus connections and can result in increased connection resistances. This may be more prevalent in heavily loaded buses.

The report does, however, summarize the aging effects for the components associated with MEBs. Bus connections of various metals can exhibit increased resistance of connection resulting from the loosening of bolts caused by thermal cycling and ohmic heating, and elastomeric enclosure assemblies can exhibit surface cracking, crazing, scuffing, dimensional change (for example, ballooning or necking), shrinkage, discoloration, hardening, and loss of strength because of elastomer degradation.

2.5 EPRI Reports Pertaining to Bus Maintenance

The purpose of this section is to familiarize the reader with guidance published in other EPRI reports that pertain to bus maintenance. The guidance in these EPRI reports may in fact differ from the lessons learned through the Exelon fleetwide inspection program but are presented here as a benchmark to illustrate the evolution of maintenance practices in this area. By identifying discrepancies in industry practices, EPRI and the industry can focus future efforts on resolving any discrepancies within industry guidance.

2.5.1 EPRI Report 1013457

The intent of EPRI report 1013457, *Nuclear Maintenance Applications Center: Switchgear and Bus Maintenance Guide* [4], is to provide guidance on bus inspection and testing. The report provides an overall description of the various types of switchgear buses. Specific industry operating experience is reviewed. Bus failure mechanisms are identified and evaluated. Monitoring techniques used to detect the failure mechanisms are described. And, finally, maintenance issues are covered.

Specifically, the guidance in the report suggests lubricating (where prescribed) and tightening all components of the switchgear and considering additional diagnostic and predictive maintenance tasks, such as thermography, acoustic monitoring, and equipment inspection reports.

Section 6.4 provides the following guidance regarding the maintenance of bolted connections:

> *6.4 Bolted Electrical Connections*
>
> *Sound bolted electrical connections are the most important attribute in bus maintenance. The three most important aspects are:*
>
> - *Materials*
> - *Torque: fasten torque for bus joints and cable connections*
> - *Cleanliness and surface preparation for electrical joints*
>
> *6.4.1 Materials*
>
> *Bus materials are copper, aluminum, silver-plated copper, and silver-plated aluminum. The choice of material or plating is to minimize resistivity at the connection. Material compatibility can prevent dissimilar metals that can lead to degradation and potential failure of bus connections.*
>
> *An electrical connection must be designed to remain tight and maintain good conductivity through a large temperature range. Meeting this design requirement is difficult if the materials specified for the bolt and the conductor are different and have different rates of thermal expansion. For example, copper and aluminum bus materials expand faster than most bolting materials. If thermal stress is added to stresses inherent at assembly, the joint members or fasteners can yield. If plastic deformation occurs during thermal loading, the joint can be loosened when the connection cools.*
>
> *The following recommendations apply:*
>
> - *Special cleaning and coating requirements for aluminum prevent the formation of a high-resistivity aluminum oxide film on the exposed metal.*
> - *Aluminum bolts are recommended for use with aluminum buses in order to achieve the same coefficients of thermal expansion. Aluminum bolts are often lubricated to prevent galling during assembly.*
> - *Bronze bolts are ideal for use with copper buses. The two materials have nearly the same coefficients of thermal expansion.*
> - *Low carbon steel bolts are not recommended for power connections.*
> - *High-strength steel bolts are recommended for use with copper or aluminum buses because of their low cost. Coating these bolts with zinc (that is, galvanizing) reduces oxidation and corrosion. Because high-strength steel bolts have a relatively low coefficient of thermal expansion, Belleville washers should be used.*
> - *The coefficient of thermal expansion for austenitic stainless steel bolts is comparable to that of copper bus. These bolts are suitable for corrosive environments. Class 1 bolts are not recommended for use with aluminum buses. Class 2 bolts are appropriate for any application.*
> - *The bolt length of bus connections (including bolts, washers, and nuts) should not impact the dielectric integrity of the bus. In other words, the bolt should be of sufficient length to fully engage the nut, but it should not protrude beyond the nut to a point where minimum live part clearances become an issue or insulating materials are mechanically stressed.*

6.4.3 Torque

Torque provides a measure of force at the bus connection that reduces the resistivity of the connection and minimizes the possibility of contamination of the joint or corrosion due to contaminants. However, torque is not a direct measure of force, which is the key element in a sound electrical connection. Friction can impact the torque values. A well-lubricated fastener is stressed to a higher force for the same torque than one that is not lubricated. For example, a lubricated fastener can fracture at the higher force.

Torque values for a bus connection can be provided by the manufacturer. Torque values on bolts can range ±25% using a torque wrench. The use of a Belleville washer or direct tension indicator might reduce inaccuracies associated with torque values and the variability associated with bolt lubrication.

A torque procedure includes initially tightening the bolts finger tight followed by the use of a torque wrench to half of the recommended torque value. The torque sequence should ensure a uniform pressure applied to the mating connection surfaces. The appropriate symmetrical torque sequence can ensure full clamping force and contact area.

6.4.3.1 Torque for Electrical Bus Bars

The measurement of torque on bolted connections provides an indication of the force at a connection point. Force is related to torque. Torque readings can be affected by lubrication; therefore, different torque values apply to lubricated versus fasteners that are not lubricated. Care should be taken not to exceed the listed torque values, which could lead to failure of the fastener hardware or damage to the associated bus or connector plates.

Bolted connections must meet minimum torque specifications or low resistance appropriate for the application. If torque values are not given by the manufacturer, a baseline can be developed based on existing connections, and torque values can be trended. A decrease in the as-found torque readings is an indication of a relaxation of the connection. Subsequently higher operating temperatures at the connection can occur, leading to degradation of the insulation system.

Key Technical Point

Care should be taken not to exceed the listed torque values, which could lead to failure of the fastener hardware or damage to the associated bus or connector plates.

2.5.2 EPRI Report 1015057

Section 11 of EPRI report 1015057, *Nuclear Maintenance Applications Center: Isolated Phase Bus Maintenance Guide* [5], provides detailed maintenance guidance for maintenance. For general bus ducts, the following visual inspections and tests are recommended to be performed after every major outage:

Visual Inspections:

- *General appearance of the non-segregated bus duct and its associated systems (preservation, cleaning, and debris)*
- *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*
- *Makeup air filter integrity and cleanliness*

Testing:

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.

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.

For bus enclosures, the following visual inspections and testing are recommended whenever disturbed for other maintenance, one-third of bus every major maintenance outage, or every 7 to 10 years:

Visual Inspections:

- *Exterior general cleanliness and wildlife intrusion and/or nesting*
- *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)*

Section 12 of EPRI report 1015057 provides the following guidance regarding the deterioration and repairs of internal bolted joints:

> *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. 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 nonmagnetic 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 overtorque 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.*

2.5.3 EPRI Report 1003471

Section 3.3 of EPRI report 1003471, *Electrical Connectors Application Guideline* [6], provides the following guidance regarding the inspection of bolted electrical connectors. Note that Exelon's operating experience with, and strategy for maintaining, the reliability of bolted connections differs from the position presented in EPRI report 1003471.

> *3.3.3 Inspection of Bolted Electrical Connectors*
>
> *Upon assembly, utility personnel typically check electrical connections by hand or with a wrench to ensure that bolts are not loose. The applied torque is not checked after assembly. Retorquing the joint after assembly is not an appropriate method to confirm installation torque because repeated tightening could actually damage the connector and eventually lead to failure.*
>
> *Some plants also verify that the connection has low electrical resistance using a low range ohm meter. Critical connections are periodically inspected visually for evidence of overheating, burning, or discoloration, and indication of loose bolts.*
>
> *3.3.4 Maintenance of Bolted Electrical Connectors*
>
> *Bolted connections do not require periodic retightening. As described previously, after a connector is installed with the proper torque, repeated tightening could actually damage the connector and eventually lead to failure.*

2.5.4 EPRI Report 1015336—Bolted Joint Fundamentals

EPRI report 1015336, *Nuclear Maintenance Applications Center: Bolted Joint Fundamentals* [7], reviews the fundamentals of the bolted joint and the importance of preload. The report then describes the different methods of applying preload, including torquing, hydraulic tensioning, and fastener stretch. The focus is on torquing as the primary method used in a power plant, and the report provides torque tables and the basis for the torque tables. It does not, however, contain any specific guidance regarding the inspection of bolted electrical connections for non-segregated buses.

