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Calculation and measurement of ampacity for class 5 flexible aluminum cable at 110 °C

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Article Info	ABSTRACT
	Class 5 flexible aluminum conductors are not common in cable manufacturing industry due to insufficient study on cable joints and connectors. The table of ampacities for aluminum conductors at 110 °C in AS/NZS3008.1.1 standards are also not available as a reference guide for electrical system designers that restricts the installation of aluminum low voltage (LV) cabling system to operate at 90 °C of conductor maximum operating temperature where 110 °C cables are permitted in Australia. In this paper, the cable ampacities of various LV Class 5 flexible aluminum cables at maximum operating temperature of 110 °C are calculated using IEC60287 and AS/NZ3008.1.1 standards. The calculated ampacities from the formula presented in clause 4.4. of AS/NZS3008.1.1 are verified by using the 6kA inductive current generator to determine the suitability for use. The joint temperature between cable and shear bolt mechanical connectors are simultaneoulsy simulated using the calculated ampacities to determine the suitability of mechanical shear bolt connectors when the coefficient of thermal expansion of material is considered. The observed differences between the calculated and measured values demonstrate the relevance of formula used in determining the current ampacity at 110 °C conductor temperature in free air.

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1. INTRODUCTION

Class 2 stranded aluminum and copper are the commonly used conductors in power system network. The low resistivity and cost of these materials make them very logical choice of metal for use in power cable industry. Annealed copper has a resistivity of 17.24 nΩ m at 20 °C whereas aluminum has 28.03 nΩ m. The resistivity of aluminum translates to 61.2% conductivity of that of copper which means that the cross-sectional area of aluminum shall be 1.6 times of Copper to have the same conductor resistance [1]. Moreover, the density of aluminum is less than one-third of Copper that makes aluminum the very cost-effective cable solution for the power industry [2].

Conductor types can be solid, stranded or flexible and can be circular, compacted and sectioned [3], [4]. The most common type of conductors for LV application are the stranded and flexible conductors. Flexible conductors are common in Copper material due to its superior tensile strength over aluminum and can either be Class 5 or 6 depending on the number of wires in conductor construction. Studies are currently

being done by the author in the implementation of high temperature aluminum cable with flexible conductor construction in LV power industry as presented in Table 1. There are also various studies in the use of high temperature superconductive (HTS) cable in the power utility network conducted by Al-Khalidi, *et al.* that could enhance the reliability of power networks [5], [6].

Table 1. Typical construction of class 5 flexible aluminum conductor taking into consideration the DC resistance of class 2 conductor

Cross-sectional area (CSA) (mm^2)	Total number of wires	Diameter of individual wire (mm)	Maximum DC resistance at 20 °C (Ω/km)
16	90	0.5	1.9100
25	133	0.5	0.1200
35	182	0.5	0.8680
50	231	0.5	0.6410
70	361	0.5	0.4430
95	494	0.5	0.3200
120	627	0.5	0.2530
150	760	0.5	0.2060
185	924	0.5	0.1640
240	1221	0.5	0.1250
300	1520	0.5	0.1000
400	2013	0.5	0.0778
500	1792	0.6	0.0605
630	2280	0.6	0.0469
800	2912	0.6	0.0367
1000	3640	0.6	0.0291

The operating temperature of cabling system affects the choice and type of cable used in electrical power installation. For LV long route installation, the 90 °C rated cables are always utilized whereas the 110 °C rated cables are used for higher ampacity load and short distances. Voltage drop is very essential in cable sizing calculation.

AS/NZS3008.1.1 provides the guidelines in cable selection with respect to the temperature rating of insulation and cable. This standard specifies the ampacity ratings for both Copper and aluminum conductors. However, there are no available ampacity rating tables for aluminum cables at 110 °C operating temperature [7]. The absence of ampacity ratings for aluminum cable at higher temperature limits the opportunity to further reduce the cost of the cabling system and therefore this paper focuses on the study, calculation, and simulation of ampacity of class 5 flexible aluminum cables at higher temperature. The proposed ampacity values can then be utlized by the electrical system designers as a reference guide to reduce the cost of cabling system while still maintaining the reliability of power network.

