International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

IEC 62561 Electrical Testing of US Connectors and Stranded Cable

Mitchell Guthrie
Independent Engineering Consultant
Blanch, NC USA
esecmg@embarqmail.com

Greg Martinjak
ERICO International Corporation
Solon, OH USA
greg.martinjak@pentair.com

Harold (Bud) VanSickle III
Lightning Protection Institute
Maryville, MO USA
lpi@lightning.org

***Abstract*— This paper provides a summary of the testing of Underwriters Laboratories (UL) certified connectors to the electrical requirements of IEC 62561-1, Edition 1. The connectors were tested in configurations interconnecting Class I UL-certified stranded conductors. A discussion of deviations to the pass/fail criteria is provided along with recommendations on modifications to IEC 62561-1, including considerations on modification of pass/fail criteria for connectors used with stranded cable. Observations from the results of the testing reported also identify lightning protection system maintenance and inspection considerations that should be addressed in national and international lightning protection system standards.**

Keywords - connectors; stranded cable; IEC 62561-1; lightning protection, components, test procedures

I. INTRODUCTION

United States (US) lightning protection standards specify that main-sized lightning protection system (LPS) conductors, such as those used to interconnect air-termination components and as down conductors, may be in the form of stranded cable [1, 2], solid strip [1, 2], and solid rod (wire) [2]. In over 99% of installations in the US where made connectors are used, they interconnect stranded conductors. Unlike IEC 62305-3 [3] where the LPS materials and conditions of use are not dependent upon the Class of LPS, US standards NFPA 780 [1] and UL 96 [2] define the class of materials based on the height of the structure on which it is to be installed. Class I materials may be used on structures up to 23 meters tall while taller structures require Class II materials. The primary variable is the size of conductors as most manufacturers develop connectors and other components that may be used with either Class I or Class II conductors. The three primary types of stranded conductors used in the United States in lightning protection applications are rope lay, smooth weave, and concentric strand; with concentric strand use primarily limited to Class II aluminum conductors. Fig.1 shows the different stranded conductor construction for both US Class 1 and Class II LPS conductors.

Figure 1. Typical conductor strands used in United States. Upper – Class II aluminum concentric strand; 2nd – Class I aluminum smooth weave; 3rd – Class II copper rope lay; Lower – Class I copper smooth weave.

The Lightning Protection Institute (LPI) commissioned a study to determine whether there would be logistical issues in applying IEC 62561-1 [4] to UL-certified connectors designed for stranded cable and to quantify the response of any industry connectors to the threats identified in the standard. Of particular concern was the 90-degree bend specified in the test configuration when using cable much less resistant to bending forces than a solid 8 mm diameter conductor. While such bends are not uncommon in European installations, they are not allowed by US installation standards [1, 5]; which require a minimum bend radius of 0.2 meters.

II. TEST DESCRIPTION

A. *Test Procedure*

A test program was developed around the requirements in IEC 62561-1 and the information provided in [6]. It was decided that the testing would include the most commonly used connector configurations in the industry made of the two primary materials allowed in US standards; copper and aluminum. Each of the manufacturer members of LPI provided the following connectors for the test program:

- In-line (straight splice) made of copper and made of aluminum
- Two-conductor parallel made of copper and made of aluminum
- Tee-connectors made of copper and made of aluminum.

From these samples a total of 6 of each type were selected (4 from each manufacturer consisting of 2 each aluminum and 2 each copper), assembled in accordance with the manufacturer's recommended torque values, and subjected to environmental conditioning. The environmental conditioning consisted of a salt mist treatment followed by a humid sulphurous atmosphere treatment. Some of the connectors were designed to be used with both Class I and Class II cables (as defined by NFPA 780-2014, 4.1.1) so it was decided to conduct all testing using the minimum sized cables (Class I) as required in IEC 62561-1, 6.2.1.

The original intent of the test program was to conduct the testing as a Type test using the pass/fail criteria in the standard. A test will consist of three new specimens, each subjected to an impulse current of 100 kA (± 10%) with a specific energy (W/R) of 2500 kJ/Ω (± 35%). The pass/fail criteria identified II.C must be met by each of the 3 samples in order to consider the test successful. If only one of the specimens does not satisfy a test, the test shall be repeated using 3 new samples of the same connector type. All of the 3 new samples must meet the pass/fail criteria for the test for the result to be considered successful.

B. Items Under Test (IUT)

The six samples of each configuration were broken down into 3 primary samples and 3 secondary samples. For each manufacturer, 2 connectors were selected as primary and 2 as secondary; with 2 made of copper and 2 made of aluminum. These designations were made prior to environmental conditioning of devices. An attempt was made to have one of each type connector tested from each manufacturer. This was possible for all but two of the manufacturers.