2.5.5 EPRI Report 1015337—Assembling Gasketed, Flanged Bolted Joints

EPRI report 1015337, *Nuclear Maintenance Applications Center: Assembling Gasketed, Flanged Bolted Joints* [8], reviews the fundamentals of flanged joints and the use of spiral-wound and sheet gaskets. It explains the reasons for preload and provides a basis for the target preloads to be used with spiral-wound and sheet gaskets. Similar to EPRI report 1015336, it describes the different methods of applying preload, concentrating on torquing as the primary method used in a power plant. It provides torque tables and the basis for the torque tables. It does not, however, contain any specific guidance regarding the inspection of bolted electrical connections for non-segregated buses.

3

EXELON BUS INSPECTION STRATEGY

The purpose of this section is to present the sequence of steps that were implemented at all of the Exelon nuclear stations when investigating the as-found torque on the non-segregated connection bolts. Exelon ensured that this technique was consistently implemented so as to establish a baseline with the way the data were measured and recorded across the Exelon fleet. The technique was reviewed and received significant support as being an effective means to measure residual bolt torque. Contributors who reviewed the inspection process and strategy included representatives from two major manufacturers and from Exelon Corporate Plant Engineering, as well as Commonwealth Edison substation electricians.

After the connection bolts on a non-segregated bus connection had been exposed by removing the necessary bus duct covers and any boots, tape, and/or putty that was installed around the bolted connections, the steps explained in the following sections were performed and the data were recorded in a data table that was provided to site plant engineering departments on a daily basis for evaluating/compiling the condition of the connections.

3.1 Grounding

Proper grounding procedures should be followed at all times. With respect to grounding, Exelon found that grounding the bus at both ends results in creating a parallel path around each of the connections on which the resistance is measured. That introduces an error in measured resistance so that the measured value across each connection will be lower than the true connection resistance. The degree of error introduced will be dependent upon the length of the bus and the number of bolted connections in series from one end of the bus to the other. The longer the bus and the more the connections are in series, the less error will be introduced into the resistance measurement taken at each connection. For the sake of accuracy, it is much preferred that all of the connection resistances be performed with a ground at only one end of the bus.

Key Technical Point

Proper grounding procedures should be followed at all times. With respect to grounding, Exelon found that grounding the bus at both ends results in creating a parallel path around each of the connections on which the resistance is measured. That introduces an error in measured resistance. Exelon's preference was to take resistance measurements with the bus grounded at only one end.

3.2 Measuring Electrical Resistance Across Connections

Measurement of as-found electrical resistances across connections was performed using a digital low-resistance ohmmeter (DLRO) using as high a current scale as the instrument will allow if the test current is adjustable. Exelon recommends taking the measurement several times, each time lifting the test lead terminals and reconnecting them to confirm that the measurement obtained is consistent and accurate. Record the lowest measured resistance as applicable to that particular bus connection.

3.3 Acceptance Criteria

Exelon's acceptance criteria determined through Exelon's own extensive operating experience and discussion with bus manufacturers are provided in the following paragraph.

For non-segregated buses that are rated 3000 amperes or lower, the resistance across any bolted connection is not to exceed 10 micro-ohms. For buses rated above 3000 amperes, the resistance is not to exceed 6.25 micro-ohms. If the measured resistance of a bolted connection is outside of these acceptance criteria, bring the issue to the engineering organization immediately for evaluation as to whether that bolted joint should be disassembled, cleaned, reassembled, and retested. If such a connection must be disassembled, cleaned, and reassembled, it is recommended that new hardware of the same type and material be used to make up the connection.

3.4 Confirmation of Physical Configuration

Determine whether the specific bolted bus connection design employs swage nuts that are pressed into one side of the connection or whether the connection employs separate nuts and lock washers or Belleville washers.

Figure 3-1 illustrates splice plates from Dresden Unit 2.

Figure 3-1
The splice plates installed at Dresden Unit 2

Figure 3-2 illustrates the configuration of a General Electric 4-kV non-segregated bus joint from Quad Cities during a 2012 inspection.

Figure 3-2
A 4-kV non-segregated bus joint at Quad Cities

Figures 3-3 through 3-5 illustrate the configuration of non-segregated bus bolted flex connections installed at Braidwood station.

Figure 3-3
A non-segregated bus bolted flex connection, Example 1

Figure 3-4
A non-segregated bus bolted flex connection, Example 2

Figure 3-5
A non-segregated bus bolted flex connection, Example 3

Figure 3-6 illustrates the configuration of non-segregated bus connections installed at the Byron station.

Figure 3-6
Non-segregated bus bolted connections

3.5 Measurement of As-Found Torque

The following are the steps used in the measurement of as-found torque:

1. For those connections that use bolts and nuts, determine which side of the connection (bolt or nut) allows the better access for a torque wrench to be used. It is acceptable to use the torque wrench on either the bolt or the nut. It has been determined to be preferable for the torque wrench to be used on the nut side wherever possible because the nut is usually deeper/thicker and the wrench is less likely to slip off.
2. If a connection employs swage nuts, mark the heads of all of the bolts for reference so that, when retightening the bolt/nut after each bolt head has been loosened, it can be determined when the bolt head has been brought back to its original position during the steps to measure the as-found (that is, residual) torque.
3. If a connection employs nuts and bolts, mark the as-found positions of both the nuts and the bolts. When the loosening and retorquing is performed, it is important that, at whichever end (head or nut) is going to be held stationary with a second wrench, this stationary bolt head or nut be maintained in its as-found position. The marks will confirm whether this is the case after the as-found torque measurements are taken.
4. After marking the bolt heads (and also nuts if they are used) as listed in Step 2 or 3, measure the as-found torque by loosening the bolt head (or nut) approximately one-quarter to one-half turn and then using a torque wrench that holds the highest value of torque it detects to retighten the bolt in a continuous motion until the bolt head or nut on which the torque wrench is used reaches its original position as determined by the markings made in Step 3. Record that torque measurement indicated on the torque wrench as the as-found bolt torque. If, during the tightening sequence, the torque wrench motion is stopped before the bolt head/nut reaches its original marked position, the bolt head/nut has to be reloosened and another attempt made to torque the bolt to its as-found condition. It is important that the torque wrench be moving continuously up to the point where the bolt head/nut reaches the marked position. The reason behind this is because the coefficient of friction on a bolt is higher on a bolt at standstill than when the bolt is being rotated. The correct torque value is captured while the bolt is in motion. An erroneously higher torque value would be indicated if the torque measurement were to be made when trying to tighten a bolt that is at standstill.

Note that if the bus connections employ bolts and nuts, it must be verified that the nut or bolt head that was held steady while the torque wrench was used on the opposite end of the bolt did not move from its original position. If it did move, the as-found torque measurement recorded in Step 4 will be erroneous and must be repeated

3.6 Adjusting Torque to Design Value

After the as-found torque has been measured on all of the bolts on a composite non-segregated bus connection, a torque wrench that is calibrated to click or stop at the final design installation torque for the bolt size and type at that connection can be used to first loosen each bolt a small amount and then retorque each of the connection bolts in a continuous motion up to its full design installation torque value.

3.7 As-Left Connection Resistance Measurement

After all of the connection bolts on a composite non-segregated bus connection have been retorqued to their design installation torque value, an as-left connection resistance measurement is to be made with a DLRO and recorded by connecting the test leads in the same locations as was done in Step 1 to measure the as-found resistance. Take each measurement several times to confirm that consistency is being obtained for that resistance value, and then record the lowest measured resistance. If any final connection resistance does not meet the acceptance criteria listed in the preceding section, immediately bring it to the attention of site engineering personnel for resolution.

3.8 Ongoing PM Tasks

As part of Exelon's overall PM on each non-segregated bus, other potential failure mechanisms that continued to be inspected included the following:

- Signs of water intrusion
- Corrosion on any connections
- Dirty or cracked standoff insulators
- Deteriorated cover gaskets and so forth

Also, mounting bolts for standoff insulators are to be checked and retorqued as necessary.

4

CONSIDERATIONS FOR BUS MAINTENANCE INSPECTION AND TESTING

4.1 Accessibility of Connections Based on Bus Design

Exelon has found it impractical and time-consuming on certain designs of non-segregated bus to check the electrical resistance across the connection joints and the bolt torques on all of the connection bolts because of the difficulty in gaining access to those connections. On other bus designs, it has indeed been practical to collect these data and collection has already been performed on 100% of the connection bolts in several non-segregated buses at Exelon nuclear stations. A third design of non-segregated bus in service at an Exelon plant features louvers cut into the metal enclosure surrounding the bus conductors that allows a direct line of sight to the taped-over connection bolts. These louvered openings make it possible to take accurate reliable thermographic scans to detect any connections with temperatures out of line with the others on that bus. Thermographic scans have identified connections requiring maintenance in approximately four locations.