The reliability of connection is an on-going issue for aluminum conductors due to higher coefficient of thermal expansion of aluminum compared to Copper. There are several studies that have been conducted on the reliability of aluminum cable connection [8]-[14]. The thermal behaviour of class 5 flexible aluminum conductors and mechanical shear bolt connectors are also investigated and evaluated to determine the heat dissipated on insulation, sheath, and cable termination points. The study also aims to identify the suitable connectors for class 5 flexible aluminum conductors.

2.   THERMOMECHANICAL CONSIDERATION

Cables are subjected to cyclic loads during operaton hence, experience temperature variations and the effect of which depend on manner of installation categorized into two extreme cases; completely unrestricted and fully restrained. For the completely unrestricted case, the cable experiences expansion with the change in length primarily differd by coefficient of thermal deformation [15] and can be calculated using (1).

$$\Delta\ell = \alpha\ell_0\Delta T \tag{1}$$

where ℓ is the length, T is the temperature, α is the coefficient of thermal expansion (°C)$^{-1}$
α=25 x 10^{-6} (°C)$^{-1}$ for aluminum
α=17 x 10^{-6} (°C)$^{-1}$ for Copper

Hence for the same length and temperature variation, the thermal deformation of aluminum is greater than Copper by about 47%. For the fully restrained case, the cable experiences thermomechanical force in the longitudinal direction which can be calculated using (2).

$$F = EA\alpha\Delta T \tag{2}$$

Where F is the thermomechanical force in the conductor, E is the modulus elasticity of conductor, and A is the conductor cross-sectional area. Jointly considering these three parameters for the same temperature variation, Aluminium experiences 30 to 70% more thermomechanical force than Copper. Furthermore, maintaining a similar property of metallic termination is very important to the reliability of connection. Cables are subjected to cyclic load throughout its service life and poor contact due to stress relaxation which increases the resistance at the termination point could led to failure and overheating of termination. Thermomechanical design when used to limit the differential movement of the connection is also very important in achieving negligible expansion at the termination point [16].

3. DETERMINATION OF AMPACITY RATING

The formulae, methods, and standards used in this paper to determine the cable ampacities of class 5 flexible aluminum cables at higher temperature are presented in IEC60287 and clause 4.4 of AS/NZS3008.1.1. The formulae given in IEC60287 consider the construction of conductors, thermal resistivity of insulating material and the parameters related to the surrounding conditions such as the trefoil formation in free air whereas AS/NZS3008.1.1 is a straightforward derivation when the initial rated ampacities are known.

3.1. Conductor resistance of class 5 flexible aluminum

The DC and AC resistance per unit length of the conductor at various operating temperature are calculated using (3) and (4). Tables 2 and 3 summarize the conductor resistance results from the calculation.

$$R = R'(1 + y_s + y_p) \tag{3}$$

$$R' = R_0 [1 + \alpha_{20} (\theta - 20) \tag{4}$$

where R is the AC resistance of conductor at maximum operating temperature (Ω/m), R' is the DC resistance of conductor at maximum operating temperature (Ω/m), y_s is the skin effect factor, y_p is the proximity effect factor, R_0 is the DC resistance of conductor at 20 °C (Ω/m), α_{20} is the constant mass temperature coefficient and θ is the maximum operating temperature [17].

Table 2. Calculated AC resistance of conductor

CSA (mm²)	AC resistance (Ω/km)									
	20 °C	25 °C	40 °C	50 °C	60 °C	70 °C	80 °C	90 °C	100 °C	110 °C
16	1.910	1.949	2.064	2.141	2.218	2.295	2.372	2.449	2.526	2.603
25	1.200	1.224	1.297	1.345	1.394	1.442	1.490	1.539	1.587	1.635
35	0.868	0.886	0.938	0.973	1.008	1.043	1.078	1.113	1.148	1.183
50	0.641	0.654	0.693	0.719	0.745	0.770	0.796	0.822	0.848	0.874
70	0.444	0.453	0.479	0.497	0.515	0.533	0.551	0.568	0.586	0.604
95	0.321	0.327	0.347	0.359	0.372	0.385	0.398	0.411	0.424	0.437
120	0.254	0.259	0.274	0.285	0.295	0.305	0.315	0.325	0.335	0.346
150	0.207	0.212	0.224	0.232	0.240	0.249	0.257	0.265	0.273	0.282
185	0.166	0.169	0.179	0.185	0.192	0.199	0.205	0.212	0.218	0.225
240	0.127	0.130	0.137	0.142	0.147	0.152	0.157	0.162	0.167	0.172
300	0.103	0.105	0.111	0.115	0.119	0.123	0.127	0.131	0.134	0.138
400	0.082	0.083	0.088	0.091	0.094	0.097	0.100	0.103	0.106	0.109
500	0.065	0.066	0.070	0.072	0.074	0.077	0.079	0.081	0.084	0.086
630	0.053	0.054	0.056	0.058	0.060	0.062	0.063	0.065	0.067	0.069
800	0.044	0.045	0.047	0.048	0.049	0.050	0.052	0.053	0.054	0.056

