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PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD

colour inside

Multicore and symmetrical pair/quad cables for digital communications – Part 1-4: Symmetrical pair/quad cables with transmission characteristics up to 1 000 MHz – Conductor heating of bundled data grade cables for limited power transmission based on IEEE 802.3

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CONTENTS

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MULTICORE AND SYMMETRICAL PAIR/QUAD CABLES FOR DIGITAL COMMUNICATIONS –

Part 1-4: Symmetrical pair/quad cables with transmission characteristics up to 1 000 MHz – Conductor heating of bundled data grade cables for limited power transmission based on IEEE 802.3

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The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document
Draft PAS	**Report on voting**
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MULTICORE AND SYMMETRICAL PAIR/QUAD CABLES FOR DIGITAL COMMUNICATIONS –

Part 1-4: Symmetrical pair/quad cables with transmission characteristics up to 1 000 MHz – Conductor heating of bundled data grade cables for limited power transmission based on IEEE 802.3

1 Scope

This PAS is a technical supplement to IEC 61156-1, edition 3 (2007): *Multicore and symmetrical pair/quad cables for digital communications – Part 1: Generic specification*.

This PAS, covering exclusively four-pair data grade cables, is intended to provide a test method for the determination of the maximum attained conductor temperatures which occur due to the deployment of the IEEE protocol for PoE /PoEP.

It gives as well the required background information about the thermodynamic behaviour of such bundled cables, if they are located in areas with restricted heat dissipation, a reality which occurs in every installation situation. However, only the basic principles are given, as the rigorous application and solution of these problems fall into the relevant cabling standards.

NOTE 1 The restriction to four-pair data grade cables is very important, as the heating of a multiple pair cable, especially if it has a protective screen, is much worse, since the ratio of the heat generation within the cross-section versus the overall circumferential surface to dissipate the heat is dramatically decreased, thus yielding substantially higher conductor temperatures. Additionally, the screen acts as a near perfect IR–reflector, thus increasing additionally only the excess heat within the cable.

This restriction is of importance considering the installed base, where individual four-pair cables in a loose bundle arrangement may need to replace multiple pair cables.

Hence, the main objective is

a) the indication of a suitable measuring method to assess the heating gradient across bundled data grade cables subject to d.c. power transmission, using for the incident and return conductors the common mode circuits of either two or four pairs;
b) to provide, toward this end, the worst case assessment of the conductor and cable heating in bundled cable configurations, where the densest hexagonal packing configuration is required. This assessment of the heating is anticipated to be carried out under the extremely lenient condition of freely suspended cable bundles in an air-conditioned environment free of any air draft, the heat dissipation thus being achieved by undisturbed convection into the surrounding environment;
c) to provide some explanatory background information on the heat dissipation of heated conductors, insulated conductors, pair and cables, both screened or unscreened;
d) to provide means to assess the installed base of data grade cables with a view to their compliance with the requirements of either PoE or PoEP, if required in a comparative way, but based on the resistance assessment of at least one short cable length withdrawn from the installed base by replacement;
e) to indicate the basic physical assessment proceedure, based upon the testing of a cable bundle according to item b). A comparable heating trial on the same cable bundle, but under restricted heat dissipation conditions, yields then some indication of how to assess the maximum occurring temperatures under these conditions;
f) towards this end, the densest hexagonal packing configuration has to be simplified, using an equivalence in order to allow a consecutive evaluation of the heating under any heat dissipation restriction using a layered structure of the cables and the interstitial air spaces within the bundled structure.

For this purpose a test method is provided:

– to allow the evaluation of the heating of the conductors of cable bundles where all (or a certain percentage of the cables) are exposed to powering. Additionally is considered the case that either two of four pairs in a cable are used for d.c. power transmission;

– to measure the temperature of $\left(1+\sum_{n=1}^{N} 6 \cdot n\right)$ cables in hexagonal densest packing structure, in order to allow the assessment of the temperature gradient and the heat insulating properties of the cables. The densest packing of cables represents the worst case situation [1];

– to provide a means to assess the performance potential of an installed base of data grade cables for power transmission. Evidently such a process has to take into account the specified d.c. resistance for categorized cables. If an experimental assessment of the installed cables is not feasible, then a normalizing procedure to IACS could be envisioned, though the specified cable d.c. resistances are substantially below 100 % IACS;

– to allow the assessment of the d.c. current transmission performance potential of the newly developed cables (these cables may be made based on the most recent design principles);

– to indicate a comparative test for a cable under 2- or 4-pair heating conditions and under free and restricted heat dissipation conditions, as encountered for instance with frame-wall, insulating material ducts etc.;

– to give the mathematical approach for this procedure;

– to allow also the extension of the results of two heating trials to any cable bundle size, i.e. also to higher bundle sizes, provided the heat insulation conditions to which the cable bundle is exposed to are known.

NOTE 2 The scope of this PAS exclusively covers the cable performances. The variable heat insulating properties of the cables resulting out of the installation practices for channels (for instance feeding bundled cables through insulating materials) is outside the scope of this PAS. This has to be initiated and be taken care of in ISO/IEC JTC1/SC25 WG3 in a suitable technical report or installation guide. This is the reason that here only general guidelines are given.

The test method described lends itself also to cable testing if higher currents than those resulting out of the basic specified d.c. resistances and the specified currents for the IEEE 802.3 PoE / PoEP protocol are required. This would eventually allow the transmission of higher powers at the same maximum ambient temperature of 60 °C, without exceeding the maximum permissible conductor temperatures in the cable. This may be applicable to higher performing cable categories in cases where the user really needs the transmission of higher power levels than anticipated in the IEEE 802.3 PoE / PoEP protocol.

In these cases, a verification of their conductor heating properties has to be assessed, and the cable performance has to be guaranteed by the manufacturer.

The PAS is written in a general way, thus covering not only horizontal cables. Stranded cord cables will have to be evaluated as well, and this very carefully, as they are so far installed in the equipment rooms in higher cable count bundles as well. This PAS establishes some basic guidelines to deal with these problems.

The heating in this PAS is the result of the resistance which is specified in IEC 61156-5 and IEC 61156-6 as 19 [ohm / 100 m] and 29 [ohm / 100 m].

1 Later in this document, a method is given to determine the equivalent diameters for bundles of densest packing, having approximately the same dissipation properties with respect to convection and radiation. This may be interesting for modelling purposes, in case a statistical current loading situation may have to be evaluated, especially in cases where the convection is severely restrained due to surrounding insulation material or any other means to prevent the targeted heat dissipation by radiation and convection.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61156-1:2007, *Multicore and symmetrical pair/quad cables for digital communications – Part 1: Generic specification*

IEC 61156-5:2009, *Multicore and symmetrical pair/quad cables for digital communications – Part 5: Symmetrical pair/quad cables with transmission characteristics up to 1 000 MHz – Horizontal floor wiring – Sectional specification*

IEC 61156-6:2010, *Multicore and symmetrical pair/quad cables for digital communications – Part 6: Symmetrical pair/quad cables with transmission characteristics up to 1 000 MHz – Work area wiring – Sectional specification*

IEEE 802.3af-2003, IEEE *Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications – Amendment: Data Terminal Equipment (DTE) Power via Media Dependent Interface (MDI)*

IEEE 802.3at-2009 Part 3: *Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications – Amendment 3: Data Terminal Equipment (DTE) Power via the Media Dependent Interface (MDI) Enhancements*

3 Terms, definitions, symbols, units and abbreviated terms

3.1 Terms and definitions

Open thermodynamic systems - In this PAS, thermodynamic open systems are considered.

Such systems differ from the usually considered systems in the classic thermodynamics, which have generally a constant mass flow going in and out over the system borders. In the present case, the systems have a constant mass flow equal to zero and an energy transfer over the system borders, i.e. an energy influx and/or outflux. This energy influx/outflux may be based on electrical energy going into the system and being transformed therein into heat or on any other kind of heat transfer, be it by radiation, conduction or convection, or any combination thereof.

Two-dimensional systems - In this PAS, a two-dimensional thermodynamic system is understood as a cable or cable bundle which is homogeneous in longitudinal direction, heated by an electric energy influx, dissipating and/or absorbing energy over the system borders in radial direction. The dissipated and/or absorbed energy may be transferred by radiation, conduction and convection or any combination of the latter.

Hence the cross-sectional system borders of a two-dimensional system are subject to a radial energy flow, which is only in case of a thermal equilibrium constant and equal to the sum of the internally produced heat and energy influx minus the energy outflux by radiation, conduction and convection.

Excess energy	-	is the sum of the internally produced heat and energy influx minus the energy outflux under thermal equilibrium conditions. It is this excess heat which is the culprit for the heat increase of the conductors.
Concatenation of systems	-	concatenations of thermodynamic systems are only understood in this PAS as concatenations in any of the radial directions, while all the concatenated systems have the same longitudinal dimension.
Longitudinal open systems	-	such systems are understood here as systems which in the main dimension – here the cable length – are homogeneous with respect to the electrical energy conversion into heat within the systems.
Electrical energy influx	-	is the electrical energy influx over the open thermodynamic system borders at one or both ends of their longitudinal extensions (this allows the very unlikely testing under a powering of the pairs from either one or both sides open)
Internally generated heat	-	is the internally generated heat by the electric influx corresponding to $I^2 \cdot R \cdot t$ [Watt·sec/ length] and is length homogeneous, i.e. constant over the length.
Radial energy in – or outflux	-	is the energy either picked up over the radial borders of the system or increments thereof or the radial outflux of energy out of the system or increments thereof. Both the influx and the outflux can occur for bundled cables by radiation, conduction and convection or any combination thereof.

NOTE As a result of the above definitions, any cable is considered to heat up homogeneously over its length in the described bundled systems, and this independently of reaching the thermal equilibrium. If the above-system definitions are not met, then the cable heats up inhomogeneously over its length – dependent upon the locally varying dissipation conditions length –resulting in a length distributed resistance increase. This may happen under installation conditions, when the heat dissipation is restricted locally over the length of the cable bundles. This may easily yield local conductor temperatures which substantially exceed the maximum specified temperature of 60 ºC.