Figures 4-1 and 4-2 illustrate as-found conditions at one Exelon plant indicating that dust does enter the emergency diesel generator non-segregated bus internal because the inspection covers (clam shells) are not sealed. The manufacturer recommended cleaning all of the internals before a high-potential test of these buses at 4 kV, and although they are dusty inside, they are not extremely dusty.

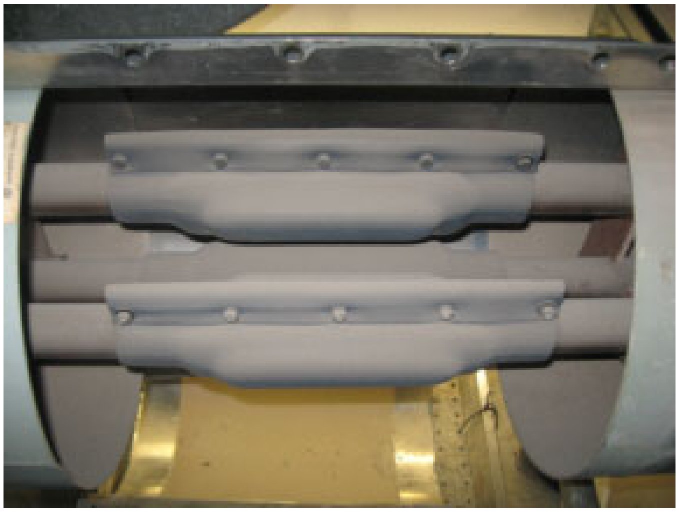

Figure 4-1
Dust found in non-segregated bus internals, Example 1

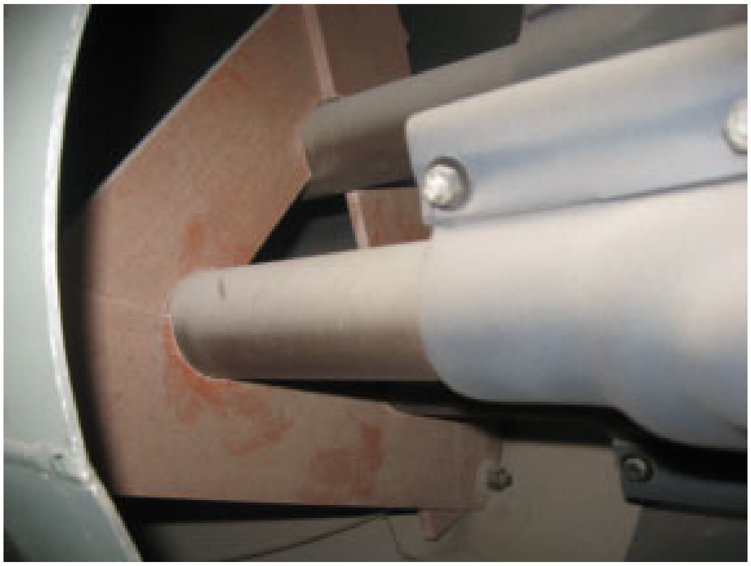

Figure 4-2
Dust found in non-segregated bus internals, Example 2

Figure 4-3 illustrates that there can be long runs between clam shells where it is not possible to reach from the inspection points to reach all internals to clean them thoroughly before a high-potential test.

Figure 4-3
Long runs between clam shells preventing thorough cleaning

4.2 Appropriate Consideration of Vendor Information

One bus connection manufacturer agreed with Exelon’s technical position that loosening the bolt and then retorquing it to the design torque value was acceptable and that typically there would be no need to replace the bolt. However, if the bolt were to be overtorqued, which would stretch the bolt and change its mechanical properties, the bolt would need to be replaced. Exelon’s inspections did not find any bolts that had been overtorqued; therefore, no bolts were replaced. Instead, maintenance personnel simply performed the retorquing process that was integrated into the Exelon procedures and is described in this report.

Although one major manufacturer did not document the minimum acceptable resistance values for the bus connections, the information that follows was based on the design information for each type of bus duct specified. These values were based on 1linear foot of bus and included one joint. An unverified rule that one manufacturer used was that *the resistance of the bus joint could not be greater than the total resistance of 1 linear ft of bus bar*. As such, Exelon took into consideration the following design information when establishing the appropriate acceptance criteria:

- 4000A bus (6-in. [152.4-mm] aluminum tubes): 1.54 micro-ohms per foot (includes a connection)
- 3000A bus (dual 6-in. [152.4-mm] flat copper bar): 3.75 micro-ohms per foot (value is for each individual bar/connection)
- 2000A bus (6-in. [152.4-mm] flat copper bar): 3.75 micro-ohms per foot (includes a connection)
- 1200A bus (4-in. [101.6-mm] flat copper bar) :11.5 micro-ohms per foot (includes a connection)

As mentioned previously, the information was based on the original design information for each type of bus duct. The manufacturer did not identify acceptable resistance readings for maintenance testing when it was manufacturing the bus duct. The primary focus was ensuring that the clamping force for each connection was met. This was confirmed through the torque values provided in the manufacturer’s published product manual.

Exelon also noted that the manufacturer’s acceptance criteria were presented in terms of micro-ohms per foot (including connections). However, to make it clearer for the electricians in the field making the measurements, the acceptance criteria were modified to micro-ohms across the bus bar splice plate, which made it clearer that one lead was to be placed on one bus bar and the other lead was to be placed on the bus bar that was on the other side of the splice plate.

4.3 Sampling of Non-Segregated Bus Connections

One of the main lessons learned at the first plant that underwent bus connection inspections was that checking a 10% sample of the number of connections on each bus was a good starting point.

Key Technical Point

Although sampling was effective in many cases, a fully executable contingency plan needs to be in place to expand the scope to 100% of the bolted connections on any bus that has an aluminum conductor.

One station initially got through about 80% of the connections on its aluminum bus during a recent outage. On the bolted connections checked on the station's aluminum non-segregated bus inspected during that most recent outage, however, nearly 75% failed to meet the acceptance criteria for residual torque. Exelon ensured that this lesson learned was quickly shared throughout its fleet so that other plants with upcoming outages could make their bus connection inspections as effective as possible.

Key Technical Point

Exelon's inspection results suggest that the remaining connections in a bus are acceptable if within the initial 10% sample, there are absolutely no bolts with residual torque less than 70% of the design installation torque, **and** there are no connection resistances greater than 10 micro-ohms for buses rated up to 3000 amperes and 6.25 micro-ohms on buses rated 4000 amperes.

These criteria were arrived at after collecting data on more than 100 locations of bolted connections and taking into consideration some factory acceptance data from manufacturers, which were much more stringent than these resistance values.

Key Technical Point

A consensus rule developed by Exelon technical personnel is that the total resistance of the bolted joint measured at ambient temperature has to be low enough so that, at rated bus current through the connection, the I^2R heat generated at that joint should be no more than about 100 W.

4.4 Conducting Bus Connection Inspections

4.4.1 Cleaning the Mating Surfaces

The presence of the corrosion at the side of the interface between the mating connection surfaces should necessitate that this connection be taken apart and the mating surfaces cleaned carefully with Scotchbrite[1] (being careful not to rub off any silver plating). If any pitting on the mating surfaces is detected, Exelon's research suggested going the extra mile to blue-check the contact area. Machinist's bluing ink should be applied to one side, and then the connection should be bolted together. Then, they should be separated again to check the percentage of contact area.

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[1] *Scotchbrite* is a registered trademark of 3M.

Exelon established a minimum of 70% contact area between the two mating surfaces. That acceptance criterion was established back in the early 1990s, when generator neutral links were getting very hot in service. The connections were improved by careful filing off the high spots on the surfaces to get 70% contact area and then replating the surfaces with silver on any of the contact area where the silver plating had worn off.

4.4.2 Replacing Washers

One technique that has been used across the industry to improve the quality of bolted electrical connections is to enhance the bolting hardware by using much thicker washers than were originally used to ensure that they would not physically deform (cup or dish) under the bolt heads if the original washers had done so. Connection inspection results suggest that when the washers cup under the bolt heads because they are not thick enough, they are pulled into the holes in the links. This causes most, if not all, of the current through the bolted connection to concentrate immediately around the hole where the washer gets cupped, because the clamping pressure is much higher at that location. That configuration can lead to overheating under higher-current operation. When it is discovered that washers have physically deformed/cupped, a recommended effective method to eliminate that condition is to replace them with new ones, preferably of 316 stainless steel, that are at least 1/8 in. (3.17 mm) thick and with holes in them that are just barely larger than the bolt diameter. This would ensure that the clamping force from the bolts will be distributed widely over the available contact area instead of just around the metal nearest the bolt hole.