The resistance across the connectors was not measured prior to environmental conditioning. Prior to placing the sample into the test chamber the resistance across the connector was measured and recorded, along with connector locations on the conductor and dead-end overlap lengths.

Upon completion of the 3 current impulses, the test specimen was removed from the test chamber and a visual inspection was conducted. The resistance across the connector was measured and recorded. The movement of the conductors inside the connector was recorded and the loosening torque was measured and recorded. The results were compared with the pass/fail criteria below.

The test samples predominately used Class I copper or aluminum main sized conductors in a smooth weave construction. The construction is similar to ASTM B172 [7] rope lay with bunch stranded conductors. This maximizes surface area per unit weight of conductor, and also provides improved flexibility in routing conductors through bends. The minimum size required by the UL 96 standard is based on weight – for copper Class I the weight requirement is 278 grams/meter and for aluminum Class I is 141 grams/meter. The aluminum conductors used in this testing had a construction consisting of 24 strands of 1.63 mm wire (#14 AWG) with an overall diameter of 12.2 mm. The copper conductors consisted of 29 strands of 1.14 mm wire (#17 AWG) with an overall diameter of 11.2 mm.

C. Pass/Fail Criteria

In order to pass the test, the following criteria must be fulfilled:

- the contact resistance measured as close as possible to the connection component is equal to or less than 1 mΩ;
- there is no crack nor any loose parts or deformation impairing its normal use;
- the loosening torque is greater than 0.25 and less than 1.5 times the specified tightening torque;
- the dead end overhang of parallel splices and cross connectors do not move more than 17 mm.

D. Deviations from IEC 62561-1 Test Techniques

The testing reported in this paper was generally conducted in accordance with the requirements of IEC 62561-1. However, some deviations were made where it was determined it would not significantly affect the results and/or would provide additional information that may be used in discussions on the modification of test criteria for testing connectors with stranded cables or used in analysis of any deviations to the pass criteria.

IEC 62561-1, 6.3.a requires the contact resistance be measured with a source of at least 10 amperes. Rather than incur the additional expense of renting a 10 ampere micrometer for the testing, it was decided that the calibrated micrometer available in the laboratory that uses only 5 ampere source current would provide acceptable results for this testing.

The standard draws a distinction between Tee-connectors and cross connectors, with some difference in pass/fail criteria. Two of the manufacturers provided cross connectors for their requested Tee-connector. One each copper and aluminum cross-connector was used as an alternative to the Tee-connector in the secondary sample set. The criteria for cross-connectors were used in the testing of the cross-connectors instead of the criteria for the Tee-connectors. This decision played no role in whether the style of connector would have passed the test, even though one of these connectors (AT1C) is one of the connectors that did not meet the pass criteria (it would not have passed either criteria).

During preliminary testing it was found that limiting the length of conductor passing through parallel and cross conductors to 20 mm may inhibit the movement of the conductor through the connector. It was found that the diameter of the small length of cable would expand during the testing. Consideration was given to taping the ends of the cut cable but there was also concern about the possibility that the addition of the tape could also deter the movement of the cable. For this reason, greater than 20 mm overlap was used in some of the assemblies. The conductor overlap length was measured prior to the specimen being loaded into the test fixture and measured upon completion of the testing. The resulting difference was required to be no more than 17 mm, as defined by the standard.

Finally, instead of limiting the number of connectors tested to the minimum number required by the standard, it was decided that all connectors subjected to environmental conditioning would be tested. This would provide a more significant baseline for information on the response of the connectors to the test threat. It was also decided to measure torque and movement of connectors above and beyond what is required by the standard to provide additional information for resolution of any discrepancies noted. Upon completion of testing of each component and gathering the required data, the component was disassembled, photographed and observations recorded.

III. SUMMARY OF TEST RESULTS

For ease in comparison of data, the tabulated results are included in Tables I through IX located at the end of the paper. Tables I through VI forward the results of data gathered on the connection components before and after subjecting the components to the electrical threat specified in IEC 62561-1, Edition 1. Each of the components chosen for testing was assigned an Item Under Test (IUT) designation that is used in this report to identify a specific product. The tables identify the peak current for each of the three impulses to which the specific IUT was subjected. Also identified is the resistance across the connector before and after the test, as well as the tightening and loosening torque. IEC 62561-1, 6.3 specifies the recorded loosening torque is the value of the first bolt, nut, or screw measured. However, the value of each of connection points was recorded as a part of this post-test analysis. All measured torque values are forwarded in Tables VII through IX. The first measured torque value is highlighted by bold type.