Table 3. Calculated DC resistance of conductor

CSA (mm²)	DC resistance (Ω/km)									
	20 °C	25 °C	40 °C	50 °C	60 °C	70 °C	80 °C	90 °C	100 °C	110 °C
16	1.910	1.948	2.064	2.141	2.218	2.295	2.372	2.449	2.526	2.603
25	1.200	1.224	1.297	1.345	1.393	1.442	1.490	1.539	1.587	1.635
35	0.868	0.885	0.938	0.973	1.008	1.043	1.078	1.113	1.148	1.183
50	0.641	0.654	0.693	0.718	0.744	0.770	0.796	0.820	0.848	0.873
70	0.443	0.452	0.479	0.497	0.514	0.532	0.550	0.568	0.586	0.604
95	0.320	0.326	0.346	0.359	0.372	0.384	0.397	0.410	0.423	0.436
120	0.253	0.258	0.273	0.284	0.294	0.304	0.314	0.324	0.335	0.345
150	0.206	0.210	0.223	0.231	0.239	0.248	0.256	0.264	0.272	0.281
185	0.164	0.167	0.177	0.184	0.190	0.197	0.204	0.210	0.217	0.223
240	0.125	0.128	0.135	0.14	0.145	0.150	0.155	0.160	0.165	0.170
300	0.100	0.102	0.108	0.112	0.116	0.120	0.124	0.128	0.132	0.136
400	0.078	0.079	0.084	0.087	0.090	0.093	0.097	0.100	0.103	0.106
500	0.061	0.062	0.065	0.068	0.070	0.073	0.075	0.078	0.080	0.082
630	0.047	0.048	0.051	0.053	0.054	0.056	0.058	0.060	0.062	0.064
800	0.037	0.037	0.040	0.041	0.043	0.044	0.046	0.047	0.049	0.050

3.2. Calculation of dielectric losses

The thermal resistivity of insulating material and the associated wall thickness influence the heat dissipated to the surrounding layers. This energy loss is called dielectric loss and can be calculated using (5) and (6). Table 4 summarizes the calculated dielectric loss of the samples.

$$W_d = \omega C U_o^2 \tan\delta \text{ (W/m)} \tag{5}$$

where W_d is the dielectric loss, ω is equal to $2\pi f$, C is the capacitance per unit length, U_O is the voltage to earth (V). C is calculated using (5).

$$C = \frac{\varepsilon}{18 \ln\left(\frac{D_i}{d_c}\right)} 10^{-9} \ (F/m) \tag{6}$$

where ε is the relative permittivity of insulation, which is 3.0 for X-HF-110, D_i is the external diameter of insulation, d_c is the diameter of conductor [17].

Table 4. Calculated dielectric loss

CSA (mm²)	W_d (W/m)
16	0.00025
25	0.00027
35	0.00031
50	0.00035
70	0.00036
95	0.00042
120	0.00043
150	0.00041
185	0.00040
240	0.00042
300	0.00045
400	0.00046
500	0.00049
630	0.00050
800	0.00056

3.3. Calculation of thermal resistance T1, T4 and rated ampacities

The thermal resistance T_1 between one conductor and sheath, and the external thermal resistance T_4 are calculated using (7) and (8), respectively. Table 5 summarizes the calculated values of T_1 and T_4. Cable samples are LV single-core double insulated (SDI) without metallic coverings and therefore T_2 and T_3 are being neglected.

$$T_1 = \frac{\rho_T}{2\pi} \ln\left[1 + \frac{2 t_1}{d_c}\right] \tag{7}$$

$$T_4 = \frac{1}{\pi D_e h (\Delta\theta_s)^{1/4}} \tag{8}$$

$$h = \frac{Z}{(D_e^*)^g} + E \tag{9}$$

where ρ_T is the thermal resistivity of X-HF-110 insulation (K.m/W); t_1 is the thickness of insulation between conductor and sheath (mm); d_c is the diameter of conductor (mm); h is the heat dissipation; Z, E and g are constant; D_e is the external diameter of cable (m) and $\Delta\theta_s$ is the excess cable temperature above ambient temperature [17], [18].