As this aspect has to be considered more in detail in the appropriate installation guidelines, it is outside the scope of this report.

This report will however adress the subject of restricted heat dissipation as a guide to developing the appropriate installation guidelines.

3.2 Symbols, units and abbreviated terms

N	number of cables in the bundle [-]
n	number of cable layers around the centre conductor [-]
R_{Ri}	round trip loss of a pair in the cable [Ω/100 m]
R_B	resistance of the concatenated quad conductors of a cable for one- or two-pair heating at 20 °C [Ω/l_B] or [$2\cdot\Omega/l_B$] depending upon one- or two-pair heating
l_B	length of the cable bundle [m]
i	summation counter for one- and two-pair heating [-]
m	indicator for 2-pair (m = 2) or 4-pair (m=4) heating [-]
R_{BT}	resistance of the entire concatenated bundle at the temperature T in [Ω/l_B] or [$2\cdot\Omega/l_B$]
R_{Bm}	measured resistance of the entire concatenated bundle under heating condition, but after having reached thermal equilibrium [Ω/l_B] or [$2\cdot\Omega/l_B$]
α	temperature coefficient of the resistance [-]
T	temperature under heating and thermal equilibrium conditions [°C]

T_R	reference temperature of 20 °C or the measured temperature of the air conditioned room. In the latter case, the resistance at room temperature has to be measured precisely [°C]
$U_{Test\ min.}$	minimum voltage which has to be precisely measured by the used volt-meter [V]
I_{Test}	constant current applied to the conductors [A]
Q	generated heat in the conductor at any time t [W·sec/m]
Cond.	suffix to describe the heat generated in one of the conductors forming the “common mode” lead for powering
$R(t)$	conductor loop resistance at the time t
t	time elapsed during which the conductor is exposed to the current. This time has to be sufficiently long to reach thermal equilibrium
$Q_{EX\ t \to \infty}$	excess heat remaining in the conductor under thermal equilibrium [W·sec/m]
$Q_{GE\ t \to \infty}$	generated heat in the conductor at thermal equilibrium [W·sec/m]
$Q_{t \to \infty}$	dissipated heat from the conductor after reaching thermal equilibrium [W·sec/m]
$Q_{Radiation\ t\ \ \infty}$	heat dissipated by radiation at thermal equilibrium
$Q_{Conduction\ t\ \ \infty}$	heat dissipated by conduction at thermal equilibrium
$Q_{Convection\ t\ \ \infty}$	heat dissipated by convection at thermal equilibrium
- / +	the preceding superscripts to indicate the heat dissipated (-) and absorbed (+) from the outer and inner cable or cable layers, respectively
ΔT	temperature difference between T and T_R [°C]
$R(T_R)$	specified or measured d.c. loop resistance of the conductors at 20 °C per m
$U_{M\ t \to \infty}$	voltage measured across the conductors under thermal equilibrium
$\rho\ (T)$	specific resistance at a temperature of T [$\Omega \cdot mm^2/m$]
ρ 20 °C	specific resistance at a temperature of 20 °C [$\Omega \cdot mm^2/m$]
r_0	corresponds to the radius of a single cable
r	outer radius of the cable jacket
$r_{C\ n}$	outer equivalent radius of the n^{th} cable layer
$r_{A\ n}$	outer equivalent radius of the n^{th} air layer
q	amount of heat in a general way
F	surface area through with the heat is conducted
k	heat transfer coefficient
k_o	heat transfer coefficient at a temperature T_R
κ	coefficient of the temperature dependence of the heat transfer
k_A	heat transfer coefficient of air
T_i	temperature at the inner surface of a layer
T_a	temperature at the outer surface of a layer
R_a	outer radius of a layer
R_i	inner radius of a layer
$Q_{A\ n}$	heat transferred through the n^{th} air layer
$\Phi_{A\ n}$	logarithmic mean of the inner and outer transfer surfaces of the n^{th} air layer
$Q_{C\ n}$	heat transferred through the n^{th} cable layer
$\Phi_{C\ n}$	logarithmic mean of the inner and outer transfer surfaces of the n^{th} cable layer

$Q(n)$	total heat generated in the n^{th} cable layer
$Q(0)$	heat generated in the centre cable
$T(n)$	logarithmic mean temperature of the helical conductors within the cable jackets
$T_{Ambient}$	ambient temperature the cable bundle is exposed to
Φ_{C0}	dissipating surface of the centre cable
$Q(N)$	heat transferred to the environment through the multiple layers

4 The testing of bundled cables

4.1 General comments

Any standard and code considering the "ampacity" of conductors refers to the conductor surface temperature. This results from the historical fact that sometimes conductors are also used for the power transmission at high frequencies. In this case, the heating of the conductor surface is affected by the mode of transmission.

Some concepts to correlate the attenuation to the d. c. resistance could be used, however in this case, for all practical purposes, they are not applicable, as here the 4-pair data grade cables are used as quads for the d.c. transmission, yielding either six or three "twisted conductor" combinations for the power transmission over one or two pairs. It is for all practical purposes beyond the scope of any cable standards to specify the attenuations of these "twisted conductor" configurations, to be able to derive there from any d.c. resistance at a zero frequency. Furthermore, it has to be realized that:

a) the impedance variations as well as the impedance roughness scatter so widely for different cable designs of the same data transmission performance that such an approach is not more than impractical;
b) the impedance roughness has an impact on the attenuation;
c) there are no methods available to measure the common mode impedance and attenuation between the twisted conductors used for the power transmission, and these would be the only ones required to make an honest assessment of the d.c. resistance.

Hence, this PAS strictly refers to the conductor temperature as the current transfer within the IEEE PoE / PoEP protocols covers only d.c. currents over the common mode circuits of either 2 or 4 pairs. In this case, the conductor temperature is based on the specified cable d.c. resistances and is assumed to be uniform across the cross-section, though there is in reality a very minor temperature gradient occurring due to the heat dissipation through the insulation. However, this effect is absolutely negligible due to the very good heat conductivity within the conductor. In fact, this effect is so small that it escapes any measurement accessibility.

As a result, in this PAS, the conductor surface temperature is equated to the conductor temperature.

This temperature is of outmost importance for the suitability of the insulation material at the interface, in order to avoid an overheating and a consecutive degradation of the insulation. Otherwise the health and safety issues cannot be guaranteed, as a melt down and the potential danger of self-ignition may otherwise occur.

The PAS is written in a general way, thus covering not only horizontal cables. The testing of stranded cord cables is covered as well, as they are installed in and close to the equipment rooms in higher cable count bundles as well.

4.2 The bundling of cables

To determine the maximum permissible heating of the data grade cables under simultaneous PoE / PoEP deployment, the consideration of the worst case conditions prevailing has to be considered. This condition occurs in tightly bundled cables in the hexagonal densest packing configuration. Therefore, this PAS focuses basically on such configurations.

The hexagonal densest packing structure is characterized by the following number of cables in a bundle:

$$N = \left(1 + \sum_{n} 6 \cdot n\right) \qquad (1)$$
$$n = 1,\ 7,\ 19,\ 37,\ 61,\ 91,\ 127,\ ....$$

where

N is the total number of cables in the hexagonally densest packing structure;

n is the number of layers, surrounding the center cable.

Here the value n has to be selected in such a way as to cope with the potentially largest cable bundle sizes envisioned by the user.

In this case, the outside surface area of the hexagonal densest packing structure is responsible for the entire heat dissipation to the environment. The heat dissipation is here considered only under unrestricted conditions in an air conditioned environment. The heat dissipating surface of the tightly bundled cable structure is slightly different for radiation, conduction and convection. In the considered case, only the radiation and convection are occurring, as the cable structure should be freely suspended in the air conditioned environment. In this case, the convection over the strings to suspend the bundled cable structure can be neglected.

If a layered equivalent of the bundled cables is considered, then obviously two routes may be pursued, either taking an extension of the above-mentioned different surfaced for radiation and convection into account or simplifying it to an equal surface, as done in Clause 10.

The bundling of the measurement cables has to be made using appropriate lay plates, as schematically indicated in Figure 1. The cables are kept in place using either insulated copper wire as a string or binder, or better a poly-aramid yarn, as it has a negative temperature coefficient (best is obviously a glass fiber-poly-aramid fiber composite yarn or rowing having a mix such as to reach a temperature expansion coefficient equal to zero). Such binders are recommended in a tex-count of ~300 ÷ ~700 Tex as yarns or rowing.

Before taking the cable bundle out of the lay plates, the bundle has to be secured, starting from the middle between the two lay-plates in both directions with either a poly-aramid rowing or an insulated copper conductor, and this in an helicoidally way, up to a point close to the lay-plates.

It is advisable to prepare the cable ends extending from the lay-plates for the interconnections, the looping and the measurements, and this prior to pulling off the lay-plates from the cable bundle.

Close to the lay-plates, a straight tangential fixation of the cables should be used.