In-line (straight splice) connectors were found to be the least susceptible configuration to the lightning threat of the three styles tested, based on evaluation to the pass/fail criteria. All six of the aluminum connectors were found to meet the pass criteria of the standard. Only one of the copper in-line connectors did not meet the pass criteria (SS2C), and another that passed was near failure due to a conductor almost pulling out of the connector (AS1C). Fig. 2 shows the 22.9 mm movement of the source conductor between the white line on the conductor and the connector. However, the standard does not identify a maximum conductor movement for such connector configurations. The loosening torque for Sample SS2C was less than the minimum criteria. However, since this sample was not included in the primary series of samples, the copper in-line splice connectors met the pass/fail criteria of the standard.

Figure 2. Movement of conductor from Connector AS1C. Conductor movement is distance from connector body to white stripe on conductor.

Five of the six aluminum Tee-connectors were found to successfully meet the pass criteria of the standard. The third aluminum Tee-connector tested (PT3A) was found to have a loosening torque below the minimum allowable level but the remaining 3 connectors were tested and found to meet the pass criteria of the standard. Following the pass/fail criteria of IEC 62561-1, the aluminum Tee-connectors passed the electrical test.

Unlike the aluminum Tee-connectors, the copper Tee-connectors did not successfully meet the pass criteria of the standard but the deviations to the pass criteria were not typical of the other connectors. The first copper Tee connector tested (PT1C) was the only connector tested that was found to have a loosening torque which exceeded the maximum value allowed by the standard, even though it exceeded the maximum by only 0.68 Nm and the second bolt on the connector was within specified limits. The other two deviations were related to the source conductor pulling out of the connector. These will be discussed later in the report.

Most of the deviations to the requirements of the standard were related to the 2-conductor parallel splices. Three copper and four aluminum parallel splice connectors had loosening torques less than the minimum allowable. These deviations were not specific to connector material nor design. An equal number of aluminum and copper 1-bolt and 2-bolt parallel conductors were tested. For the four aluminum connectors with issues, two were 1-bolt and two were 2-bolt. For the three copper connectors, two were 1-bolt and one was 2-bolt.

With the exception of the two cases where a conductor pulled out of the connector, there were no deviations to the pass criteria related to the maximum connector resistance. Excluding the two connectors mentioned above, the highest resistance measured post-test was 0.56 mΩ. There were three connectors that exceeded the 1 mΩ maximum resistance after being subjected to the environmental conditioning but before being subjected to the test series of current impulses. Two of the connectors were made of aluminum (a 2-conductor parallel and an in-line connector with resistances of 1.48 and 81.1 mΩ, respectively) and the other was a copper in-line connector with a resistance of 1.65 mΩ. After being subjected to the electrical test, resistances were reduced from 15.6% to 0.4% of the original value or 0.18 to 0.39 mΩ post-test resistances.

Observations on changes to connector resistance versus material and style of connector follows. Overall, the majority (14 of 18) of aluminum connectors exhibited a decrease in resistance across all styles of connectors tested. On the other hand, copper connectors generally exhibited an increase in resistance after testing. Four of the five copper connectors in which the resistance decreased after testing were part of the six in-line copper connectors included in the test plan. The in-line connectors were consistent across materials with four of the six connectors decreasing in resistance for both aluminum and copper connectors. A final observation is that all six of the aluminum parallel connectors decreased in resistance after testing while all copper parallel connectors increased in resistance.

There appears to be no relationship between change in resistance and loosening torque failures. These deviations are discussed in Clause IV.

IV. DISCUSSION OF DEVIATIONS

Fourteen data points (involving 13 connectors) were found to be outside the pass criteria identified in IEC 62561-1. Seven of the connectors with issues were made of copper and six were aluminum. Over half of the deviations were associated with 2-conductor parallel connectors (three copper and four aluminum) with no clear relationship to connector design (one or two bolt). The breakdown of the deviations is: two for excessive resistance (each due to pulling out of the source conductor on Tee-connectors), two for excessive conductor movement and ten for torque deviations. The connectors with excessive conductor movement were copper 2-conductor parallel designs (PP3C and SP1C) with movement of 17.3 and 17.05 mm of the 17 mm allowed (a deviation of only 1.7 percent and 0.3 percent above the value allowed in the standard). Fig. 3 shows the result of conductor movement after 3 impulses. It is also noted that the loosening torque of PP3C (17.3 mm movement) met the loosening torque minimum requirement but SP1C (17.05 mm movement) did not. More details on the relationship between loosening torque and conductor movement will be discussed later in this section. Of the ten torque deviations, nine were due to loosening torques of less than ¼ tightening torque. The one connector that exceeded the upper level allowed was a two-bolt copper Tee-connector (PT1C) and it was only 0.68 Nm (2.7 percent) above the allowed loosening torque. The other bolt of this connector was found to be within the pass criteria.