4.4.3 Grease Applied to Contact Surfaces

When a bolted connection is restored to its design torque value, maintenance personnel need to ensure that the correct kind of grease is applied to the contact surfaces. If a contact area is bare aluminum, the appropriate type of corrosion inhibitor specifically for aluminum connections should be used and wire-brushed into the surface right before they physically make up that connection. Aluminum oxidizes in a matter of minutes, which is why it needs to be applied quickly.

If two contact surfaces that are both silver-plated are being bolted together, a different kind of grease should be used. This type of connection would most often require a zinc chromate type of product or other acceptable alternative.

4.4.4 Spare and Replacement Parts Availability

Ensure that there is a reasonable amount of spare replacement bolting hardware available in those cases when the original bolting hardware has to be completely removed at a connection for any reason. If any original bolting hardware is completely removed, it should be replaced with new and unused components of the same material. Also ensure that if any special high-voltage taping materials will be required to restore tape on connections on which it gets removed for the bus inspection, the appropriate type of taping and insulating materials are purchased ahead of time and are available when required.

Be aware that if smoothing putty is found installed under connection insulating tape, it could contain asbestos if it had been installed prior to about 1980. Removal of asbestos-containing putty must be done by a qualified asbestos removal company and the area declared asbestos-free before work on the connection can resume.

Key Human Performance Point

Prior to about 1980, some installations could have contained smoothing putty underneath insulating tape. This putty could contain asbestos.

4.4.5 Performing Overpotential Testing

Exelon personnel recognized that overpotential (high-potential) testing was not done solely as a post-maintenance test to confirm that a bus is still serviceable after it has been inspected or worked on. Rather the testing will be required every six to eight years for the life of the plant as a means to verify that the insulating supports inside the bus still have adequate remaining voltage-withstand capability. Exelon continued to perform a visual inspection of the internals of each non-segregated bus followed by an overpotential test every six to eight years. Exelon's PM templates and procedures for MEBs both require every non-segregated and isophase bus throughout the Exelon nuclear fleet to be overpotential tested every six to eight years. It was unacceptable and technically inappropriate to extend the PM frequency on non-segregated buses regardless of whether they have had the hardware replaced and connections retorqued.

The connection hardware and bolt tightness are two issues addressed by Exelon, and they are related to current-carrying capability. Overpotential testing is done to confirm that the insulation supporting the bus conductors has adequate voltage-withstand capability. The reason that it is wise to overpotential test after an internal bus inspection and/or disturbing the connections is because doing that kind of intrusive work can potentially damage the bus insulation. The overpotential test at the end of the job is an effective validation that the bus still has adequate margin between normal operating voltage and its voltage-withstand capability and that the insulation was not damaged.

4.4.6 PM Work Management

The following is a list of lessons learned regarding the work management process:

- A cognizant person at the station should perform a review of the full work scope to be performed during the non-segregated bus inspections to ensure that there are adequate resources and time allotted to perform all of the required tasks within the designated outage window. Those tasks include opening external covers, measuring and recording the as-found and as-left resistances across all bolted connection in each non-segregated bus using a DLRO several times to confirm that the measurement is consistent and accurate, and measuring and recording the as-found torque values on at least 20% of the bolted connections in each bus. Plant personnel should also ensure that 20% of the connections are distributed proportionately among the various configurations of bolted connections within each bus (that is, in a straight portion of the bus, at a 90°bend, and so forth).

- Ensure that a prejob brief is conducted before any of the physical work begins, during which every supervisor and worker who will be assigned to the non-segregated bus inspection work is in attendance. The entire set of work instruction steps should be gone through at that prejob brief to allow for questions to be asked and answered and for any clarifications to be made.
- If contractors are used, ensure that the contractor performing the work arranges to have a crew of personnel dedicated specifically to the job on each shift. There is a learning curve involved in this scope of work, and if different people are assigned to this job every day, the job will be slowed down and work performance will be adversely affected.

Key Human Performance Point

If contractors are used, ensure that the contractor performing the work arranges to have a crew of personnel dedicated specifically to the job on each shift. There is a learning curve involved in this scope of work, and if different people are assigned to this job every day, it will slow down and adversely affect work performance.

5

RESULTS AND LESSONS LEARNED

The purpose of this section is to present results and critical lessons learned from the inspections conducted by Exelon throughout its fleet. Eight different stations within the Exelon nuclear fleet—seven of which are dual-unit plants—took part in the inspection program. It should be noted that when this report was published, the Exelon inspections were not complete. As a result of bus availability and other factors, the inspection process will continue for several more years. This EPRI report captures the data and lessons learned to date. If additional lessons learned or conclusions are identified, EPRI will consider updating this report to reflect these conclusions.

5.1 Loose Connections

Exelon collected as-found bolt torque data on numerous connection bolts in non-segregated buses at eight Exelon stations over a two-year period and found that approximately 75% of the bolts on buses with aluminum conductors have as-found torque levels below the acceptance criterion, which is 70% of the design installation torque.

Extensive bolt torque data were produced during the ongoing bus connection assessments. Data illustrated in Figure 5-1 were collected at one site and are typical of those for all Exelon plants. Figure 5-1 illustrates that, with the exception of two locations, the vast majority of bolts inspected were found to be unacceptable, meaning that the as-found torque was <70% of the rated value.

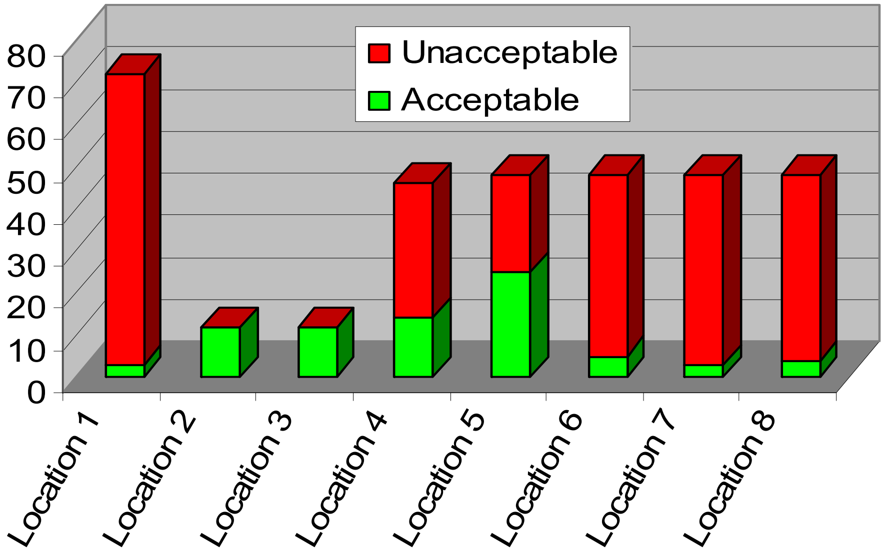

Figure 5-1
Typical results of bolt torque inspections

Note that in some cases the torque values were as low as10 ft.lb (13.56 joules), whereas the normal torque value should have been 50 ft.lb (67.79 joules).

In the technical assessment by Exelon corporate engineering and the engineering departments at the Exelon stations, this condition of widespread reduction in connection bolt torque warrants restoring the connection bolt torque back to the design installation levels. Exelon's objective was to restore the clamping force from the bolting so that it did not drop to a point after undergoing periodic thermal cycling where the resistance starts to climb, and the bolted connection operated at a progressively higher temperature.

Key Technical Point

Exelon's objective was to restore the clamping force from the bolting so that it would not drop to a point after undergoing periodic thermal cycling where the resistance starts to climb and the bolted connection operates at a progressively higher temperature.

Industry experience (such as that documented in the GALL report) suggests that the reason that so many of the bolted connections were loose was primarily because of thermal cycling and ohmic heating. Exelon's experience suggests that there is a need for periodic non-segregated bus connection assessments.

Key Technical Point

Exelon's experience suggests that there was and is a need for ongoing non-segregated bus connection assessments.