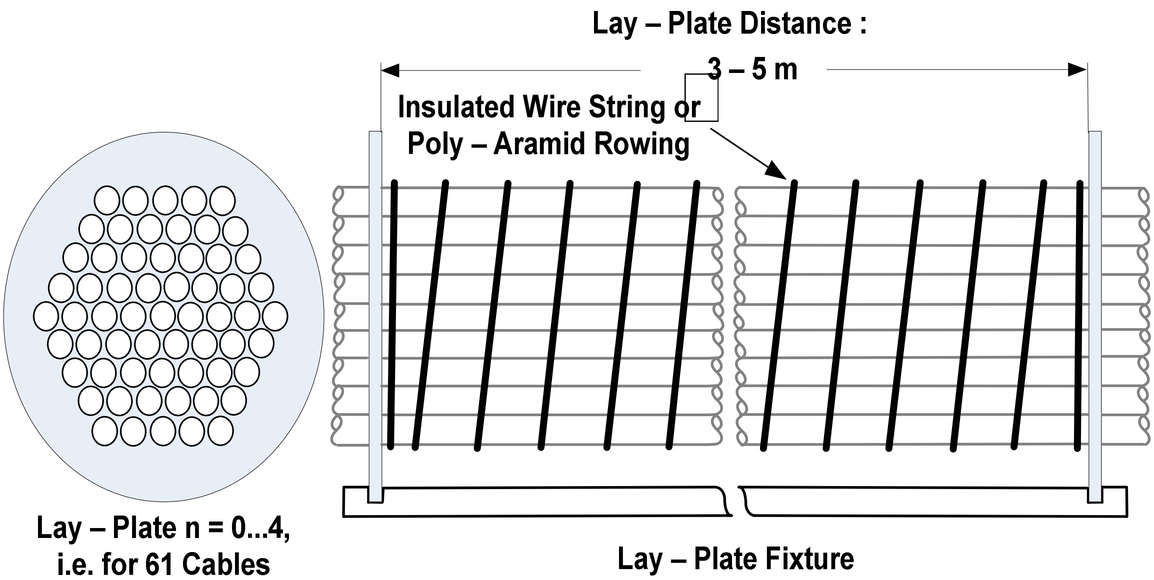


Figure 1 – Lay-plate arrangement for stringing up and fixing the cables to maintain the densest hexagonal packing structure, here shown for a 61-cable bundle

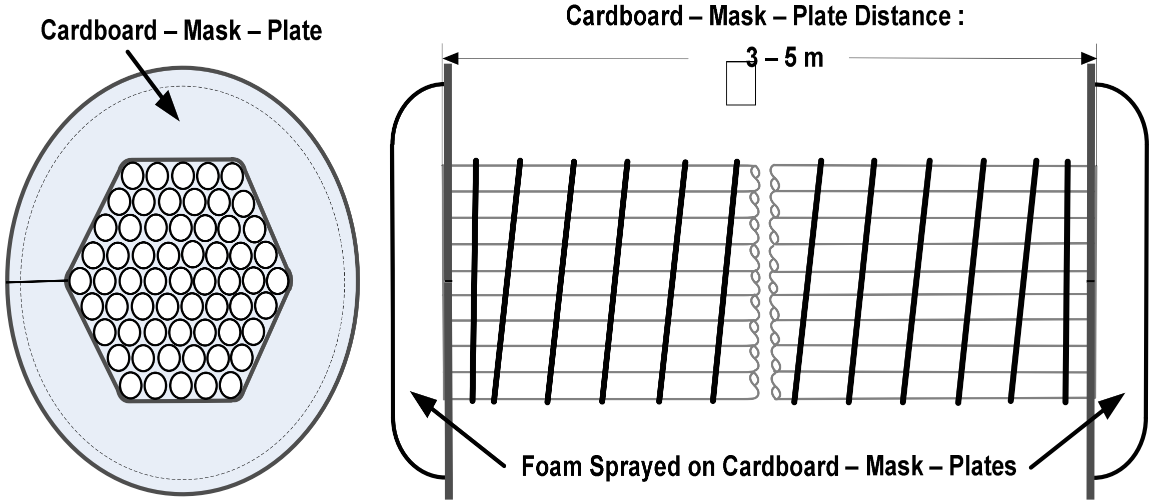


Figure 2 – Arrangement of cardboard–mask–plates over the ends of the cable bundle to apply the insulating foam over the ends of the bundle

Once the cable bundle is tightly fixed, it can be taken out of the lay-plates, after finishing the preparation for the concatenation and interconnections of the cables in the layers and between the layers. This may also entail a precise cutting of the length of the cables relative to the lay-plate distance. Only after removal of the lay-plates can these interconnections between the layers and the preparation of the ends for measuring purposes be made.

Then – and this is important – the ends of the bundle have to be covered with a thermal insulating foam. Such foams are available in every hardware store in the form of pressurized spray cans. The end, where the connections between the concatenated common mode circuits of the pairs are only located, can thus be insulated, using a cardboard mask to avoid spilling of the foam over to the radial exposed surfaces of the cable bundle.

A similar mask shall be used also on the connection and measuring side of the cable bundle. Here small pieces of a polymeric tube should be used to protect the access of the end of the cables used for the measurements. These tubes can be removed after application of the insulating foam, provided they do not adhere to the foam. This implies the use of pieces of either polytetrafluorethylene (PFTE) tube or other polymeric tube pieces covered with silicon oil.

The applied foam spray layer on the ends of the cable bundle should be of approximately 2 cm to 3 cm.

4.3 The suspension of the cable bundle

The cable bundle has to be suspended in a free space in order not to restrict the convection of the heat into the surrounding environment. This normally happens via the inherently occurring draft around the cable bundle due to the dissipated heat. There shall be no additional draft created at all, as this only increases the heat dissipation of the cable bundle.

In order to maintain the conditions of a linear thermodynamic system, there should be no heat transfer over the ends of the cables, i.e. over the ends of the cable bundle. Therefore, it is mandatory to apply a heat insulating foam spray at the ends of the bundle, such that only the measurement ends of the conductors are accessible that will have to be used for the temperature assessment and for the 2- or 4-pair current heating of the pairs in each cable and eventually also the interconnections between the cable layers, if a selective layer heating is envisioned.

The cable bundle should be suspended, in order to have it in a horizontal position, with an undisturbed convection to the surrounding air. The completed bundle should be freely suspended in air using a suitable support structure or rack, such that there is a sufficient distance between the support or rack and the cable bundle, a distance of approximately 1 m to the ground and neighbouring walls and a distance to the ceiling of approximately 2 m, as schematically shown in Figure 3.

A draft which may be created eventually by the air conditioning system should be minimized by suitable baffles, to protect the bundle from a direct draft exposure.

Only when the cable bundle is suspended should the remaining connections between the cable ends be completed. The cables should be connected in series, including the measurement cables. In the case that some layers should not be connected at all, suitable jumpers have to be installed.

According to the option described in the Scope under Clause 1 item d), it is preferable to use the measurement cables also as power feeding cables. Figure 7 schematically shows the suggested concatenation for heating of additional layers from the inside toward the outside or from the outside toward the center. To introduce jumpers in between the cables is trivial and not elaborated here in more detail.

If the measurement cables are used for the inter-layer connections, then it is also feasible to simply heat any layer by itself and measure the resulting temperatures in the other layers, including the center cable.

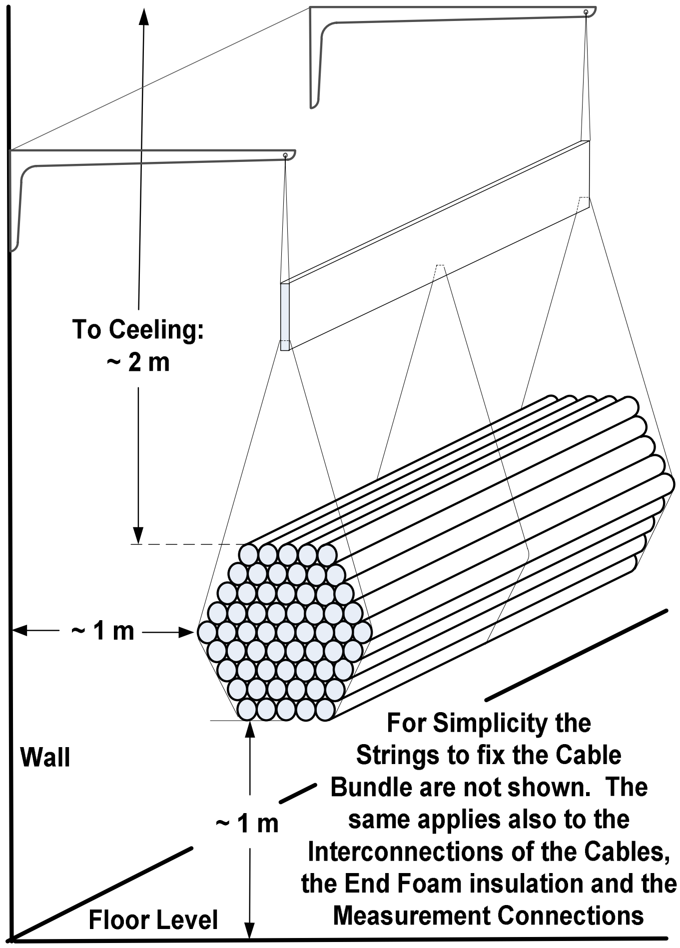


Figure 3 – Schematic of the suspension of the cable bundle

If a small heavier gauge size lead is connected and soldered to the inlet and outlet, without affecting the concatenation of the pairs in between the cables, then the cut back to a lower or higher number of heated layers is easily feasible. In this case, it is also feasible to heat only some of the outer layers for instance and measure the temperatures in the inner layers. This would yield a very good approximation for the required down rating in real installations.

Once all the interconnections have been made, the power feeding circuit (s) should be tested for continuity.

Then the reference conductor pairs of the measurement cables should be connected to a high precision resistance meter or, better, a bridge, usually used for determining the conductivity, using flexible heavy gauge-size leads. The measurement itself has to be made after a sufficient time to guarantee thermal equilibrium of the cable bundle with the surrounding room temperature (normally a minimum of 4 h to 6 h, though shorter times may be used, depending on the bundle size of the cables. Thus for instance, it has been shown that 4 h are close to the equilibrium condition for a 37-cable bundle).

To minimize the end-effect, it is recommended to use an insulation foam spray, to cover all the cable ends, with the exception of the feeding leads of the measurement cable access points. Such thermal insulation foam sprays (polyurethane-based) are available in any hardware store. To foam insulate the ends, two semi-circular cardboard plates with a center hole corresponding to the cable bundle and having a diameter approximately 20 cm larger than the cable bundle should be used very close to the ends of the bundle, such that the heat dissipation goes really radial off the surface of the cable bundle.

End caps on the cable ends are not recommended, as they fan out the cable ends, and thus increase only the end-effect error.

4.4 Assessment of the concatenated loop resistance of all pairs

To verify the suitability of the used constant current power supply, it is recommended to assess the total loop resistance, which has to be heated either in a 2- or 4-pair powering set-up.

Only hexagonally densest packing structures of cables have a repetitive heat dissipation performance in a well defined environment.

Therefore, it is mandatory to use bundles of $\left(1+\sum_{n} 6 \cdot n\right)$ cables, i.e. cable bundles arranged in such a configuration. These bundles shall have a minimum length suitable to match the available constant current source, the milli- or micro voltmeter available and eventually a floating resistance meter or bridge.