Figure 3. Source conductor movement on PP3C

There was one 4-bolt copper straight splice connector (AS1C) with what could be described as excessive movement (pull out) of the conductor on the source side of the connector (shown earlier in Fig. 2). As noted earlier, this is not identified as a deviation to the pass criteria for this type of connector unless it pulls completely out and can no longer perform its function. The source side of the in-line connector pulled out 22.9 mm but there was enough conductor remaining in the connector after completion of the test that it passed the resistance test (in fact the resistance decreased to 10% of original value). The loosening torque of the bolt from which the conductor had pulled completely away was the highest of the 4 bolts on the connector. The loosening torque on the two bolts on the return side (where the conductor moved only 7 mm) was the two lowest measured for the connector but all 4 torques were in the range allowed by the standard.

If the conductors remained in the connectors at the end of the test sequence, connection resistance was not found to be a problem. For two of the copper Tee-connectors (PT2C and AT1C), the “source” conductor pulled out. A post-test analysis of PT2C suggests that this conductor may not have been properly seated in the connector. It does not appear that the lower nipple was engaged based on the discoloration of the interior around the nipple and the lack of indication of connector pull around the nipple. Other markings on the cable also suggest the amount of cable seated was not sufficient to reach the lower nipple. It is unclear whether the seating issue was due to an error during assembly or pull forces as a part of the environmental conditioning process, but IEC 62561-1, Edition 1, Clause 6.1 takes this into consideration in allowing the second set of 3 specimens be tested. Connector AT1C came apart on the third shot. This connector was a cross-connector versus a Tee. The post-test analysis of the connector showed that some of both conductors’ strands were broken inside the connector (see Fig. 4). In both these cases, the loosening torque for the connectors was found to be within required limits.

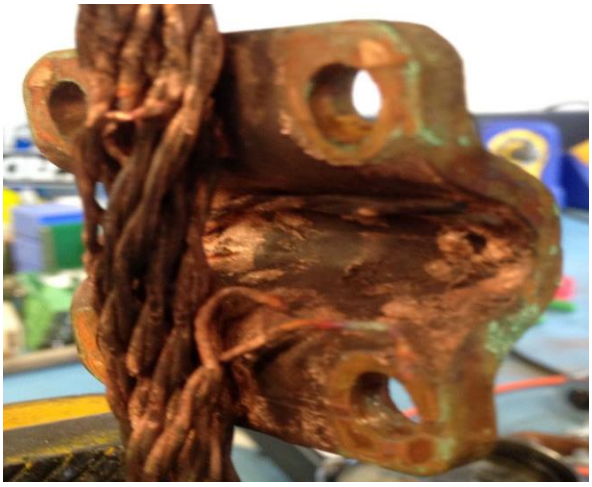

Figure 4. AT1C showing broken strands with missing source conductor.

Loosening torque was the predominant failure mode noted in this testing; especially for 2-conductor parallel connectors. Of the 14 pass criteria deviations noted, 10 were related to loosening torque criteria (71.4%) and 9 of the 10 was due to failure to achieve the minimum loosening torque criteria (64.3% of all deviations to pass criteria). The breakdown by connector for those not meeting the minimum torque requirement is one aluminum Tee-connector, one copper straight splice, three copper 2-conductor parallel, and four aluminum 2-conductor parallel. The loosening torque of six of these connectors was less than 2/3 of the minimum allowed level. These were an aluminum T-connector (PT3A = 0.23 Nm), two copper 2-conductor parallel connectors (SP1C = 0.79 Nm, PP1C = 1.47 Nm), and three aluminum 2-conductor parallel conductors (SP1A = 0.45 Nm, PP2A = 1.13 Nm, AP1A = 1.24 Nm).

Tables VII through IX forward a summary of loosening torques versus resistance across the connector and conductor movement in the connector. Connectors included in this testing can be characterized by twelve general styles, ranging from 1 bolt to 4 bolts. Torque values are given for each of the interconnection components (herein referred to as bolts) under the headings Torque (τ) A through D. Each of the bolts was measured, even though IEC 62561-1 requires only the first one to be recorded as the official value. The official value (first measured) is shown in bold type. For comparison, the minimum loosening torque value for the connector is also given. Columns “Source” and “Return” provide information on the movement of the conductors in the connector.