Table 5. Calculated thermal resistance T_1 and T_4

CSA mm²	T_I	D_e m	Z	E	g	h	KA n=3	T_4 in Air
16	0.3851	0.0099	0.96	1.25	0.2	3.664	0.0441	6.112
25	0.3913	0.0120	0.96	1.25	0.2	3.573	0.0176	5.172
35	0.3437	0.0133	0.96	1.25	0.2	3.526	0.0169	4.731
50	0.2978	0.0156	0.96	1.25	0.2	3.455	0.0169	4.118
70	0.2835	0.0176	0.96	1.25	0.2	3.402	0.0178	3.707
95	0.2578	0.0198	0.96	1.25	0.2	3.352	0.0180	3.345
120	0.2477	0.0221	0.96	1.25	0.2	3.309	0.0189	3.051
150	0.2418	0.0241	0.96	1.25	0.2	3.273	0.0199	2.827
185	0.2347	0.0271	0.96	1.25	0.2	3.226	0.0215	2.550
240	0.2271	0.0295	0.96	1.25	0.2	3.193	0.0224	2.366
300	0.2107	0.0332	0.96	1.25	0.2	3.147	0.0230	2.132
400	0.2051	0.0376	0.96	1.25	0.2	3.101	0.0250	1.911
500	0.1903	0.0430	0.96	1.25	0.2	3.051	0.0261	1.697
630	0.1858	0.0478	0.96	1.25	0.2	3.014	0.0280	1.546
800	0.1848	0.0535	0.96	1.25	0.2	2.974	0.0308	1.399

After deriving the values of conductor resistance, dielectric loss, and thermal resistance T_1 and T_4, the cable ampacities can now be calculated using (10).

$$I = \left[\frac{\Delta\theta - W_d \left[0.5T_1 + n(T_2 + T_3 + T_4) \right]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)} \right]^{0.5} \tag{10}$$

3.4. Calculation of cable ampacities using AS/NZS 3008.1.1 standard

Although the recommended equations to determine the cable ampacities are given in IEC60287, the purpose of this calculation is to verify if (11) can be used to determine the ampacity rating of cables at 110 °C for installation in air and whether the results can be safely utilized. Table 6 summarizes the calculated ampacities and differences between the values obtained from two Standards.

$$\left(\frac{I_0}{I_R}\right)^2 = \frac{\theta_0 - \theta_A}{\theta_R - \theta_A} \tag{11}$$

where I_0 is the operating current (A), I_R is the rated current (A), θ_0 is the operating temperature of cable when carrying I_0 (°C), θ_R is the operating temperature of cable when carrying I_R (°C) and θ_A is the ambient air or soil temperature (°C).

Table 6. Calculated ampacities at 110 °C and their differences

CSA mm²	IEC 60287 Amps	AS/NZS 3008.1.1 Amps	Difference %
16	84	84	0
25	115	115	0
35	141	141	0
50	176	173	2
70	223	220	1.4
95	276	275	0.6
120	325	321	1.3
150	374	370	0.9
185	440	432	1.9
240	522	518	0.7
300	613	601	1.9
400	729	709	2.8
500	869	832	4.3
630	1020	975	4.4

4. DESCRIPTION OF TEST

The laboratory facility is equipped with fully integrated and automatic induction cable cycle heating system. The system can carry out a long-term heating test of Copper and aluminum power cables and associated cable connectors with a total load current of up to 6kA. Figure 1 shows the graphical modelling of the test system that consists of the following equipment:

- Cable cycle heating test unit capable in generating up to 6kA of inductive current
- Pico technology 8 channels thermocouple data loggers and associated software
- 8 units of K type thermocouple assembly
- Current transformer and sensor
- Fluke 435 power analyzer
- DC resistance measuring device
- Windows PC
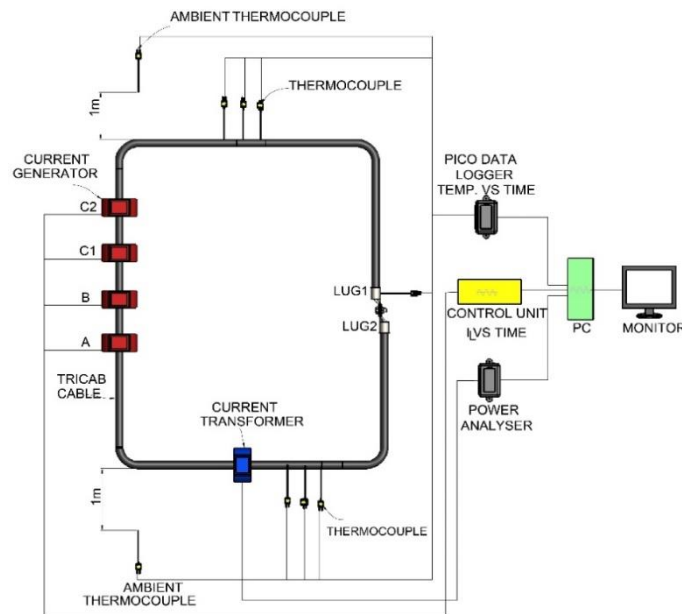
Figure 1. Graphical modelling of the heat dissipation test system

The test loop consists of three parallel X-HF-110 insulated cables with polyvinyl chloride (PVC) sheath in trefoil formation are assembled and joined in series with mechanical shear bolt connectors. Cables of 12 meters in length are placed on 450mm cable ladder tray with the distance of 650mm above the ground simulating the unenclosed spaced in free air condition. Cables are looped and passed in the 6000/0.1A current transformer. Cables are terminated with mechanical shear bolt connectors and sheared using a torque wrench. Conductors are polished and cleaned using a steel wire brush before inserting onto the connector. Film of conductive grease are applied between conductor and inner barrel of connector to ensure moisture penetration within the contact point are eliminated.

The palms of the two mechanical connectors are attached with a bolt to ensure a good contact point. The thermocouple leads are attached to the conductor, insulation, sheath of cable and to the body of mechanical connector. The other thermocouple lead is attached to a one-meter conductor, one meter away from the unit under test, for the measurement of ambient temperature. The resistance of connections is measured using the DC resistance meter prior to applying the current. Application of current is carried out using the current generator from the heat cycling unit. Current is tuned and adjusted based on the ambient temperature inside the test facility. The induced test currents from the current generators are verified and validated using the Fluke 435 power analyzer as seen in Figure 2.

Figure 2. Induced current is measured using Fluke 435 power analyzer

The temperature rises as measured on all thermocouple leads are recorded on Pico system data logger. The requirement is that the equilibrium shall reach the point for a time sufficient for the temperature rise to reach a constant value. This condition is achieved when the variation at all measured points does not exceed 1K/h [19]. The joint temperature between the conductor and connector always needs to be cooler than the temperature of the conductor as temperature rise on the joints could potentially caused a premature failure of connection on the field.

5. RESULTS AND DISCUSSION
5.1. Simulated current and conductor temperature

There is a heat generated to the conductor when the current is applied. This phenomenon is called conductor loss [20] and can be calculated using (12).

$$P_c = I^2 R \qquad (12)$$

where P_c is the conductor loss (W), I is the current flowing to the conductor (A) and R is the DC resistance of conductor (Ω/km).

Throughout the duration of test, the current generated from heat cycling unit are verified using Fluke 435 Power Analyzer attached to each conductor of three-phase system. Current source is tuned for every rise of ambient temperature due to the heat dissipated from the unit under test. Tuning of current source are completed when the unit under test reached its equilibrium stage as defined in [21] where the temperature of conductor and connectors do not change by ± 2 °C for 15 minutes.

Table 8 represents the measured average conductor temperature of 50 to 630mm^2 cables across three phases due to conductor losses with respect to the ampacity rating derived in (11). Table 7 shows that the conductor temperatures are below the 110 °C limit as used in the calculation of rated ampacity. These are the values produced in simulation test when the conductors and connectors reached their state of equilibrium.