5.2 Cleaning and Retorquing

As noted in EPRI report 1013457, connection cleanliness, lubrication, and surface preparation are important attributes in bus connections. Lubrication should be used where prescribed. Torque readings can be affected by lubrication.

Personnel at one of the Exelon stations found a small number of high-resistance connections on their non-segregated bus that were detected with thermography to be 10° warmer than other connections on the same bus. The design of this specific bus did not employ silver plating on the terminal contact faces. When Exelon checked the resistance on those connections during a subsequent bus outage, it found unacceptable resistances on those connections in the 40−70 micro-ohm range. Bolt retorquing alone on those connections did not improve the connection resistance in those cases. After they disassembled and cleaned up the contact surfaces, brushed the appropriate grease into the contact surfaces, reassembled, and properly torqued those connections, the connection resistance was then measured to be only 10 micro-ohms.

Key Technical Point

If connection resistance does not meet the criteria, bolt retorquing alone might not improve connection resistance. Cleaning, relubricating, and reassembling connections might be necessary.

5.3 The Relationship Between Connection Resistance and Bolt Torque

Exelon's inspections revealed that none of the residual bolt torques had reduced to the point where the electrical resistance on any corresponding connections increased to where the connection might overheat and cause catastrophic failure to the bus. It should be noted that there are other factors to be considered, such as to what extent the bus is loaded (for example, 50% or 70% loaded), the condition of the connections, the environment, and the bus and connection design and materials.

The testing conducted by Exelon suggests that if a bolted connection on non-segregated bus had not become oxidized nor had corrosion on the contact surfaces of the joint, the resistance as measured with a DLRO most often met the acceptance criteria, even if the residual torque was relatively low. Torquing the connection bolts back to their design installation torque value did not dramatically reduce the resistance of the connection at ambient temperature. However, it should be noted that Exelon considers it necessary for bolted connections to meet minimum torque requirements and low resistance appropriate for the application.

Key Technical Point

Exelon learned during the inspections that none of the residual bolt torques had reduced to the point where the electrical resistance on any corresponding connections increased to where the connection might overheat and cause catastrophic failure to the bus.

Key Technical Point

Exelon considers it necessary for bolted connections to meet minimum torque requirements and low resistance appropriate for the application.

5.4 Bolt Torque Versus Bus Material

5.4.1 Aluminum Bus

Exelon plants that inspected non-segregated buses over a two-year period found extensive reduction in clamping bolt torque on buses with aluminum conductors. As-found bolt torque data on numerous connection bolts in non-segregated buses at eight Exelon stations over a two-year period showed approximately 75% of the bolts on buses with aluminum conductors to have as-found torque levels below the acceptance criteria. Remember that the acceptance criterion is 70% of the original design installation torque. Aluminum is softer than copper and consequently can be more prone to torque relaxation.

During one station's last outage, 100% of the connection bolts checked on a bus with aluminum conductors had residual torque below the acceptance criteria. It was also discovered that the aluminum splice plates installed on their connections (four per connection) were distorted from 20-plus years of in-service thermal cycling; they were therefore replaced.

Key Technical Point

Exelon plants that have inspected non-segregated buses over a two-year period found extensive reduction in clamping bolt torque on buses with aluminum conductors. Torque readings from copper bus connections generally had a lower number of connections that did not meet acceptance criteria. Based on Exelon data, the conclusion could be drawn that, in general, copper bus performed better than aluminum bus with regard to maintaining bus connection bolt torque.

5.4.2 Copper Bus

Exelon's results show that torque readings from copper bus connections generally had a lower number of connections that did not meet acceptance criteria. Based on Exelon data, the conclusion could be drawn that, in general, copper bus performed better than aluminum bus with regard to maintaining bus connection bolt torque.

At one plant, no low torque readings were found on 6-in. (152-mm) flat copper bus bar connections on two buses that underwent inspection. At another Exelon station, the as-found torque on all of the connection bolts on a copper bus was measured during its refueling outage. The as-found torque on approximately 20% of the connections did not meet the minimum torque criteria (typically 35 ft.lb [47.45 joules]). It can be said that the as-found torques on copper bus connections that did not meet acceptance criteria were still higher than the typical residual torque levels found on more than 75% of the bolted connections on aluminum buses.

5.5 Bolt Torque Versus Bolting Material

Exelon's testing suggests that a contributing factor to finding lower than expected residual torques on some of the connection bolts on one station's copper bus is that the bolts in this station's application are stainless steel, whereas the bolts in other copper buses were all galvanized carbon steel. Carbon steel and stainless steel have different coefficients of thermal expansion. That alone could possibly explain the difference in the amount of residual torque found on connection bolts in use on copper bus conductors.

Inspection of stainless steel connection bolts on a non-segregated bus with copper bus conductors identified 20% of the bolts did not meet the minimum acceptance criteria. The as-found and as-left electrical resistances measured across each connection that was inspected on that bus did meet the previously established acceptance criteria.

Measurement of as-found torques on galvanized carbon steel connection bolts on one non-segregated bus with copper conductors identified that as-found torque on all of the bolts checked did meet the minimum acceptance criteria. The as-found and as-left electrical resistances measured across each connection on the bus that was inspected also met the previously established acceptance criteria.

Key Technical Point

Exelon's data suggest that galvanized carbon steel connection bolts on copper conductors performed better at retaining torque values than stainless steel connection bolts on similar copper conductors.

5.6 Adjusting the PM Task Scope and Frequency

Manufacturers could not provide in writing a known duration for connections to relax. Consequently, Exelon’s PM templates were revised to perform internal bus inspections every six to eight years. This guidance was partially based on EPRI and Nuclear Electric Insurance Limited inspection intervals.

Based on field data during the study phase, the Exelon System Managers Peer Group collectively decided that a six-to-eight-year PM interval was suitable for specific designs. The PM performed at this interval will include checking torque values on (at least) a 10% sample of the connections on a given bus.

6
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A

LISTING OF KEY POINTS

A.1 Key Technical Points

Key Technical Point

Targets information that will lead to improved equipment reliability.

Page Number	Key Technical Points
1-2	Exelon's extensive testing and inspection program on electrical bus bars represents a unique and significant opportunity for EPRI and the industry to capture data photographs, and lessons learned from Exelon's focused effort.
2-3	It should be noted that when this report was published, the Exelon inspections were not complete. As a result of bus availability and other factors, the inspection process will continue for several years. This report captures the data and lessons learned to date.
2-6	Care should be taken not to exceed the listed torque values, which could lead to failure of the fastener hardware or damage to the associated bus or connector plates.
3-1	Proper grounding procedures should be followed at all times. With respect to grounding, Exelon found that grounding the bus at both ends results in creating a parallel path around each of the connections on which the resistance is measured. That introduces an error in measured resistance. Exelon's preference was to take resistance measurements with the bus grounded at only one end.
4-4	Although sampling was effective in many cases, a fully executable contingency plan needs to be in place to expand the scope to 100% of the bolted connections on any bus that has an aluminum conductor.
4-4	Exelon's inspection results suggest that the remaining connections in a bus are acceptable if within the initial 10% sample, there are absolutely no bolts with residual torque less than 70% of the design installation torque, **and** there are connection resistances greater than 10 micro-ohms for buses rated up to 3000 amperes and 6.25 micro-ohms on buses rated 4000 amperes.
4-4	A consensus rule developed by Exelon technical personnel is that the total resistance of the bolted joint measured at ambient temperature has to be low enough so that, at rated bus current through the connection, the I^2R heat generated at that joint should be no more than about 100 W.

Page Number	Key Technical Points
5-2	Exelon's objective was to restore the clamping force from the bolting so that it would not drop to a point after undergoing periodic thermal cycling where the resistance starts to climb and the bolted connection operates at a progressively higher temperature.
5-2	Exelon's experience suggests that there was and is a need for ongoing non-segregated bus connection assessments.
5-2	If connection resistance does not meet the criteria, bolt retorquing alone might not improve connection resistance. Cleaning, relubricating, and reassembling connections might be necessary.
5-3	Exelon learned during the inspections that none of the residual bolt torques had reduced to the point where the electrical resistance on any corresponding connections increased to where the connection might overheat and cause catastrophic failure to the bus.
5-3	Exelon considers it necessary for bolted connections to meet minimum torque requirements and low resistance appropriate for the application.
5-4	Exelon plants that have inspected non-segregated buses over a two-year period found extensive reduction in clamping bolt torque on buses with aluminum conductors. Torque readings from copper bus connections generally had a lower number of connections that did not meet acceptance criteria. Based on Exelon data, the conclusion could be drawn that, in general, copper bus performed better than aluminum bus with regard to maintaining bus connection bolt torque.
5-4	Exelon's data suggest that galvanized carbon steel connection bolts on copper conductors performed better at retaining torque values than stainless steel connection bolts on similar copper conductors.

