PDHonline Course E123 (2 PDH)

Basic Electrical Connectoring

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Course Content

A. Introduction and Background of Electrical Connections

Most electrical conductors and connectors prior to World War II were made from copper. Aluminum was introduced in the industry for many reasons, including:

-- A shortage of copper was experienced due to the war effort

-- Aluminum conductors and connectors were lighter when compared to conductivity

-- Aluminum became less expensive than copper as the industry found less expensive ways to process its manufacture.

The Construction Industry began to use aluminum extensively in both industrial and residential construction. The Power Utilities also began using aluminum conductor in overhead power distribution. However, within a few years, serious problems were experienced, especially when aluminum conductor was being connected with copper connectors. This course is intended to describe some common configurations of connectors, their use and application, their appropriate performance standards and the factors to be aware of in their use.

B. Physical problems connecting aluminum to copper

It was discovered that the electrical failures occurred predominantly at the connection of aluminum wires to copper connectors, particularly in branch circuits. Investigation revealed significant incompatibilities of the connections:

-- Corrosion occurred on the connection surfaces, particularly in humid areas. This increased the electrical resistance of the connection, causing overheating and sometimes burning. While the current overheated the connection, it was not great enough to trip the breaker or fuse. It was determined that the corrosion was predominantly galvanic corrosion, which is very active with metals having a significantly different electromotive potential in the presence of an electrolyte. The electromotive difference between aluminum and copper is greater than 1.7 volts and a small amount of moisture can provide the electrolyte.

-- Surface oxidation of aluminum was identified as a problem. Copper oxide, which generally forms on copper surfaces, is relatively conductive while aluminum oxide is an electrical insulator. Furthermore, freshly cleaned and brushed aluminum surfaces can accumulate an oxide coating within minutes of exposure to the atmosphere. Unless the coating is thoroughly disturbed, the connection surfaces will not be fully effective.

-- Aluminum has a thermal rate of expansion of almost 1 ½ times that of copper. Thus, when aluminum is clamped and bounded by a copper connector, normal temperature rises due to current through the connector will cause greater aluminum expansion than the surrounding copper and create a permanent set in the aluminum, thereby loosening the connection. Repeated thermal cycling then further deteriorates the connection.

-- The modulus of elasticity of copper is 1.7 times that of aluminum, while the yield strength of soft, electrolytic copper is 2 ½ times that of aluminum. Depending on the hardness of copper, the yield can be much higher. Thus, aluminum conductors used in a tension or mechanical application cannot perform as well as copper. Also, aluminum, being a less ductile conductor, is much less suited than copper for fine stranded conductors. These conductors afford better electrical conductivity due to the phenomenon of surface conductivity and superior mechanical flexibility required for conductors placed in confined locations.

C. Engineering and Design Solutions

Solutions to the problems included efforts in Engineering, Design and Development. Also, Industry Standards requirements were instituted on aluminum to copper connectors, including restrictions on the use of aluminum connectors and conductors .

--Initial design considerations attacked galvanic corrosion with two basic approaches. The difference in electromotive potential was resolved by plating the aluminum connectors with tin. The process of plating removes any aluminum oxide on the surface and immediately applies a direct coating of tin. Tin possesses an electromotive potential between that of copper and aluminum, thus minimizing the difference in potential. Subsequent developments have employed coatings applied to de-oxidized aluminum surfaces that are pliable and seal the spots of intimate metal contact preventing moisture entrance at the points connections are made. Protection of moisture entrance is further provided by applying a heavy grease substance on the connection itself. The substance is designed to resist water entrance and deterioration. This substance is generally referred to as inhibitor. When connectors are used in dry, indoor applications, standards generally do not require inhibitor as long as the aluminum connector is plated or proven to be adequately coated.

--It was also recognized that, although galvanic corrosion was not critical on connections between aluminum connectors and aluminum conductors, surfaces of aluminum oxide were problematic due to the insulation characteristics of the oxides. Thus, in applications where inhibitor is being used, the inhibitor contains grits of varying sizes. The grit acts to break the oxidized surfaces and expose pure contact surfaces to each other while the inhibitor seals the connection. Standards and individual instruction sheets also recommend that the exposed conductor placed within the connector be wire brushed immediately prior to connection. Further considerations will be discussed below in connector descriptions.

–The difference in thermal rate of expansion between aluminum and copper was resolved by discontinuing and recalling designs that employed copper as the encompassing or bounding member of the connector. Connectors are now manufactured from aluminum when they can be used with either aluminum or copper conductor. Copper connectors are still being widely used, but generally cannot be used for aluminum conductor. However, special designs may exist that compensate for differences in aluminum thermal expansion.