Table 7. Measured current and temperature when the calculated ampacity is applied to conductor

CSA	Ambient temperature during testing	Rated current at ambient temperature	Measured current	Conductor temperature at equilibrium
mm^2	°C	A	A	°C
50	19	195	197	104
70	22	249	250	105
95	23	311	311	106
120	20	363	367	107
150	24	407	414	105
185	23	475	475	106
240	24	577	577	109
300	31	643	643	109
400	24	759	760	105
500	25	915	915	105
630	26	1073	1077	108

5.2. Temperature at connection point

The temperature measured at the connection points of various cable sizes from six thermocouples are between 62 to 72 °C when the rated ampacity is applied to the conductors. This is an evidence that the shear bolt connectors are averaging 39 °C cooler than the phase conductors and are consistent across all cable samples. The highest recorded connector temperature was 72 °C on 240 and 630 mm^2 and were low on 50, 70, 95, 120 and 150mm^2. The high cross-sectional ratio of connector and conductor presented in Table 8 contributes to the cooler termination point.

Table 8. Conductor: Connector cross-sectional ratio

Conductor cross-sectional area mm^2	Connector barrel cross-sectional area mm^2	CSA Ratio
50	324	6
70	419	6
95	419	4
120	541	5
150	541	4
185	575	3
240	575	2
300	1000	3
400	1000	3
500	1391	3
630	1656	3

5.3. Temperature of insulation and sheath

Thermal resistivity of polymeric material influenced the heat transmitted from conductor to air. Cables are subjected to electrical losses during its service and operation and these losses transform to heat that dissipate from conductor to the insulation, sheath, and metallic layers. The resultant heat dissipated from cables affects the ambient temperature of the surrounding medium which then influence the ampacity rating of cable in the form of derating factor [22]. Figure 3 represents the heat dissipated to every layer of cable samples under test taken from Pico data logger for the duration of tests. The heat dissipated from sheath of all cable samples measured from the three thermocouples were less than 90 °C which is below the maximum operating temperature of PVC material at steady state condition [22].
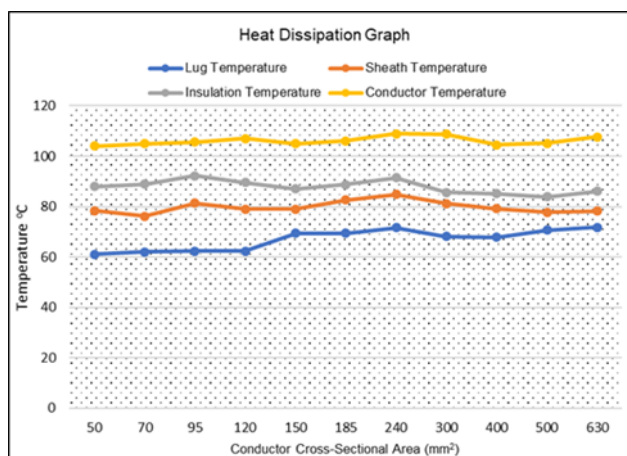

Figure 3. Graph of heat dissipated to termination, conductor, insulation, and sheath

6.   CONCLUSION

The recorded conductor temperature with respect to the calculated rated ampacity for the three-phase conductors are found to meet the value for the 110 °C operating condition. The results of the simulation tests are very encouraging and gave the authors a confident level that the calculated ampacities derived from (10) are suitable for use in electrical system that operates at 110 °C maximum operating temperature. The simulated ampacities when compared with the ampacities derived from IEC60287, the typical method in

calculating ampacities of cables, are found to be within the 5% acceptable limit with majority of the differences are less than 2%.

The analysis of the heat dissipation test between the mechanical shear bolt connectors and Class 5 flexible aluminum conductors also confirms the initial suitability of mechanical shearbolt connectors due to the low joint temperature that averages about 30 °C lower than the conductor temperature that eliminates the lateral expansion at the termination point. Results of the heat dissipation test shows that the connector-conductor cross-sectional area ratio tends to influence the temperature at termination point: lower tempretuare for high ratios about 4-6 whereas high temperature for low ratios of about 2-3. Maintaining a low temperature at connection point is vital to the reliability of termination for the aluminum conductor. Authors are now investigating the final suitability of mechanical shear bolt connectors when the cables are experiencing electrical fault.

ACKNOWLEDGEMENT

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