A.2 Key Human Performance Points

Key Human Performance Point

Denotes information that requires personnel action or consideration in order to prevent personal injury, equipment damage, and/or improve the efficiency and effectiveness of the task.

Page Number	Key Human Performance Points
4-6	Prior to about 1980, some installations could have contained smoothing putty underneath insulating tape. This putty could contain asbestos.
4-7	If contractors are used, ensure that the contractor performing the work arranges to have a crew of personnel dedicated specifically to the job on each shift. There is a learning curve involved in this scope of work, and if different people are assigned to this job every day, it will slow down and adversely affect work performance.

B

REPORT OVERVIEW PRESENTATION

The purpose of this appendix is to provide an overview of this project and report in PowerPoint slide format.

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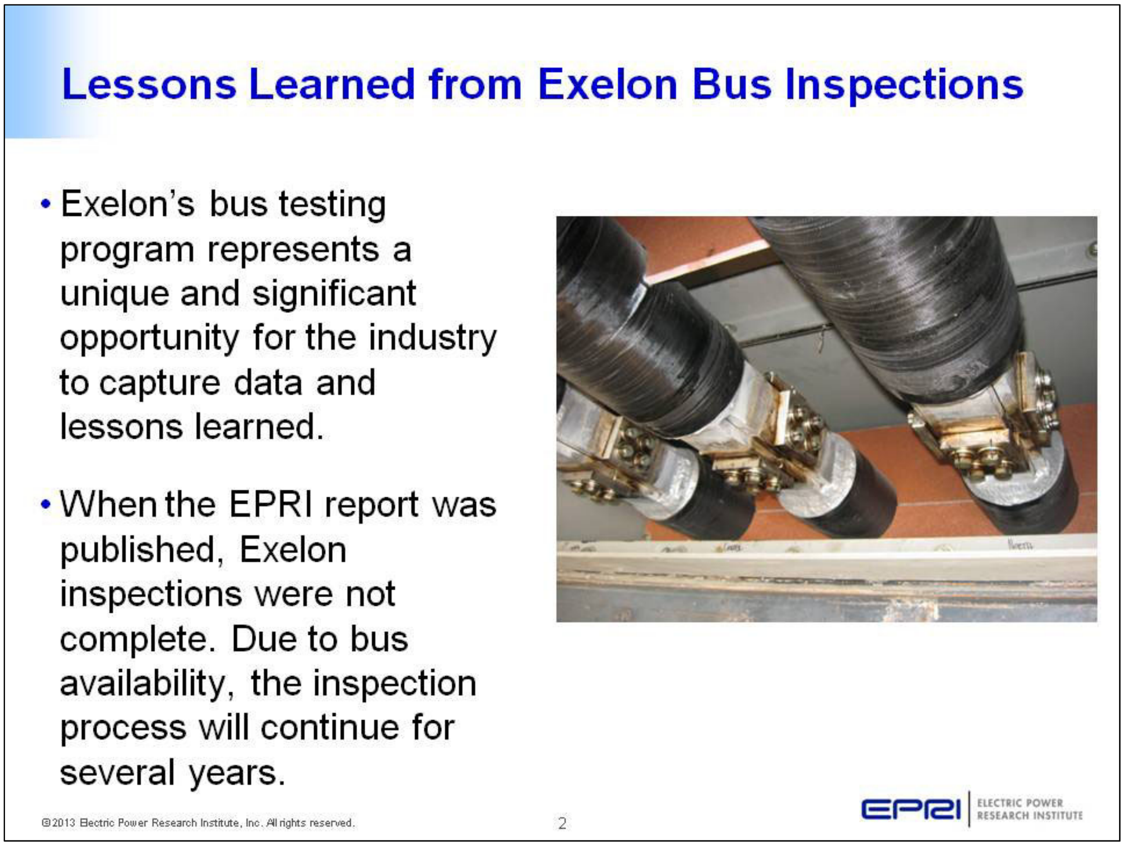
Report Overview: Lessons Learned from Exelon's Non-Segregated Bus Inspections



Lessons Learned from Exelon Bus Inspections

- Exelon's bus testing program represents a unique and significant opportunity for the industry to capture data and lessons learned.
- When the EPRI report was published, Exelon inspections were not complete. Due to bus availability, the inspection process will continue for several years.

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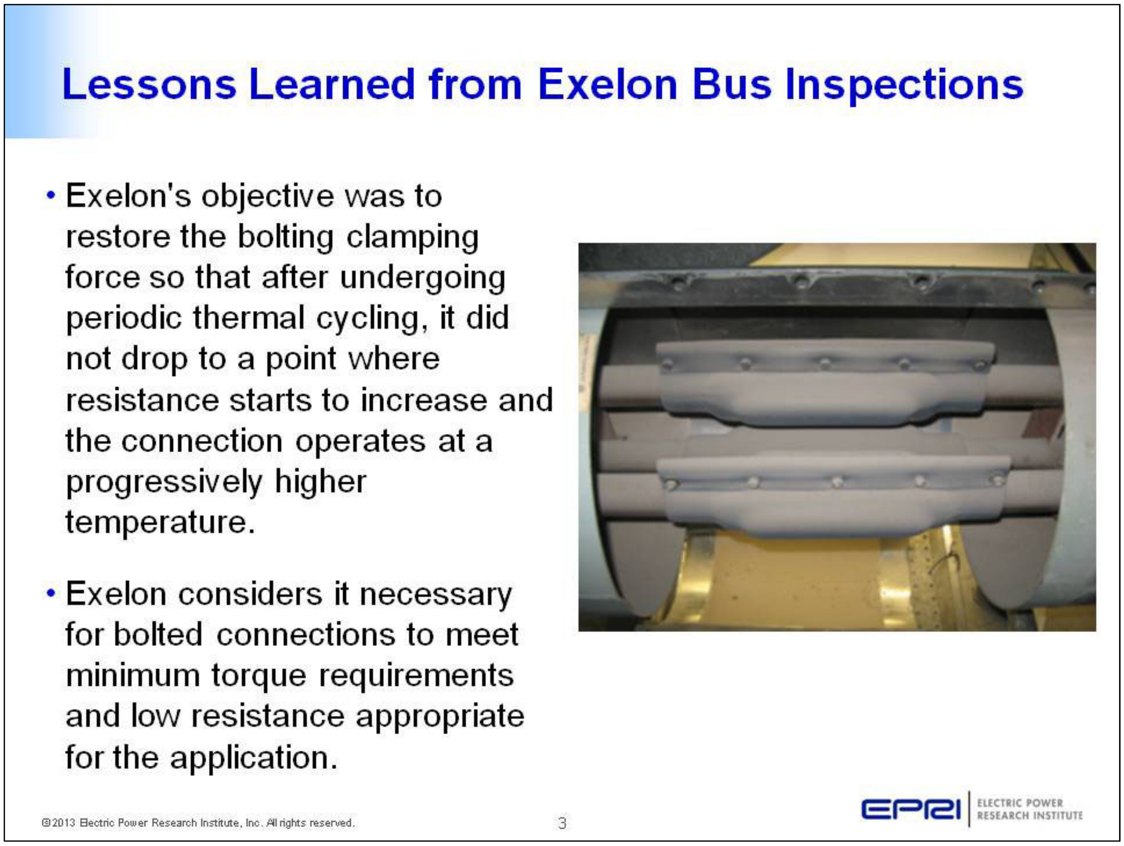

Lessons Learned from Exelon Bus Inspections

- Exelon's objective was to restore the bolting clamping force so that after undergoing periodic thermal cycling, it did not drop to a point where resistance starts to increase and the connection operates at a progressively higher temperature.
- Exelon considers it necessary for bolted connections to meet minimum torque requirements and low resistance appropriate for the application.