It is evident that the length of the bundle nevertheless has to be relatively long, in order to minimize the unavoidable heat dissipation errors occurring at the ends of the bundle. As already mentioned above, the end faces of the bundle will have to be covered with an insulating foam layer of approximately 3 cm thickness. Through this foam layer, only the wires for the measurement cables should be fed to the surface. All the interconnections between the pairs in each layer should be covered by the foam.

The bundles have to be absolutely arranged in a hexagonal densest packing configuration, as any deviation of it will necessarily yield results which are different from set-up to set-up.

Obviously, the length limitation is dictated by the maximum voltage range achievable with the constant current source required for testing.

If for a given cable we have a measured roundtrip loss of $R_{R\,i}$ in Ω/100 m for each pair within a cable, then we get for the entire resistance for the cable bundle depending upon 2- or 4-pair cable heating:

$$\begin{aligned} R_B &= \frac{\ell_B \cdot \sum_{i=1}^{i=m} R_{R\,i}}{50} \cdot \left(1+\sum_{n} 6 \cdot n\right) \qquad [\,\Omega/\mathrm{m}\,] \\ &= \frac{\ell_B \cdot \sum_{i=1}^{i=m} R_{R\,i}}{50} \cdot N \qquad [\,\Omega/\mathrm{m}\,] \end{aligned} \tag{2}$$

where

R_B is the resistance of the concatenated entire cable bundle at a reference temperature of 20 °C;

l_B is the length of the cable bundle;

$R_{R\,i}$ is the roundtrip resistance of each pair (of course, considering the common mode circuit) within the cable;

i is the summation counter of the concatenated common mode circuits in each cable under 2- or 4-pair heating;

m is the indicator for 2- pair (k = 2) or 4-pair (k=4) heating.

The temperature coefficient of the resistance increase, using Equation (15), further down yields then:

$$R_{BT} = R_{Bm} \cdot \frac{1}{\ell_B \cdot k \cdot [1 + \alpha \cdot (T - T_R)]} \qquad [\Omega/m] \tag{3}$$

where

R_{BT} is the resistance of the entire concatenated bundle at the temperature T_R [Ω/m];

R_{Bm} is the measured resistance of the entire concatenated bundle under heating condition, but after having reached thermal equilibrium [Ω/ℓ_B] or [$2\cdot\Omega/\ell_B$];

T is the temperature under heating condition in [°C];

T_R is the reference temperature of 20 °C or the measured temperature of the air conditioned room. In the latter case, the resistance at room temperature has to be measured precisely [°C].

Hence the minimum voltage $U_{Test\,min.}$ across the conductors subjected to the constant current source with a current level of I_{Test} is:

$$U_{Test\,min.} = I_{Test} \cdot R_{BT} \tag{4}$$

where

$U_{Test\,min.}$ is the minimum voltage measurable across the concatenated conductors [V];

I_{Test} is the current to be supplied by a constant current source [A].

Hence the used voltmeter has to be capable of measuring this minimum voltage level precisely.

5 The temperature as a function of the current load in conductors of bundled cables in hexagonal densest packing structure

5.1 The test description

The specifics of the test procedure are explained in the following. Some of the details are indicated for explanatory purposes, including some description to the test procedure itself, to avoid any ambiguities.

The cables in the bundle shall be arranged in the densest hexagonal packing configuration, as indicated in Figure 4. The cables used for the individual temperature measurements are located on one of the main diagonals of the hexagonal structure.

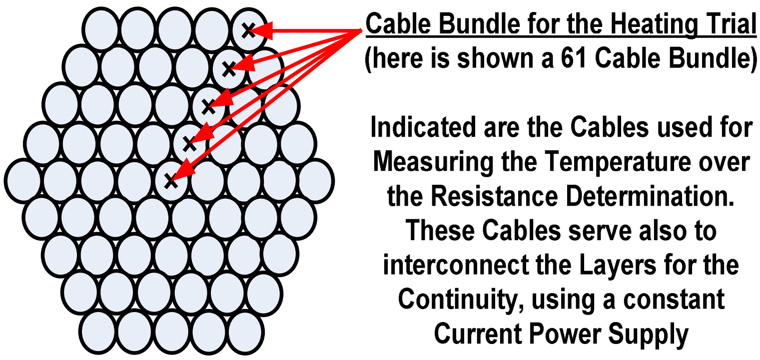


Figure 4 – Cross-section of a cable bundle used for the test, here a bundle of 61 cables

The cables used for the “temperature” measurement, are also used to concatenate the layers of the bundles. This is shown in Figure 5 as well as in Figure 6 and Figure 7 in all details.

5.2 The temperature measurement

To measure the conductor temperature poses a problem. To measure the resistance of one conductor as a means to determine the temperature may be objectionable. The use of thermocouples or resistance temperature probes in a cable bundle would yield only a point measurement. Furthermore, it results only in a very crude approximation of the real conductor temperature [2].

Thermocouples or probes will have to be minuscule in size, i.e. not only very small, and the problem of introducing them up to the conductor surface is very difficult, if not impossible without destroying the integrity of the cable and insulation.

To measure the jacket surface temperature in a cable bundle does not allow a direct conclusion on the conductor temperature, hence the measurement of the jacket surface temperature has to be discarded. The same is also true for the insulation temperature of each individual conductor.

As a result, the pairs of those cables which are powered to assess the conductor temperature are used directly to measure the conductor temperature. This makes mandatory to measure first their resistance at room temperature and then follow the voltage across the pairs connected to a constant current source over time up to the thermal equilibrium.

The schematic to connect the pairs for measuring the temperature alternatively for 2- or 4-pair heating is shown in Figure 4. To measure the temperature, always two of heated pairs are used, even under 4-pair heating conditions. These two pairs shall be selected such that they have the highest resistance values at room temperature, in order to guarantee that the worst heating conditions are really measured.

Thus, in Figure 4, it is assumed that pair # 1 and pair # 2 have the highest d.c. resistance values, respectively, of the considered four pairs of the cable, if measured at room temperature.

Figure 5 gives a complete picture of the connection of n layers of cables for alternative 2- or 4-pair heating, indicating as well the interconnections between the layers, in order to obtain a concatenation of all cables for the electric energy input.

2 Thermocouples are not defined. The rationale for this is the fact that they may have any diameter and with it any heat capacity and conductivity, which in this case renders a precise assessment of the conductor temperature impossible. Furthermore, the thermocouple should be in direct contact with the conductor, which is physically impossible without fundamentally changing the locally prevailing heat dissipation properties, and therefore also the conductor temperature.

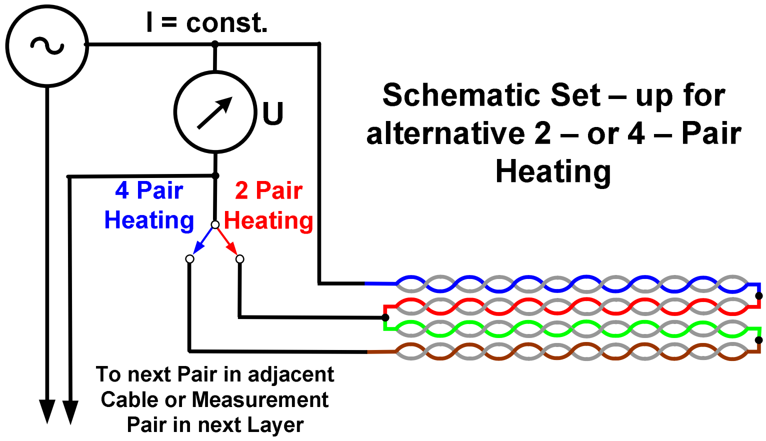


Figure 5 – Connections on both ends of the center cable to obtain two nearly identical "pair" resistances, which can then be measured using the voltage across these pairs

Again, in Figure 5, it is assumed that pairs 1 and 2 have the highest resistance ("common mode" resistance) of the four pairs in the cable. It is furthermore assumed that the cable under measurement is exposed to the heating current from a constant current source.

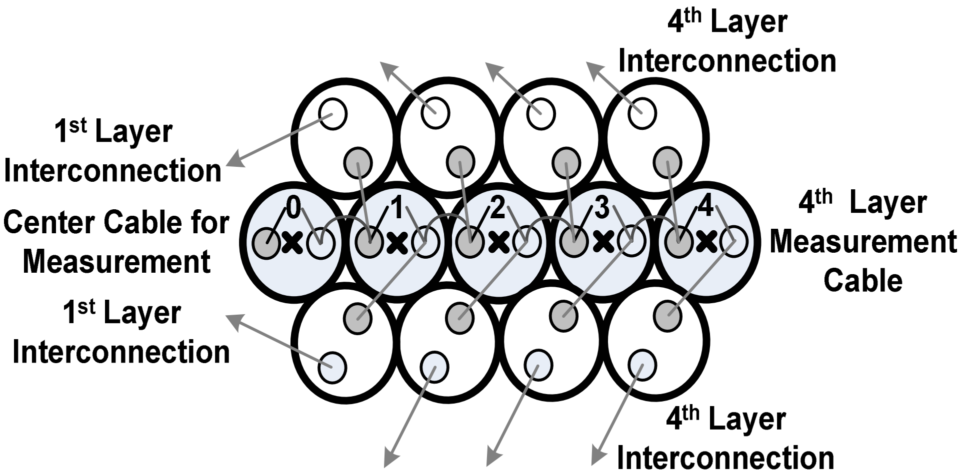


Figure 6 – View of part of the cable bundle around the measurement cables indicating the "temperature" measurement leads and those for the concatenation between the cable layers in the bundle (here for n = 0 … 4)

Figure 6 indicates a part of the end of a cable bundle used for the measurement of the temperatures. Here the same pairs as indicated in Figure 10 are also used for the measurement as well as for the interconnection between the layers.

Cables which are not exposed to a heating current can be measured with a "floating" resistance meter or a resistance bridge of suitable precision. This may be required for pursuing special cases – normally outside the scope of this document if, for instance, an entire intermediate layer or some of the outermost layers are not subjected to current heating.