To date, only a basic analysis has been conducted of the relationship between measured loosening torque and other parameters that could be predictors of the ability of the connector to perform its function. There is no statistically significant correlation between low loosening torque and conductor movement in the connectors nor is there an obvious correlation between loosening torque and change in connector resistance. The two connectors that had conductors pull completely out both had loosening torque requirements that met the requirements of the standard. A review of Tables VII through IX show that only one of the eleven cases (SP1C) where conductor movement was 9 mm or greater was associated with a connector that had a loosening torque outside the requirements of the standard; and it exceeded the pass criteria by only 0.05 mm. Four of the greatest conductor movements recorded were all associated with loosening torques that met the pass criteria. On the other hand, four of the ten connectors that exhibited no greater than 1 mm movement in both conductors did not pass the loosening torque requirement, including the two connectors that had the lowest loosening torques measured of the 36 connectors tested.

V. CONSIDERATIONS IN TESTS USING STRANDED CABLE

The testing reported in this paper identified some differences in the effect of the type of conductor used (stranded or solid) on the test results. Due to these differences, the connectors should not only be qualified to their classification (H or N), the range of conductor sizes and materials, but also to construction (stranded or solid). Following are specific issues that are suggested for review by IEC TC 81 MT14 in considering tests involving stranded cable.

There is minimal information given in the standard relating to the handling of the items-under-test between the time they are taken out of environmental conditioning and subjected to the electrical test. During the testing reported in this paper, the conditioned specimens were carefully packaged in sealed boxes to minimize the evaporation of any trapped moisture. This parameter is much more relevant with stranded conductors than with 8 mm wire as it is likely the loosening torque will be affected by the expansion of trapped moisture in the connector. Handling conditions and ambient environment between the time the samples leave environmental conditioning and electrical testing should be specified.

Minimal guidance is given on the criteria for the bolt or screw selected for measurement where there is more than one connection component associated with the connector under test. IEC 62561-1, 6.3.c identifies that in the case of connectors with more than one screw, only the loosening torque of the first screw is relevant to the test. In the testing reported in this paper, it was decided to ensure each connection component (bolt or screw) was selected for torque evaluation an equal number of times for each style connector; where practicable. It is recommended that MT 14 consider a similar recommendation to ensure that each screw location is measured.

The relevance of the loosening torque value is questionable for tests involving stranded cable and more specifically woven cable. The data set gathered during this testing suggests that there is no direct correlation between loosening torque and ability of the connector to perform its required function. Of the two cases where the conductors pulled out of the connector and the top four cases of maximum conductor movement, the loosening torques were within specification. In the nine cases where the loosening torque was below the required value only one of the nine had a conductor movement in excess of 9 mm and most were only a few millimeters of movement. In many cases, there was arcing within the connector that fused some strands of cable to the inner shell of the connector. It is suggested that MT 14 consider whether loosening torque should be defined as a failure mode for stranded cable if the connector resistance is within required limits and movement of the conductor is within a specified value.

Movement of some conductors is not required by IEC 62561-1, 6.3.d to meet the 17 mm criteria. Some of the most significant movement of conductors noted during this testing was associated with conductors that are not required to be evaluated by the standard. Examples are the source conductor for Tee-connectors and conductors associated with in-line connectors. When testing is performed using conductors less rigid than 8 mm solid conductors (such as woven LPS conductors) without support within 500 mm of the connector, the connections can experience significant repeated mechanical forces. In actual installations, where the dead-end connections are supported by other terminations, test results suggest stresses experienced by the source end of Tee and in-line connectors are as significant if not more than that of the through conductors. It is recommended that consideration be given to requiring the 17 mm movement criteria be expanded to include all arrangements shown in Annex B of 62561-1.

A final item recommended for IEC TC 81 MT14 consideration is not limited to testing involving stranded cable. IEC 62561-1, 6.3.a requires that the contact resistance be measured with a source current of at least 10 A as close as possible to the connection component. The pass criteria is a resistance of 1 mΩ or less. The testing described in this paper used a calibrated micro-ohmmeter which had a source current of 5 A. There are numerous laboratories with micro-ohmmeters operating with a test current of 1 A that are capable of accurately measuring microhms to hundreds of milliohms to accuracies of less than 1 %. Given that the item-under-test represents a load of only a single connector, the 10A source requirement is not necessary for the application and is too restrictive. Consideration should be given to reducing the 10 A source restriction and focus on a required accuracy at 1 milliohm.

VI. SUMMARY AND RECOMMENDATIONS

The testing reported in this paper was generally conducted in accordance with IEC 62561-1 for Class H connectors not to be installed in concrete. Instead of limiting the number of connectors tested to the minimum number required by the standard, it was decided that all connectors subjected to environmental conditioning would be tested. It was also decided to measure torque and movement of connectors above and beyond what is required by the standard to provide additional information for resolution of any discrepancies noted. Fig. 5 provides an example of the item-under-test in the test chamber readied for electrical testing.