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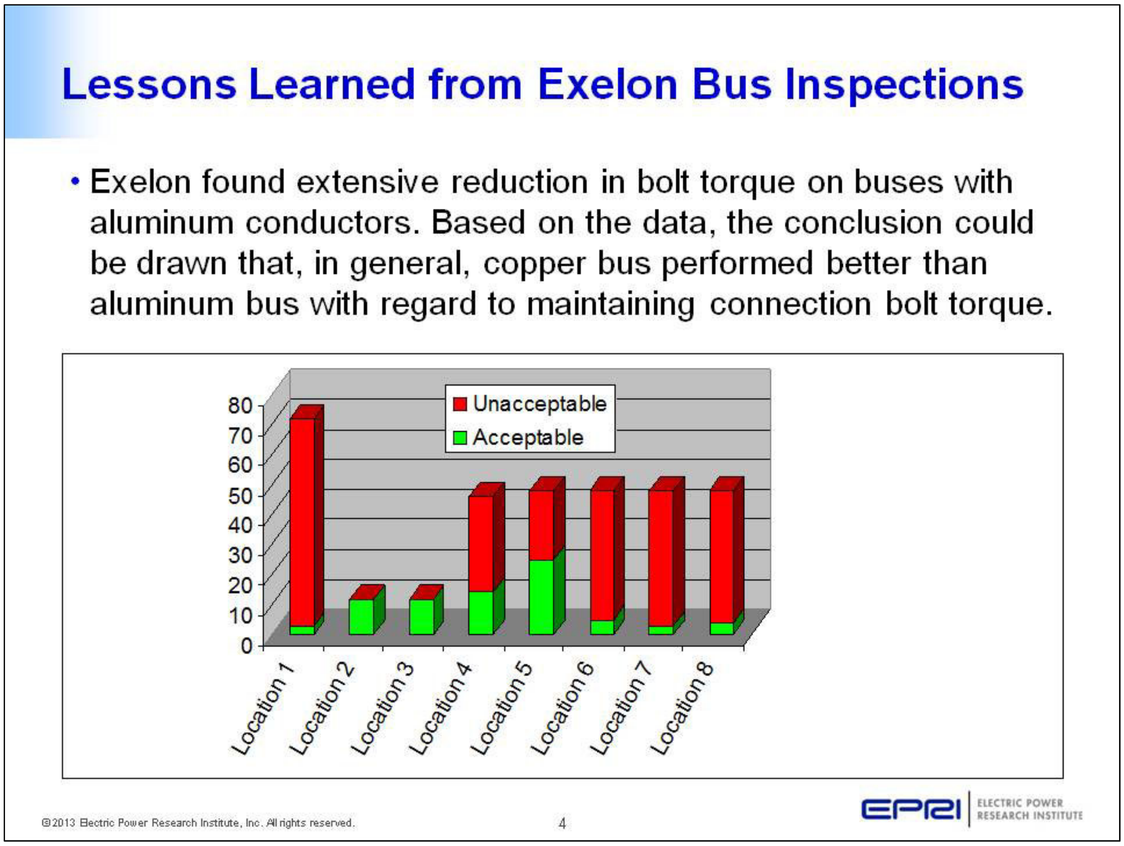

Lessons Learned from Exelon Bus Inspections

- Exelon found extensive reduction in bolt torque on buses with aluminum conductors. Based on the data, the conclusion could be drawn that, in general, copper bus performed better than aluminum bus with regard to maintaining connection bolt torque.

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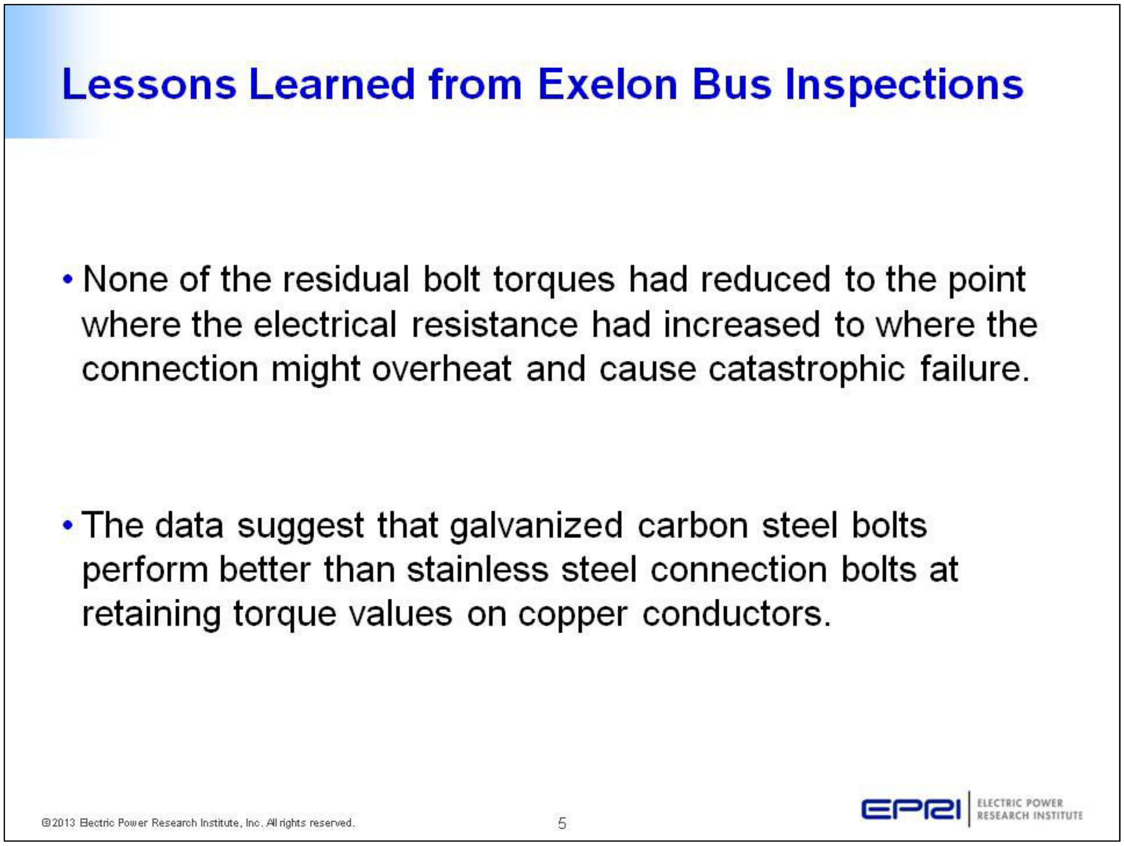

Lessons Learned from Exelon Bus Inspections

- None of the residual bolt torques had reduced to the point where the electrical resistance had increased to where the connection might overheat and cause catastrophic failure.

- The data suggest that galvanized carbon steel bolts perform better than stainless steel connection bolts at retaining torque values on copper conductors.

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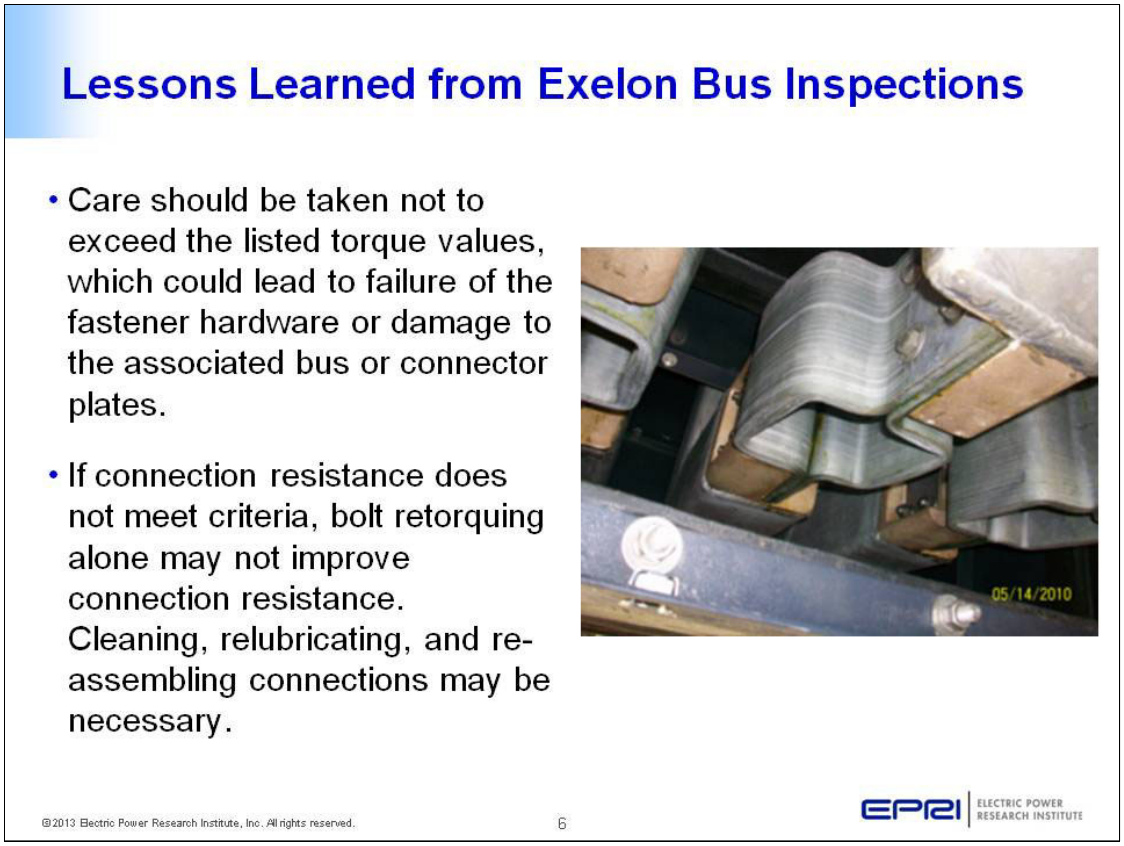