Therefore, the pairs of the cables are for the testing connected together at their ends. The current goes in all the cables through the common mode circuit.

If the cables have a cross-web, then this would act as an additional heat barrier between the different pairs. As it is generally not possible to have equal resistance across all four pairs, the pairs with the two highest and with the two lowest resistances should be concatenated for the two- and four-pair heating. In Figure 12, these are the concatenation of the common mode circuit of the pairs 1 to 2, and 3 to 4, respectively.

If the objective is the verification and validation of the maximum current limit in the cables of an installed base, which essentially contain even up to date Cat. 5 / Cat. 5e cables, then a different procedure shall be used, see 6.2 and 6.3.

Cables with an individual screening over the pairs or a common screen over all four pairs, i.e. SFTP or FTP constructions, respectively, behave slightly worse from a heat dissipation point of view. On the other side, UTP cables, although dissipating the heat better, have more copper conductor length heated per length of cable due to the tighter twist lays used in unscreened cable constructions. In so far, these effects may be considered to offset each other to some degree.

It could be conjectured that a straight aluminium shielding tape (FTP– cable construction) may help to even out the temperature difference within the cable and this faster than in a UTP cable. However, this is no more the case for polymeric-metal composite tapes, which are commonly used to ease the manufacturing process. In this case, the composite tape does not help to decrease the heat dissipation to the surrounding, as it represents an additional heat barrier.

5.3 The heat generation and the resulting increase of the resistance

The generated heat $Q_{Cond.}$ in each of the conductors (here the term “conductor” is used for each of the parallel connected conductors of a pair to simulate the behaviour of one “common mode conductor”) is:

$$Q_{Cond.} = I^2_{Test} \times R(t) \times t \qquad \left[\frac{W \cdot sec}{m}\right] \tag{5}$$

where

Q is the generated heat in the conductor at any time t;

Cond. is the suffix to describe the heat generated in one of the conductors forming the “common mode” lead for powering;

R (t) is the resistance of the conductor at the time t;

t is the time elapsed during which the conductor is exposed to the current.

Two current levels may have to be to verified, i.e. the actually standardized currents for PoE of 0,350 A and for PoEP of 0,600 A. The conductors may be solid (as used for horizontal cables) or stranded conductors (as used for equipment cords, cross-connect cords or work-area cords) [3].

---

3 Riser cables in the traditional designs as multiple pair cables have to be tested integrally or, better, replaced by bundled cables of known temperature rise in bundled condition.

We have to be concerned here only with the conditions under thermal equilibrium, i.e. when the excess heat remaining in the considered conductor (or in the 4-pair cable) is equal to the difference of the generated heat and the dissipated heat, be it by radiation, conduction or convection or any combination thereof. This state is achieved after a sufficiently long time, here indicated by $t \to \infty$:

$$Q_{Ex\ t\to\infty} = Q_{Ge\ t\to\infty} - Q_{t\to\infty} \quad \text{with:}$$

$$Q_{Ex\ t\to\infty} = Q_{Ge\ t\to\infty} - Q_{Radiation\ t\to\infty} - Q_{Conduction\ t\to\infty} - Q_{Convection\ t\to\infty} \qquad \left[\frac{W \cdot sec}{m}\right] \qquad (6)$$

where

$Q_{EX\ t\to\infty}$	is the excess heat remaining in the conductor under thermal equilibrium;
$Q_{GE\ t\to\infty}$	is the generated heat in the conductor at thermal equilibrium;
$Q_{t\to\infty}$	is the dissipated heat from the conductor after reaching thermal equilibrium;
$Q_{Radiation\ t\to\infty}$	is the heat dissipated by radiation at thermal equilibrium;
$Q_{Conduction\ t\to\infty}$	is the heat dissipated by conduction at thermal equilibrium;
$Q_{Convection\ t\to\infty}$	is the heat dissipated by convection at thermal equilibrium.

It has to be made very clear at this point that the excess heat as defined in the preceding equation is based exclusively upon the internally generated heat, and applies as such rigorously only to the center conductor of a cable bundle in the densest packing configuration. For all the other cables in the bundle, Equation (6) has to comprise as well the heat transferred by radiation, conduction and convection from layer to layer. In this case – which is important for assessing the heating under restricted heat dissipation conditions (see Clause 10) – Equation (6) has to take the precise form of:

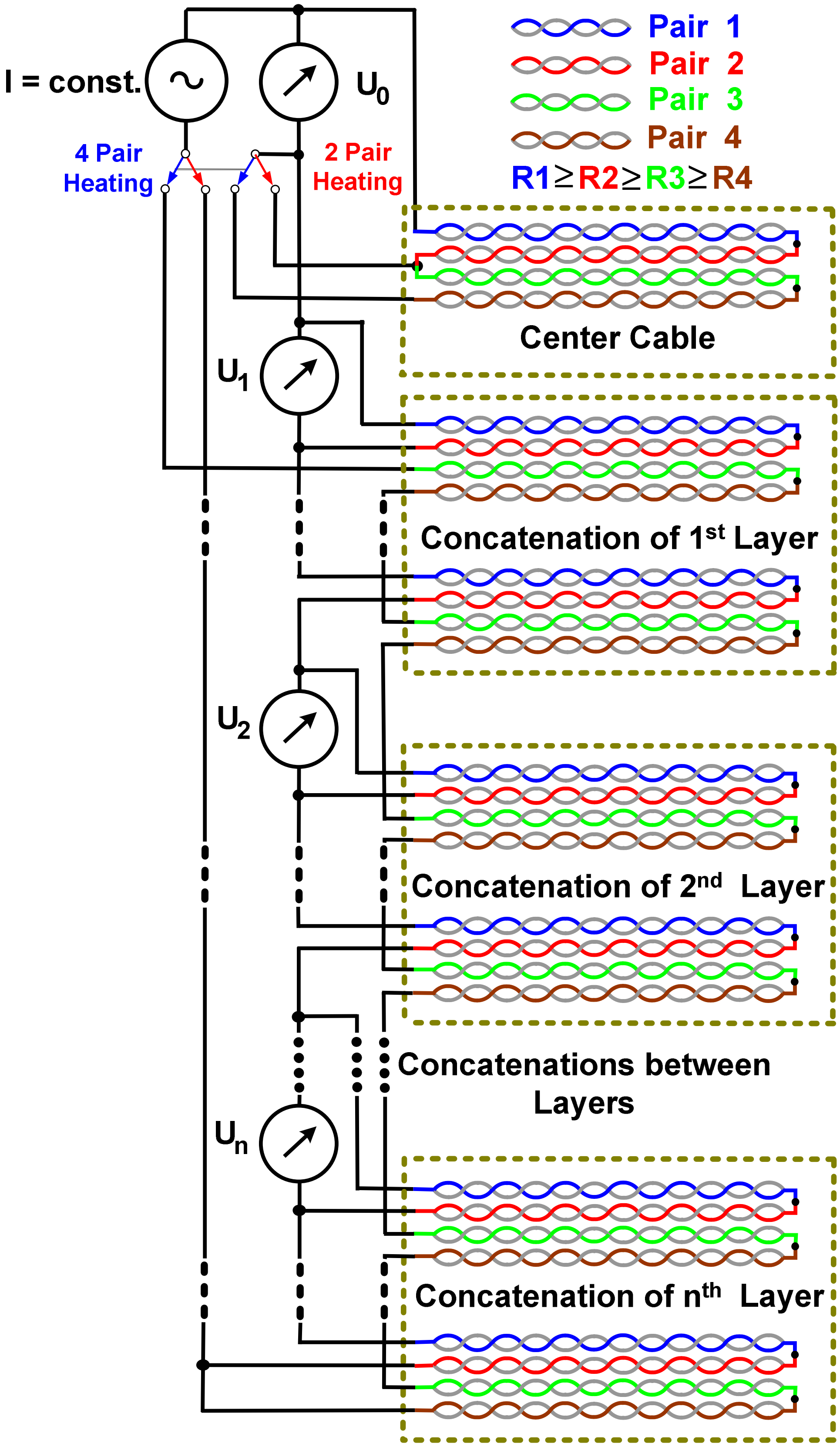


Figure 7 – Schematic for connecting the cables in the different layers for alternatively 2- and 4-pair heating

$$
\begin{aligned}
Q_{Ex\ t \to \infty} = Q_{Ge\ t \to \infty} &- {}^{-}Q_{Radiation,\ t \to \infty} + {}^{+}Q_{Radiation,\ t \to \infty} \\
&- {}^{-}Q_{Conduction,\ t \to \infty} + {}^{+}Q_{Conduction,\ t \to \infty} \left[\frac{W \cdot sec}{m} \right] \quad (7) \\
&- {}^{-}Q_{Convection,\ t \to \infty} + {}^{+}Q_{Convection,\ t \to \infty}
\end{aligned}
$$

where

- / + are the preceding superscripts to indicate the heat dissipated (-) and absorbed (+) from the outer and inner cable or cable layers, respectively.

We then get the heat generated in the conductor after having reached the thermal equilibrium:

$$Q_{Ge\ t \to \infty} = I^2 \times R(t \to \infty) \times t \qquad \left[\frac{W \cdot sec}{m} \right] \quad (8)$$

where

$R(t \to \infty)$ is the resistance of the conductor after reaching thermal equilibrium.

Or, by taking the temperature dependence of the resistance into account, we get:

$$
\begin{aligned}
R(t \to \infty) &= R(T_R) \times [1 + \alpha \times \Delta T] && \left[\frac{\Omega}{m} \right] \\
\Delta T &= T - T_R && [{}^{o}C]
\end{aligned}
\quad (9)
$$

where

α is the temperature coefficient of the resistance of the conductor material;

ΔT is the temperature raise of the conductor(s) over the ambient temperature of 20 °C;

T is the conductor temperature in °C;

T_R is the reference temperature for the conductor resistance of 20 °C;

$R_{t \to \infty}$ is the loop resistance measured with a precision instrument after reaching thermal equilibrium per m of conductor;

$R(T_R)$ is the specified or measured d.c. loop resistance of the conductors at 20 °C per m.

The temperature of the air-conditioned room has to be measured precisely.