Figure 5. PT2A in test fixture prior to first impulse

The initial sets of both aluminum and copper in-line straight splice connectors were found to meet the pass criteria of IEC 62561-1, Edition 1. One connector in the primary set of aluminum Tee-connectors did not meet the minimum loosening torque criteria but each of the secondary set of connectors tested met the criteria so in accordance with the requirements of the standard, the connectors met the pass criteria. The first two of the copper T-connectors tested were found to deviate from the pass criteria, which would result in failure of the test criteria. The supplemental set of connectors was tested and a third connector was also found to deviate from the pass criteria requirements. Both the aluminum and copper 2-conductor parallel connectors failed to meet the pass criteria of the standard. Only two of the aluminum and three of the copper 2-conductor parallel connectors met the loosening torque criteria and in each case those not meeting the criteria failed to meet the minimum required value. The deviations were almost equally divided between aluminum and copper products and 1-bolt and 2-bolt designs. Two of the copper 2-conductor parallel connectors (PP3C and SP1C) were also found to exceed the maximum conductor movement requirement of 17 mm and two of the source conductors for the Tee-connector tests pulled out of the connector.

The analysis of the test results reveals that connector resistance was not found to be a problem as long as the conductors stayed in the connector. There were only two deviations to the pass criteria related to conductor movement and each of these were within 2% of the pass criteria value. Given the mechanical forces exerted on the test configuration and the weave of the conductor, it is possible that the additional 0.3 mm length may actually be due to the lengthening of the conductor due to longitudinal forces. Consideration of such a possibility could justify the inclusion some tolerance for conductor movement when smooth weave conductors are used.

The most significant issue with the testing of connectors used with stranded cable was found to be related to the torque requirements of IEC 62561-1. Ten of the 36 connectors tested had issues with the loosening torque requirements of the standard. These were evenly distributed between copper and aluminum connectors. Seven of the ten were related to parallel connectors and these were also evenly distributed between conductor material and design (1-bolt and 2-bolt designs). An interesting observation from the data was that there appeared to be no clear link between loosening torque and the ability of the connector to perform its function. In fact, the only 2 conductors that were unable to continue to perform their function after the test were the Tee and Cross connectors where the conductors pulled out. In both these cases the loosening torque was within the limits required by the standard.

The data and observations reported in this paper will be presented to the IEC Technical Committee 81 Maintenance Team 14 (MT 14) to initiate a discussion on modification of the standard to address to the qualification of connectors to be used with stranded conductors. Of most significance is that moisture trapped between strands of the smooth weave conductors used in the testing expands within the confined area inside the connector when subjected to multiple 100 kA current impulses. While this generally does not prevent connectors from continuing to perform their function, it does directly affect the resulting torque on the screws and bolts used in the connectors. It is also noted that the testing highlighted the need for discussion of some modification of the maintenance requirements of IEC 62305-3 [3] to indicate that when stranded cable is used, the torque values of accessible connectors should be checked after an expected strike to the structure.

Finally, it is recommended that the following issues be addressed in the next revision of IEC 62561-1:

- IUT handling conditions and ambient environment between the environmental test and electrical test should be specified.
- Each connection component (screw, etc.) be selected an equal number of times as the torque evaluation point, where practical.
- Reconsider the use of loosening torque as a failure mode for stranded cable if the connector resistance is within required limits and movement of the conductor is within a specified value.
- Consider requiring that the 17 mm movement criteria be expanded to include all arrangements shown in Annex B of 62561-1.
- Consider reducing the 10 A source current restriction for the resistance measurement .and focus on a required accuracy at 1 milliohm.
- Consider whether tolerances should be given for some pass-fail criteria (such as conductor movement or loosening torque).

REFERENCES

[1] NFPA 780-2014, Standard for the Installation of Lightning Protection Systems, National Fire Protection Association, ISBN: 978-145590720-5, Quincy, MA USA, 17 June 2013.

[2] UL 96, Standard for Safety; Lightning Protection Components, 5th Edition, Underwriters Laboratories, Northbrook, IL, 3 September 2013.

[3] IEC 62305-3, Protection against lightning – Part 3: Physical damage to structures and life hazard, International Electrotechnical Commission, Geneva, December 2012.

[4] IEC 62561-1, Lightning protection system components (LPSC) – Part 1: Requirements for connection components, Edition 1, International Electrotechnical Commission, Geneva, February 2012.

[5] UL 96A, Standard for Safety for Installation Requirements for Lightning Protection Systems, 12th Edition, Underwriters Laboratories, Northbrook, IL, 12 August 2014.

[6] D. Kokkinos, J. Meppelink, and M. Guthrie, “Lightning Protection System Component Standards in IEC 62561,” 7th Asia-Pacific International Conference on Lightning, Chengdu, China, November 2011.