D. Industry Standards Solutions

Construction, Utilities and Manufacturers recognized the problems and created standards for testing and evaluating performance of Aluminum-Aluminum and Aluminum-Copper connections. EEI-NEMA standards were created by committees of Utilities (EEI) and Manufacturers (NEMA). The industries regulated by building codes cooperated with Underwriters Laboratories and manufacturers in creating standards for their applications. While many similarities exist in the standards, there are also differences due to the different applications and environments experienced in Utility and Construction use.

--The EEI-NEMA standards were eventually adopted by The American National Standards Institute (ANSI) and are presently identified as ANSI C119.4. The C119– family of standards now include other connector standards for various applications such as underground, Primary Distribution, Secondary Distribution, switching connectors, etc. Testing directly related to connector performance includes measurement of temperature rises with prescribed currents, resistance stability, mechanical strength, and current cycling. The current cycling test involves switching prescribed currents on and off for various durations which not only imposes current cycling but also resultant temperature cycling. It was discovered that successful completion of such tests verified a reliable connector design for proper performance.

--Standards are constantly reviewed and revised to accommodate newer designs and applications. Thus, to become knowledgeable about the details of any part of the standards, the latest revision should be consulted.

–Underwriters Laboratories pursued newer standards in the same fashion. Users and manufacturers were invited to participate in creating a set of standards concentrating on connecting electrical circuits. These are commonly known as the UL486-- family of standards. UL486A is for copper to copper connections and UL486B is for copper to aluminum connections. They too employ current rise and current cycling tests performed in a similar fashion to ANSI C119.4. However, their standards vary in some degree to the ANSI standard. It must be recognized that the connectors and conductors found in power distribution are normally required to carry much greater currents than those in the building trades. Also, the requirements for tensile strength are greater for distribution connectors. The building trades have very limited application for connectors used outdoors. Because the UL standards are constantly being reviewed and revised, details of the standards requirements and tests should be researched in the latest revisions.

–Consistent with all standards, connectors suitable for connecting both aluminum and copper conductor are marked accordingly by a “CU/AL”, “AL/CU” or similar marking. The details of these markings may vary slightly, so it is recommended that the latest standards be consulted.

E. Connector Standards, Configurations and Individual Considerations

Commercial electrical connectors can be placed into three categories, Power Distribution (Utilities), Construction and Contractor Industrial (CI). Power Distribution types are mostly used by Power Utilities for large ampacity conductors and in harsh environments. Most Utilities have created their own company standards and detailed instruction sheets for connector installation. However, company standards invariably recognize appropriate ANSI standards as a requirement. Utilities are probably the most common users of aluminum conductors, especially in the larger sizes. The Construction types are used in Commercial, Industrial and Residential building. Aluminum conductor is used in feeder circuits and heavier branch circuits. Generally, branch circuits which distribute power directly to smaller services and outlets employ copper conductor. Contractor Industrial connectors are normally used in equipment for industrial and consumer devices (switches, computers, television, radio, telephone, etc.). Connectors for the Construction and Contractor Industrial (CI) industries are generally required to be certified for use by Underwriters Laboratories (UL) or other testing laboratories certified by national or local agencies. These connectors and their installation also may be subject to the local National Electric Code (NEC) in conjunction with the National Fire Protection Agency (NFPA).

Although many of these connectors are available to the consumer in hardware and discount stores, their use and installation are still regulated by the local NEC regulations. It is important to be aware that the NEC requirements, although frequently examined and revised, may not be universally applied. The installation should comply to the NEC revision appropriate to the locale in question.. Examination and interpretation is best left to the local, certified electrical inspector. Connector configurations can be appropriate to any or all three types defined above, however may also be marked differently, contain different materials (inhibitors, grit, etc.) and use different tooling to be installed.

–Twist-0n (Wirenut) connectors are generally used in Construction or CI equipment and branch services directly serving the equipment or outlet. They consist of a conical hole receptacle in which the conductors to be joined are placed, either parallel or twisted. The inner cone is threaded either by configuration or with a metal spring. The outer portion is made from an insulating material. It is generally conical, but can have various configurations. The conical device is then screwed onto the assembled conductors. The appearance and construction detail varies with each manufacturer, but the application, such as wire sizes and amount of wires to be joined, are recommended by certified testing agencies. This type of connector is not used with aluminum wire because it accommodates only small conductor sizes with fine stranding. As indicated above (para. B), aluminum wire is unsuitable for such use.