The resistance of the conductor (here the conductors are connected in parallel to represent a common mode conductor) $R(T_R)$ has to be measured with a precision resistance instrument, prior to any powering. This, of course entails that the cable bundle has been exposed sufficiently long to the environment of the air conditioned room to reach throughout the same temperature, i.e. to reach absolutely a thermal equilibrium with its surroundings.

Towards this purpose, it is easiest to measure the voltage across the length of the conductor to determine the resistance and ultimately the temperature rise of the conductor, we get consecutively, using a constant current generator for the resistance at thermal equilibrium:

$$R(t \to \infty) = \frac{U_{M\ t \to \infty}}{I_{Test}} \qquad \left[\frac{\Omega}{m} \right] \quad (10)$$

And for the temperature rise:

$$\Delta T = \frac{R\,(\,t \rightarrow \infty\,) - R\,(T_R\,)}{\alpha \cdot R\,(T_R\,)} \qquad \left[{}^{o}C\right] \qquad (11)$$

The conductor temperature is then:

$$T = \frac{R(t \rightarrow \infty) - R\,(T_R\,)}{\alpha \cdot R\,(T_R\,)} + T_R \qquad \left[{}^{o}C\right] \qquad (12)$$

where

$U_{M\,t \rightarrow \infty}$ is the voltage measured across the conductors under thermal equilibrium.

In the above determination of the heating of data grade cables, arranged in bundles, one tacit assumption has been made, namely:

The resistance between the common mode circuits of the two pairs with the highest starting resistance at time t = 0 is nearly identical. This implies that the heating of the two concatenated common mode circuits is assumed to be identical though there may occur minor differences in the starting resistance, due to the different twist lays and the increased helix length. This is taken here as an average, as also in the real of the deployment of PoE / PoEP, each of these common mode circuits is used as supply and return conductor.

Experiments on cable bundles of 91 to 127 indicated that in general, a time of 4 h to 6 h is required to reach thermal equilibrium. This depends, of course, a bit on the cable design itself, thus it is recommended to use an increased lapse of time after switching on the powering, before taking any measurements of the voltage drop across the concatenated common mode circuit of the two measurement pairs.

5.4 The specific resistivity referencing the IACS

NOTE Here, reference to the IACS is made only for comparison purposes of the specified d.c resistances in comparison to the IACS, as it may have an impact on the heating of bundled cables.

In this case, it should be remembered that even to date, the majority of the installed base is essentially deployed using Cat. 5 / Cat. 5e cables.

An additional historic reminder about these cables should be given here: To reduce manufacturing costs, cables were deployed in larger volumes denominated as “3 + 1” or “2 + 2”, meaning they had either 3 or only 2 pairs insulated with fluorocarbon materials whereas the remaining pairs were insulated with flame retardant polyolefin. Obviously, in this case, the rule given in 5.2 above, to use the pairs with the highest resistance, does not necessarily apply anymore. In fact, in this case, an in depth verification of the pair usage and the resistance distribution has to be made for an adequate heating test. Even higher performing cable categories are sometimes designed with differing insulation materials in the same cable.

For the International Annealed Copper Standard, IACS at 20 °C is:

$$IACS = 0{,}15328 \qquad \left[\frac{\Omega \cdot gr}{m^2}\right] \qquad (13)$$

This value a represents copper with 100 % conductivity at 20 °C [4]. Hence the specific resistance, using the copper density of $8{,}89 \times 10^{-3}$ [gr/mm^3] is for 100 % IACS conductivity:

4 Note that the IACS was standardized in 1913. Since this time, copper refining has been improved dramatically. As a result, today copper manufacturing achieving 104 % IACS, and even better is common practice.

$$\rho_{20\ ^{o}C} = 0{,}0172418 \qquad \left[\frac{\Omega \cdot mm^2}{m}\right] \tag{14}$$

The temperature coefficient of the resistance increase of copper is:

$$\alpha = 0{,}00393 \qquad \left[\frac{1}{C^o}\right] \tag{15}$$

Hence the specific resistance of copper according to 100 % IACS is as a function of the temperature increment deviating from 20 °C:

$$\begin{aligned}\rho\,(T) &= \rho_{20\ ^{o}C} \cdot \left[1+\alpha\cdot\left(T-20\right)\right] \\ &= \rho_{20\ ^{o}C} \cdot \left[1+\alpha\cdot\Delta T\right]\end{aligned} \qquad \left[\frac{\Omega \cdot mm^2}{m}\right] \tag{16}$$

Using these values, the resistance for two 0,5 mm and 0,4 mm diameter copper conductors in parallel with a length of 1 m at 20 °C can be calculated according to 100 % IACS. It is respectively:

$$\begin{aligned} R &= 0{,}043905885 \cdot \left[1+\alpha\cdot\Delta T\right] && \text{for 0,5 mm Conductors} \\ R &= 0{,}06860294 \cdot \left[1+\alpha\cdot\Delta T\right] && \text{for 0,4 mm Conductors}\end{aligned} \qquad \left[\frac{\Omega}{m}\right] \tag{17}$$

The specified loop resistance of horizontal cables is 19 [Ω / 100 m]. The same value for stranded cables is 29 [Ω / 100 m]. The single conductor resistances are, therefore:

$$\begin{aligned} R_{Cond..} &= 0{,}0475 \cdot \left[1+\alpha\cdot\Delta T\right] && \text{for solid Conductors} \\ R_{Cond..} &= 0{,}0725 \cdot \left[1+\alpha\cdot\Delta T\right] && \text{for stranded Conductors}\end{aligned} \qquad \left[\frac{\Omega}{m}\right] \tag{18}$$

The minimum conductor diameter is specified in all cases to 0,4 mm, this both for solid and stranded conductors. In any case, the specified cable resistance requirements refer to higher resistance values (≅92,25 % IACS) than the 100 % IACS specification [5].

Given these “discrepancies”, it is advisable for any new cable design which has to be tested for its heating properties in bundled condition to use the directly measured resistance at ambient temperature, and base the temperature increase on the resulting resistance increase.

As a result, also for assessing the potential for PoE and PoEP deployment over the installed base, it is advisable

– to use short pieces of such cable which may be recuperated by replacement,
– and to base the measurements on the direct measurement of the d.c. resistance rather than on the IACS.

[5] This requirement, though appearing as less stringent than possible, has been made intentionally to cope with the fact that during installation, the cables may be stretched and excessively bend, thus slightly reducing their effective diameter. This is an essential precaution, in our case also from a health and safety point of view.

6 Assessing already deployed cable systems

The installed base of data grade cables consists to some extent still of Cat. 5 and Cat. 5e cables. However, also the more recent categories of cables are found to a large extent in premises of customers which may want to deploy the IEEE PoE / PoEP protocol over their existing system, without having any indication of the suitability of their installed system, with respect to the used cables, to accommodate these protocols.

This problem area falls essentially into the competence area of SC25. Therefore, here are given only indications of how to cope with this problem for assessing the basic heating of the installed base. The accurate extension dealing with the problems resulting out of the restricted heat dissipation capabilities in practical installations has to be therefore addressed by SC25.

6.1 Background

In the IEEE PoE / PoEP standards powering over two or four pairs are covered. As a consequence here also the powering over two or four pairs has to be considered, depending on the intended protocol to be deployed. In this case, the common mode circuits of two or four pairs as incident and return conductors have to be taken into account in each case.

6.2 The installed base

To compare any result of a heating test of bundled cables to the behaviour of the installed base, it has to be carried out on a comparable type of cable, not only with respect to its conductor diameters, but also with respect to its design regarding the heat transfer properties of the cable. There will have to be taken a similar design with respect to the conductor insulation and jacket material such that approximately the same heat dissipation properties are reflected as well as possible. Slight variations of conductor size and the resulting differences in the results of a heating trial can be taken care of by suitably selecting the applied current level.

This also includes cable designs containing overall or individual screens with bonded metal polymeric foils, which generally decrease the heat dissipation properties not only due to the additional polymeric materials by conduction, but they also represent ideal IR reflectors. More details on the component performances with respect to the heat dissipation properties are found in Clause 9.

Though the specified d.c. resistance of all categorized cables has been wisely frozen since a long time, it should be measured. Hence, the d.c. resistance should be verified on shorted pieces obtained from the installed base by replacement.

If for a comparative test, a cable is available with a similar design to that of the installed base, then the current has to be either increased or decreased proportional to the resistance ratio of these two cables. This is clearly described in the following equations for the PoE / PoEP protocol deployment:

$$I_{\text{Comparison}} = \begin{cases} 0{,}350 \times \dfrac{R_{\text{Installed}}}{R_{\text{Comparison}}} \\ 0{,}600 \times \dfrac{R_{\text{Installed}}}{R_{\text{Comparison}}} \end{cases} \qquad (19)$$

where

$I_{\text{Comparison}}$ is the d.c. current applicable to the comparison cables;

$R_{\text{Installed}}$ is the measured d.c. resistance of a piece of cable of the installed base;

$R_{\text{Comparison}}$ is the measured d.c. resistance of a piece of the comparison cable.

A precise resistance definition of the d.c. resistance of higher performing category cables has wisely not been given in the standards, so as to leave all the cable design options open at the expense of a more stringently defined d.c. resistance. In fact, the d.c. resistances of higher performing cables vary so widely that each cable type has to be tested individually, if ever any current levels are envisioned which exceed the currently by IEEE specified values for PoE / PoEP. As a result, if the d.c. resistance is lower than the specified limits of 19,0 Ω and 29,0 Ω per 100 m round trip resistance for solid and stranded conductor cables, respectively, then for simplification purposes, a normalization to ≅92,25 % IACS could be envisioned. This is a very safe route for the installed base.

6.3 A simplified assessment of the installed base

As already mentioned above, a heating test of the installed cable type is impractical, as it may be difficult to get enough cable for such a test by replacing the cables in the installed bas by newer cables of known heating performance.

If a bundled heating test of a comparable cable type is too awkward, then a similar cable design of known heating performance could be taken as a comparison base-line.