[7] ASTM B172, Standard Specification for Rope-Lay-Stranded Copper Conductors Having Bunch-Stranded Members, for Electrical Conductors, ASTM International, West Conshohocken, PA, 2015.

TABLE I. ALUMINUM TEE CONNECTORS

IUT	$I_{pk}1$	$I_{pk}2$	$I_{pk}3$	R_{ci}	R_{co}	τ_{in}	τ_L
PT1A	94	96	96	54.3	49.4	11.3	13.8
PT2A	99.2	99.2	98.4	22.1	32.7	11.3	4.86
PT3A	100.8	101.4	100	91.0	107.3	5.08	0.23
ST1A	102.4	101.6	91.2	62.5	15.3	16.9	7.23
ST2A	101.6	93.6	101.6	364.1	16.6	16.9	8.02
AT1A	102.4	102.4	102.4	59.1	17.3	16.9	11.6

TABLE II. COPPER TEE CONNECTORS

IUT	$I_{pk}1$	$I_{pk}2$	$I_{pk}3$	R_{ci}	R_{co}	τ_{in}	τ_L
PT1C	100.8	100.8	100.8	148.2	309.7	16.9	26.1
PT2C	101.6	-	-	137.8	Open	10.2	12.8
PT3C	101.6	101.6	101.6	201.8	132.7	16.9	15.5
ST1C	101.6	102.4	101.6	42.3	44.2	20.3	12.1
ST2C	101.6	100.8	102.4	94.1	123.0	5.08	5.08
AT1C	100.8	101.6	100.8	413.7	Open	16.9	11.4

TABLE III. ALUMINUM STRAIGHT SPLICE CONNECTORS

IUT	$I_{pk}1$	$I_{pk}2$	$I_{pk}3$	R_{ci}	R_{co}	τ_{in}	τ_L
PS1A	104	100.8	101.6	67.3	41.9	20.3	15.5
PS2A	100	103.2	101.6	55.5	26.0	16.9	14.2
PS3A	102	98.4	100	36.9	103	5.08	5.08
SS1A	102.4	101.6	101.6	106.9	559.4	16.9	11.4
SS2A	102.4	101.6	101.6	81,140	394.6	11.3	7.46
AS1A	102.4	101.6	101.6	71.1	29.4	6.78	8.5

TABLE IV. COPPER STRAIGHT SPLICE CONNECTORS

IUT	$I_{pk}1$	$I_{pk}2$	$I_{pk}3$	R_{ci}	R_{co}	τ_{in}	τ_L
PS1C	102.4	101.6	102.4	32.7	33.3	20.3	8.13
PS2C	101.6	102.4	102.4	80.5	51.3	16.9	8.02
PS3C	97.6	101.6	101.6	62.5	42.0	6.78	3.84
SS1C	101.6	102.4	102.4	32.7	25.7	8.5	8.7
SS2C	101.6	102.4	102.4	11.4	52.1	16.9	2.82
AS1C	101.6	101.6	101.6	1654	175.0	11.3	9.26

TABLE V. ALUMINUM 2-CONDUCTOR PARALLEL CONDUCTORS

IUT	$I_{pk}1$	$I_{pk}2$	$I_{pk}3$	R_{ci}	R_{co}	τ_{in}	τ_L
PP1A	100	101.6	100	221.3	15.3	16.9	4.29
PP2A	101.6	101.6	100.8	1484.5	232.2	6.78	1.13
PP3A	98.4	101.6	100.8	202.8	22.3	16.9	15.8
SP1A	102.4	102.4	102.4	60.5	47.6	9.04	0.45
SP2A	101.6	101.6	101.6	46.8	18.4	16.9	3.62
AP1A	103.2	101.6	103.2	76.8	72.6	20.3	1.24

TABLE VI. Copper 2-Conductor Parallel Connectors

IUT	**$I_{pk}1$**	**$I_{pk}2$**	**$I_{pk}3$**	**R_{ci}**	**R_{co}**	**τ_{in}**	**τ_L**
PP1C	100.8	101.6	100.8	34.2	200.4	11.3	1.47
PP2C	101.6	101.6	101.6	26.1	49.4	16.9	4.63
PP3C	101.6	101.6	100.4	171.0	237.7	11.3	3.39
SP1C	100.8	100.8	100.8	51.4	225.5	6.78	0.79
SP2C	101.6	100.8	100.8	180.7	376.5	5.08	5.65
AP1C	102.4	100.8	100.8	41.0	63.6	16.9	3.39

TABLE VII. Relationship between Loosening Torque, Conductor Movement and Connector Resistance for Tee-Connectors