Lessons Learned from Exelon Bus Inspections

- Care should be taken not to exceed the listed torque values, which could lead to failure of the fastener hardware or damage to the associated bus or connector plates.
- If connection resistance does not meet criteria, bolt retorquing alone may not improve connection resistance. Cleaning, relubricating, and re-assembling connections may be necessary.

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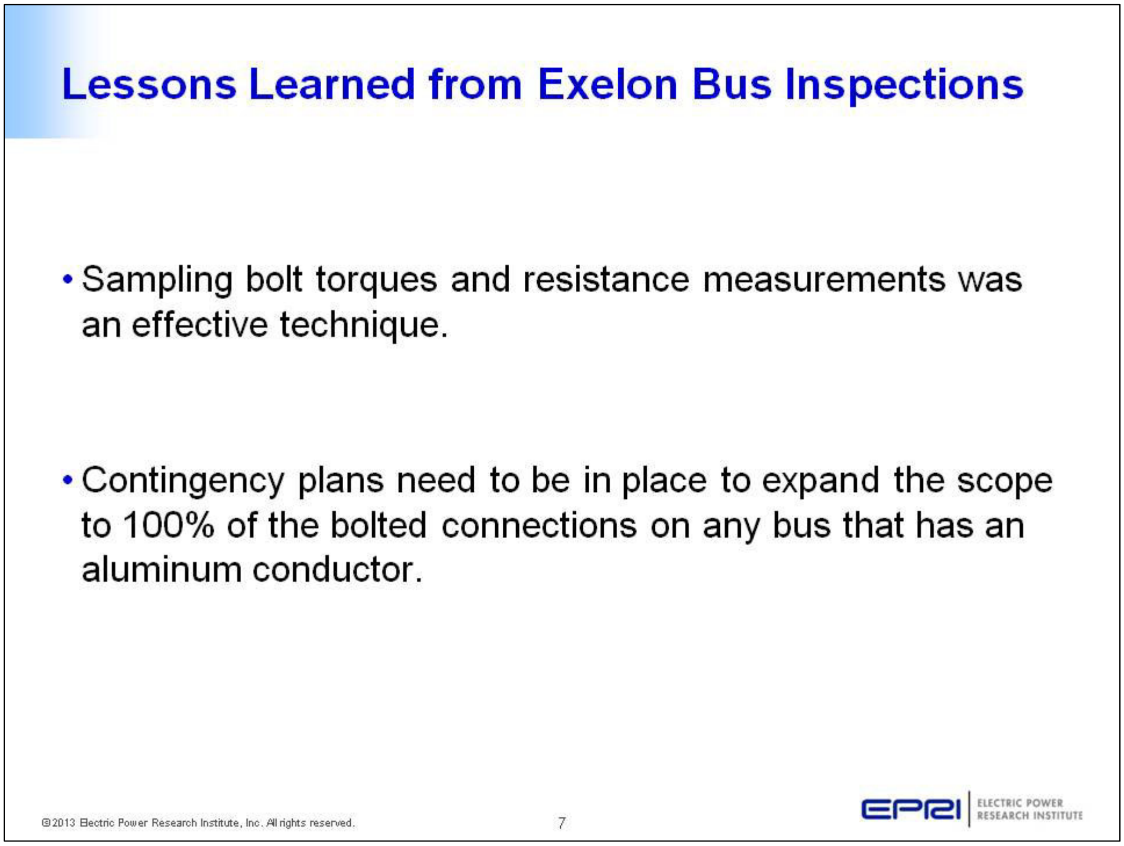

Lessons Learned from Exelon Bus Inspections

- Sampling bolt torques and resistance measurements was an effective technique.
- Contingency plans need to be in place to expand the scope to 100% of the bolted connections on any bus that has an aluminum conductor.

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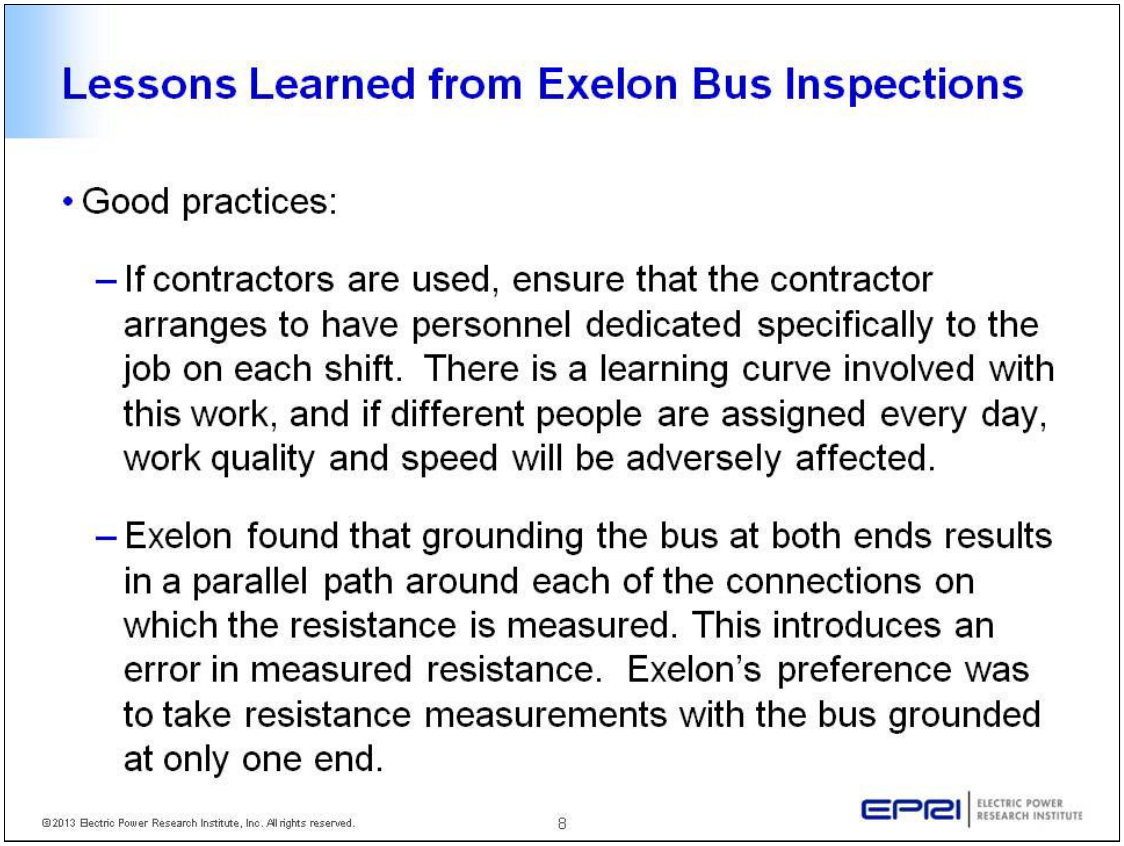

Lessons Learned from Exelon Bus Inspections

- Good practices:
  - If contractors are used, ensure that the contractor arranges to have personnel dedicated specifically to the job on each shift. There is a learning curve involved with this work, and if different people are assigned every day, work quality and speed will be adversely affected.
  - Exelon found that grounding the bus at both ends results in a parallel path around each of the connections on which the resistance is measured. This introduces an error in measured resistance. Exelon's preference was to take resistance measurements with the bus grounded at only one end.

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