Then heating tests should be carried out on single cables taken out of the installed base by replacement and of the comparison cable. The current applied to the comparison cable is to be corrected according to Equation (19) above, whereas the current applied to the cable taken from the installed base is according to the PoE / PoEP protocol either 0,350 or 0,600 A. An adequate heating trial on these cables, freely suspended, according to Figure 7 above, should then be carried out, following the schematics given in Figure 5 above.

The proportionality of these two heating trials could then be transposed to the bundled cable heating trial of the base-line cable type, to assess the approximated heating performance of the installed base in a bundled configuration, taking the indications given in Clause 10 into account.

It should be kept in mind, however, that this simplified method yields only an approximate assessment. Hence it does not replace the more precise method described in 6.2.

7 The higher performing data grade cables

7.1 Conductor and cable diameters

The conductors of Cat. 6 / Cat. 6_A, and Cat.7 / Cat 7_A cables and similar data grade cables of different manufacturers may span a wide range of conductor diameters as well of jacket outside diameters, and this due to substantial cable design differences. Both these diameters have a pronounced impact upon the heating and heat dissipation of the conductor under a specific current load.

The conductor diameters of the higher performing cables may have increased values, sometimes up to 20 % to 25 %, and have as such also a reduced d.c. resistance as compared to the Cat. 5 / Cat.5e cables. However, the opposite is also feasible, i.e. cable achieving the basic performances with conductor diameters passing the d.c. resistance requirement with a relatively small margin due to special cable design options.

As a result, such cables may carry slightly higher currents under comparable conditions if compared to the specified minimum d.c. resistance requirement. However, this is not a “condition sine qua non”, as their conductor diameter may span a wide range depending upon the cable design.

For the testing of such cables, to evaluate their full potential, a heating trial is mandatory and has to be carried out by the manufacturer to be able to guarantee to its customers higher current loadings, if so required which may eventually exceed the PoE / PoEP requirements.

It should be noted however, that this is contrary to any standardization concept, as it may restrict the use of such cables for deployment in generally accessible networks, as then the compatibility is no longer guaranteed and can lead not only to equipment failures, but to major safety problems.

8 The heat dissipation on heated and bundled cables

Here a very short summary is given of the phenomena of the heat transfer as occurring in the problem of the heating of bundled cables.

8.1 Radiation

All bodies radiate heat. Radiation is based on the emissivity and absorptivity of heated bodies. Thus a body having a maximum absorptivity, equal to unity, is called a black body. A black body is also a perfect radiator, with an emissivity of unity. The Stefan-Boltzmann law states that the heat radiated from a black body is proportional to the 4^{th} power of the absolute temperature.

Real bodies, however have emissivities and absorptivities smaller than unity.

These values depend for metals, for instance upon their surface state, i.e. matte or glossy, depending upon their surface roughness. Polymeric materials, however, have spectrally distributed coefficients, a fact which is widely used in chemistry, for instance for the IR–spectroscopy. But for heat transfer analysis, integral values for emissivity and absorptivity may be assumed.

8.2 Conduction

Conduction is the heat transfer between bodies or other media by a direct contact, taking their heat conductivity coefficients into account. The latter are for metals generally proportional to the electric conductivity.

While the conduction between solid bodies is straightforward, the transfer from any combination of solid, liquid or gaseous media is more complex. But only solid and gaseous media are addressed here.

In this case, the conduction may be described directly by a heat transfer coefficient, and this also for the air within the pairs of cables as well as in the interstices between the cables in the bundle.

The reason for this is that the volumes are so small, from a heat transfer point of view, both in radial and tangential direction. In fact, the air space is so small, that it does not allow the formation of laminar gaseous layers around the solid bodies. See 8.3 for more details.

As a result, the heat transfer between cables within the bundle occurs due to radiation and conduction.

8.3 Convection

Convection is – in our present case – the heat transfer essentially from a solid body over a gaseous media to the gaseous environment. For cable installations in air, it is also subject to some extent to the relative humidity and pressure of the air.

Convection is applicable to the present problem of bundled cables only under the condition that the cable bundles are freely suspended. The reason for this is that convection goes on over an essentially laminar gaseous layer around the heated body or cable bundle. In the present case, the volume of this laminar layer of air has a lower specific density than the surrounding atmosphere and as a result rises up. This happens close to the cable bundle first also in a laminar air stream rising up which becomes turbulent afterwards. The laminar layer surrounding a basically round structure, suspended horizontally, is approximately 1 cm, while the laminar flow rising up is approximately 5 cm to 10 cm and then becomes turbulent. The size of the laminar uprising air depends a bit upon the diameter of the heated body.

Any laminar air layer represents effectively an insulating layer, increasing thus the excess heat. Turbulent air dissipates the heat more efficiently into the environment.

For any testing, it is therefore a “conditio sine qua non” that the environment is absolutely free of any air draft, and that all air condition outlets are baffled such that the cable bundle is really protected from any air movement.

Obviously, for any installation conditions, the maintenance of the laminar layered structure of the air around a cable bundle is generally not achievable.

In the same moment, a cable bundle is placed in an open tray, the convection is severely affected, as the free convection is reduced to less than half the circumference, depending upon the width of the tray. Closed trays restrict the heat dissipation by convection even more, if they do not render it outright impossible.

For any realistic assessment of the heating problem in an installation environment, the convection as an effective heat dissipation means has to be excluded.

9 The heat dissipation in a heated conductor, pair or cable which has to be taken into account

The entire concept for the assessment of the heating of data grade cables has been based on the governing thermodynamic principles of heating and heat dissipation of a data grade cable and its constituent components, described in this clause.

A simplified approach to treat the heat dissipation of bundled cables, using a layered approach, is found in Clause 10, as a basis for an analytical approach, which may ultimately also be used to assess the heating performance of bundled data grade cables based on a statistical distribution of the current carrying cables within the bundle.

9.1 The heat dissipation of individual components

The heat generated by an electric current is dissipated from:

1) A single bare conductor, freely suspended, by radiation and convection (convection depending on the surrounding atmosphere, its humidity and pressure).

   Convection evidently requires an atmosphere. Around the conductor, there is formed under heat dissipation conditions a laminar layer of the surrounding liquid or gaseous medium, in our case surrounding air atmosphere, which is in general in the order of approximately 1 cm. This atmosphere then rises up in a turbulent free fashion for approximately 5 cm to 10 cm to become absolutely turbulent.

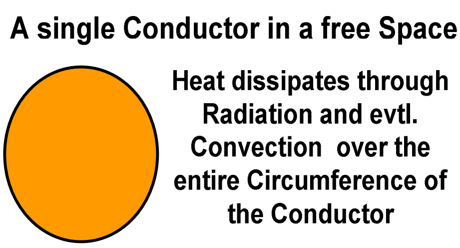


Figure 8 – Heat dissipation of a freely suspended conductor

This is the reason why any heating trial on individual or bundled cables has to be carried out in an absolutely undisturbed surrounding atmosphere, while the cable bundle of the individual cable has to be suspended in an absolutely undisturbed atmosphere.

2) An insulated conductor, freely suspended, by radiation, conduction and convection.

In fact, the heat generated in the conductor is partially dissipated by conduction into the insulating material, and passes through the insulating material also by conduction (depending upon the heat conductivity of the material) to the surface of the insulation. From there, it is dissipated either by radiation, conduction and convection or a mixture of these into the surrounding environment.

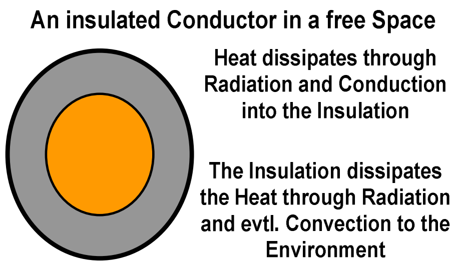


Figure 9 – Heat dissipation of a single insulated conductor

3) An insulated conductor pair without a screen, freely suspended, by radiation, conduction and convection.

Some heat is dissipated through the insulating material (depending upon the heat conductivity of the material) by conduction. From the insulation surface, the heat dissipates by radiation and convection or a mixture of these two into the surrounding environment.

Only at the junction point of both conductors of a pair may there occur some mutual conduction.

This junction point results in a straight line between the normally twisted conductors. It may be slightly deformed to a flat line or a ribbon-like surface between the conductors due to the radial force occurring during the twisting operation. This of course reduces the conductor spacing somewhat. However, for simplification purposes, here a straight junction line between both conductors is assumed.

Note that in this case, there is also a minimal conduction between both insulated conductors feasible due to the linear tangential line between both helices of the insulated conductors, which are here depicted as being circular. In reality, there is a small surface formed between the conductors by the flattening of the insulation as a result of the pressure between the insulated conductors during the twisting operation. However, this mutual heat transfer by conduction between the eventually twisted insulated conductors can be neglected.

The impact of radiation into the surrounding environment is illustrated in Figure 10 in a somewhat approximated fashion. It should be noted that the heat emissivity of polymeric materials as used for insulations and jackets is generally described by a factor for the infra-red wave regions. However, the heat absorption of these polymeric materials is more pronounced in specific wave bands.

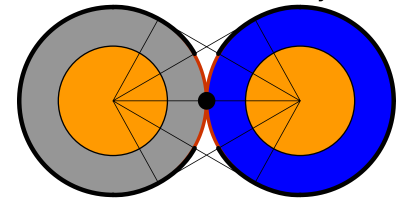


Figure 10 – Dissipation of an unscreened twisted pair exposed to current heating

In reality, part of the radiation from one insulated conductor to the other yields some heat in the conductor and also in the insulation. This heat in the insulation is partially transferred back to the insulated conductor and partially is dissipated by radiation, conduction and convection from the insulation into the surrounding environment. In any case, it increases slightly the excess heat retained by the “twisted insulated conductors”.

Under the above conditions, we have the two full circumferences of the insulated conductors for the heat dissipation by convection, whereas the dissipation by radiation is reduced by a factor x relative to two full circumferences of the insulation. This factor is:

$$x = \frac{2 \cdot \pi \cdot r}{3 \cdot 4 \cdot \pi \cdot r} = \frac{D}{3 \cdot 2 \cdot D} = \frac{1}{6} \qquad (20)$$

where

r is the radius of the insulated conductor.