IUT	**Style**	**τ A**	**τ B**	**τ C**	**τ D**	**τ min**	**Source**	**Return**	**R (μΩ)**
PT1A	1	**13.8**	17.6	2.94		2.82	min	min	49.4
PT2A	2	4.52	**4.86**			2.82	?	1 mm	32.7
PT3A	3	**0.23**	0.45	0.45	2.26	1.27	< 1 mm	0.77 mm	107.3
ST1A	4	13.6	**7.23**			4.24	?	none	15.3
ST2A	5	16.0	8.7	**8.0**		4.24	6 mm	none	16.6
AT1A	6	**11.6**	12.7	13.2	10.6	4.24	none	1 mm	17.3
PT1C	4	23.6	**26.1**			4.24	4.5 mm	0.5 mm	309.7
PT2C	7	**12.8**	12.0			2.54	Open	None	Open
PT3C	5	14.2	12.9	**15.5**		4.24	none	5.4 mm	132.7
ST1C	8	**12.1**	17.4			5.08	4.5 mm	1.7 mm	44.2
ST2C	3	4.29	4.52	1.41	**5.08**	1.27	4 mm	10.6 mm	123.0
AT1C	6	12.4	12.0	**11.4**	12.4	4.24	Open	5.7 mm	Open

TABLE VIII. Relationship between Loosening Torque, Conductor Movement and Connector Resistance for 4-bolt In-Line Connectors

IUT	**Style**	**τ A**	**τ B**	**τ C**	**τ D**	**τ min**	**Source**	**Return**	**R (μΩ)**
PS1A	9	15.8	18.0	23.4	**15.5**	5.08	3.4 mm	0 mm	41.9
PS2A	9	12.9	8.6	**14.2**	7.34	4.24	3 mm	0 mm	26.0
PS3A	9	**5.08**	2.71	6.44	3.95	1.27	4 mm	10 mm	103.0
SS1A	9	4.63	**11.4**	9.6	8.7	4.24	9.7 mm	3 mm	559.4
SS2A	9	**7.46**	10.3	14.8	8.7	2.82	9 mm	min	394.6
AS1A	9	8.8	7.6	9.7	**8.5**	1.69	4 mm	3mm	29.4
PS1C	9	6.21	6.44	**8.13**	7.34	5.08	2 mm	2 mm	33.3
PS2C	9	6.33	7.91	5.65	**8.02**	4.24	min	min	51.3
PS3C	9	**3.84**	4.18	5.65	2.82	1.69	5.9 mm	4.4 mm	42.0
SS1C	9	10.6	**8.7**	11.8	7.01	2.19	min	min	25.7
SS2C	9	5.31	2.94	**2.82**	1.36	4.24	1 mm	I mm	52.1
AS1C	9	7.34	**9.26**	10.2	9.49	2.82	22.9 mm	7 mm	175.0

TABLE IX. Relationship between Loosening Torque, Conductor Movement and Connector Resistance for 2-Conductor Parallel Connectors

IUT	**Style**	**τ A**	**τ B**	**τ A%**	**τ B%**	**τ min**	**Source**	**Return**	**R (μΩ)**
PP1A	10	4.29	**4.29**	25.3%	25.3%	4.24	none	none	15.3
PP2A	10	**1.13**	1.36	16.7%	20 %	1.69	3.2 mm	5.3 mm	232.2
PP3A	11	**15.8**		93.3%		4.24	13.5 mm	min	22.3
SP1A	11	**0.45**		5 %		2.26	min	min	47.6
SP2A	10	4.63	**3.62**	27.3%	21.3%	4.24	min	min	18.4
AP1A	11	**1.24**		6.1%		5.08	5.3 mm	min	72.6
PP1C	11	**1.47**		13 %		2.82	8.8 mm	2.5 mm	200.4
PP2C	10	**4.63**	4.52	27.3%	27.3%	4.24	4 mm	1.2 mm	49.4
PP3C	11	**3.39**		30 %		2.82	17.3 mm	3 mm	237.7
SP1C	10	**0.79**	0.45	11.7%	6.7 %	1.69	17.05mm	3.6 mm	225.5
SP2C	12	5.08	**5.65**	100 %	111 %	1.27	15.7 mm	none	376.5
AP1C	11	**3.39**		20 %		4.24	8.1 mm	2.1 mm	63.6

Key for Tables

The following legend is applicable for all of the tables so rather than repeating it in each table it is given below:

1. I_{pk} given in kilo amperes.
2. Rci is connector resistance in micro-ohms prior to testing.
3. Rco is connector resistance in micro-ohms after testing.
4. τ_{in} is manufacturer’s specified torque rating for connector given in Newton-meters.
5. τ_L is loosening torque of connector after testing given in Newton-meters,
6. τ % is percentage of specified torque rating.