–Setscrew connectors are used in a wide range of conductor sizes. They are generally used to connect conductors to equipment or busses. They consist of a setscrew, generally impinging directly on the conductor while it is seated on a receptacle surface of the connector. The connector body may also include a tang or flat surface that can be bolted directly to a connecting surface of the equipment or buss. Although the design and configuration of these types of connectors can be greatly varied, they still appear to be quite simple. However, the engineering can be more involved than realized, especially when connecting aluminum. Because the device employs threaded screws, prescribed screw torques must be observed. Also, inhibitor use must be kept to a minimum, particularly with inhibitors containing grit. Should this material contaminate the screw thread , it can affect the torque-force characteristics dramatically. Also, when using aluminum conductor, we have the potential problem of aluminum oxides. While the connector can be tin plated and the outer strands of the conductor can be wire brushed, the inner strands must be disturbed at installation to break up the oxide coating and afford a good electrical connection. The force imposed by the screw, keeping within the confines of its torque-force capabilities, must be adequate to upset all strands of the conductor properly within the range of conductors the connector is approved to accept. Thus, the shapes of the screw and receptacle at the contact surfaces are engineered to provide proper upset to disturb all strands, but not excessive enough to reduce the area of the strands to the point of breakage. Of course, there are also connectors manufactured to connect only copper conductor. They are generally made of copper; however, where environmental conditions prevail, alternate materials are employed.

–Compression connectors are widely used in power distribution. They are configured to provide connection to various terminations (equipment, splices, busses, etc). The most popular configuration is simply of a hollow cylinder. The inner diameter is a hole that accepts the conductor and the connecting end can assume many different configurations. When both ends of the connector are cylindrical, the connector is used to splice two conductors. The conductor(s) are placed inside the hole and a compression (crimping) tool with compression dies is then applied to the outside surfaces. The cylinder is compressed radially until the connector and conductors are properly compressed. This type of connector is well suited for aluminum conductor. The hole normally contains inhibitor with grit. Although the outer conductor strands are brushed, the inhibitor is“pumped” inside the interstices of the inner strands when the conductor is forced inside the hole. Thus, when the compression is made, the oxide coatings are thoroughly disturbed and a good electrical connection is afforded to the inner strands. Copper connectors are also used, but are primarily restricted to connecting only copper conductor. In some special circumstances, depending on the environment, copper can be used on other conductors. They are also used to connect conductor to heavy power equipment and to busses. Their application in power distribution includes tension splices for overhead wires where they are required to sustain 90% of the tensile strength of the conductor. These connectors require special design parameters, materials and configurations. Various other configurations exist that are capable of providing power conductors tapped from existing main lines.

–Crimp connectors are widely used in the Construction and CI markets. Smaller crimp connectors are employed in low ampacity branch circuits used for wall plugs and other outlets. They are frequently used for small electrical equipment and appliances. The variations and applications are countless. Again, the connector mechanism seems very simple but the engineering required is involved. The connectors must be capable of accommodating a varying size and range of conductors. The compression for each size must be controlled to insure the connector and conductor are compressed adequately for electrical connection but not excessively so as to damage the conductor beyond its tension properties. In order to do this, each connector is identified as to the proper die to use for each conductor size. This is marked directly on the connector where possible. Further complications arise when we consider that the tools and dies used for compression differ between the Utilities and the Construction/CI industries. Many times the identical connector will be used for any of the different markets, except the marking is different. It should be readily appreciated that instructions for proper use and installation must be closely observed. Compression tools and dies are thoroughly investigated and tested for connector performance before they are recommended for use.

–Separable connectors are types that deserve mention. Extensive use of these connectors is made in the CI industry, however the huge majority are used for small copper conductors. They are made to be easily connected and disconnected on one termination end and normally attach to the conductor by compression connection. They also frequently incorporate preinstalled insulation sleeves over the compression portion. These connectors are covered by standards and tests by certified laboratories. However, there exists a type of separable connector that is primarily used by Underground Power Distribution and is also being employed in huge buildings where primary voltage is employed to distribute power to various floors of skyscrapers, for example. These connectors have been called “Loadbreak” connectors or switching connectors. They accommodate primary voltages from 8kv to 35kv., and can be connected and disconnected (using a standard hotstick) while carrying loads of up to 200 amperes. These connectors were developed early in the use of underground primary systems. They are used extensively in primary distribution radial systems. They replace more expensive switchgear and are valuable in isolating faulted circuits or branches on radial underground distribution. Standards for these connectors were originally created in the ANSI C119-- family.

Understandably, they are quite involved and incorporate stringent requirements for performance. Because they are also sanctioned for use on Primary Underground Conductors, the standards also include rigorous insulation tests on the connector assembly. Understandably, these connectors consist of a product line all their own. The engineering design is highly specialized to include high voltage switching and insulation systems. Use of these connectors can be effective in reducing installed costs of equipment. However, their operation requires trained personnel to operate the connectors properly. Performance standards must be carefully examined for each installation to insure circuit parameters are compatible.

F. Summary

When connecting electrical conductors, design and installation should be carefully done. The proper standards must be consulted. The nature of the project can determine the proper standards to be applied. Attention must be given to the conductor materials and insure that the proper connectors are employed for proper performance. Installation of the connections must be accomplished properly and in accordance with standards, using tooling recommended by the manufacturer. +-Although the job of connecting electrical conductors may appear to be quite simple, in order to insure safe and reliable results, an understanding of the task is important for accomplishments.