4) A screened twisted pair, see Figure 11, by conduction and convection on a full conductor circumference covered by the screen.

Between the conductors essentially only by conduction over the interstitial atmosphere captured between the insulated conductors and the screen. The heat transfer by radiation is negligible in this area between the conductors, as the screens are nearly ideal IR reflectors. As a result, the heat dissipation by conduction in between the pairs to the screen and from the screen to the outside is by far not as efficient as the direct heat dissipation by convections in an unscreened pair.

The heat dissipation over the screen covering directly the insulation is a bit more efficient. However, it has to be taken into account that for identical impedance, unscreened pairs need slightly higher insulation thicknesses than screened pairs. The efficiency of the heat conduction is reduced, though the metallic screen is an excellent heat conductor, but the additional polymeric coating represents an additional heat barrier.

The dissipation outside the screen goes again through radiation, conduction and convection, however the surface for the radiation and convection is reduced by a factor x relative to an unscreened cable with the same conductors, which is larger than for unscreened cables:

$$x = \frac{r \cdot (\pi + 1) + \pi \cdot s}{2 \cdot \pi \cdot r} \qquad (21)$$

where

s is the thickness of the metal or metal / polymeric composite tape.

Evidently, the dissipating surface for radiation and convection may increase. However, this could happen only under the very unlikely condition that the screening tape has a very substantial thickness, more than equal to a submarine armouring:

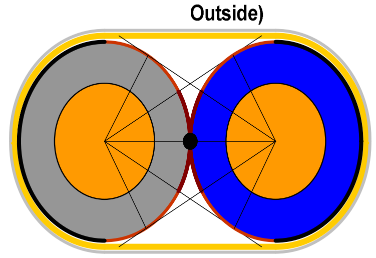
$$s \geq \frac{r \cdot (\pi - 1)}{\pi} \approx 0{,}682 \cdot r \tag{22}$$

Here is not yet taken into account that under equivalent d.c. resistances, the insulation for individually screened twisted pairs has to be increased compared to unscreened twisted pairs, to cope with the 100 Ω characteristic impedance requirement. However, even neglecting this severe constraint for the dissipation of heat generated in the conductor, it is obvious that screened twisted pairs have a higher excess heat, i.e. the heat retention within the conductor is higher, yielding a temperature increase under thermal equilibrium conditions which is definitely higher than in unscreened twisted pairs.

Screened twisted Pair

Radiation on both full Circles limited due to Reflection of the Screen

Composite Polymer – Metal Tape Screen (Metal on Outside)



- Conduction and reflected Radiation between Insulation and Screen over one full outer Circumference
- Radiation and Convection over one full outer Circumference of the Metal Layer of the Screen over Insulation
- Between the Conductors only Convection over the Screen
- Radiation partially to the Screen and partially back–scattered to the other Conductor
- Conduction over tangential Line between Insulations

Figure 11 – Dissipation of a screened twisted pair exposed to current heating

NOTE This definitely means that for screened twisted pairs, the excess heat within the considered conductors of the pairs is definitely higher than in unscreened pairs. As a result, the screened twisted pairs heat up more than the unscreened twisted pairs under comparable design conditions of twist lay length, conductor diameter, insulation thickness etc.

In practice, this effect is amplified by the limited heat conductivity of the insulating materials, as screened twisted pairs have to have higher insulation thicknesses to cope with the required conductor to conductor spacing than unscreened twisted pairs of the same d.c. resistance, in order to comply with the characteristic impedance requirement.

However, these last restrictions can be considered to be partially offset by the increased insulation thickness required in unscreened cables to meet, by using very short twist lays, the characteristic impedance requirements while complying at the same time to the crosstalk / alien crosstalk requirements, whereas screened pair cables do not require these tight twist lays.

5) An unscreened twisted pair cable, see Figure 12, dissipates its heat exactly as an insulated conductor, but in this case, the heat is dissipated over the outside surface of the jacketing material by conduction or convection. The heat is dissipated for a cable part of a bundle, i.e. surrounded by other cables over the airspace, which is too small to allow any convection of heat, by conduction. It is dissipated by radiation and convection if the cable is located on the surface of a cable bundle.

However, within the interior of the jacket, the heat of the insulated unscreened conductor pairs is dissipated by radiation and conduction from the unscreened pairs, primarily into the atmosphere contained within the jacketing inside diameter. Also this air space is far too small to allow any convectional heat transfer.

The heat transferred by conduction from the pairs over the enclosed environment within the jacket is by far the outweighing mode of the heat transfer from the pairs to the inner side of the jacket material.

Here also an amount of heat is transferred to the jacket and absorbed by it by radiation. Convection within the space inside the inner surface of the jacket is practically not occurring, as the space is too small to really create a laminar flow of the atmosphere within the jacket.

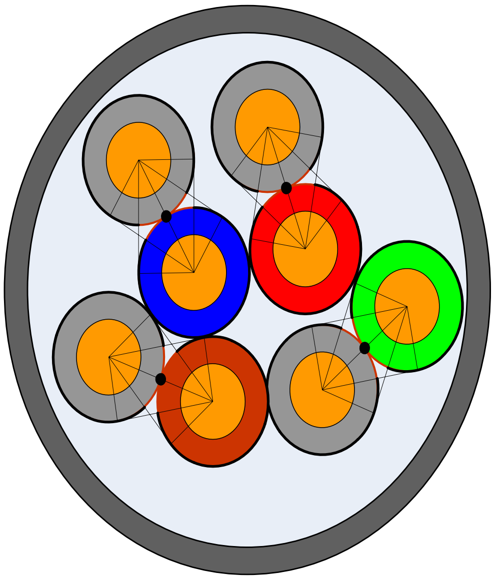


Figure 12 – Heat dissipation in an unscreened cable

The jacket outside surface – after conductive heat transfer through the jacket material – dissipates part of the heat, depending on the location of the cable peripheral or within to the hexagonal densest packing structure, by radiation and convection and by radiation and conduction, respectively, into the surrounding environment.

6) Overall screened twisted pair cable, see Figure 13, dissipates its heat by radiation and conduction from the screened pairs, as in the case of an unscreened cable. The conduction moves the heat directly over the environment within the jacket to its inner surface as the radiation which hits directly the inside of the jacket. However, if there is an overall metallic tape used inside a braid, then it is basically totally reflected at the inside of the metal / polymer composite tape.

The jacket surface – after conductive heat transfer through the metal / polymer tape and the jacket – dissipates part of the heat by radiation and convection or by radiation and conduction and into the surrounding environment, depending on the location of the cable in the hexagonal structure, i.e. on the outside or on the inside of the cable bundle, respectively.

An overall screened twisted Pair Cable

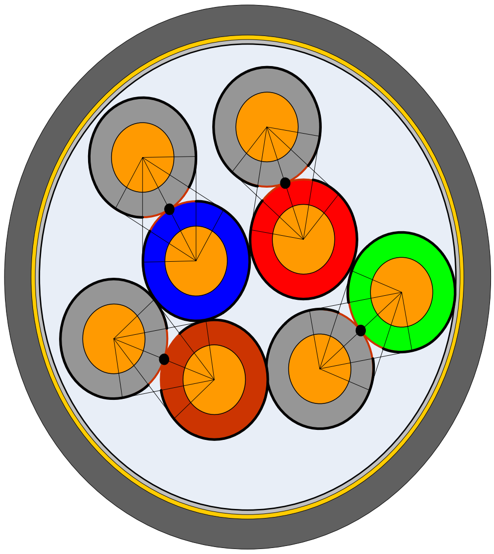


Figure 13 – Heat dissipation of an overall screened cable

7) An individually screened twisted pair cable, having an overall braid and/or metal polymeric composite tape with an eventual drain-wire, see Figure 14, by radiation and conduction from the screened pairs. The conducted heat goes into the environment within the jacket, whereas the radiation hits directly the inside of the jacket, and in the case of an overall metal polymeric composite tape is fully reflected and in the case of an overall braid partially reflected, depending upon the scattering of the reflections and the coverage of the braid.

An individually screened twisted Pair Cable

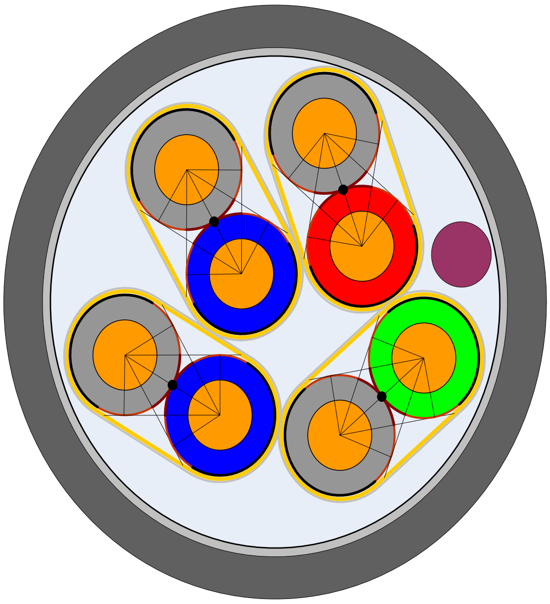


Figure 14 – Heat dissipation in an individually screened pair cable with overall braid or drain-wire with an overall metal / polymeric composite tape

The jacket surface – after conductive heat transfer through an eventually present braid and the jacket material – dissipates part of the heat by radiation and convection into the surrounding environment. Some heat will be dissipated at the junction lines between the adjacent cables in a densest cable packing structure, see under items 6 and 7 above.

The drain wire itself will in thermal equilibrium condition have the same temperature as the environment within the cable jacket.

The above gives only a general overview of the heat dissipation of simple cable designs. It is easy to extrapolate the heat transfer conditions for bundled cables. In this case, they may be screened or unscreened. What is important in each case is the temperature at the surface of each cable either located in a layer within the hexagonal structure or at the periphery.

This does not mean, however, that these temperatures are the most important ones. This temperature remains in all cases the conductor temperature of either the two or four pairs heated over their common mode circuit in the center cable of the hexagonal densest packing structure.

The installers use cable bundles very close to the densest packing structures to make their installations appear tidy. The result is that the cables have a small junction surface instead of a junction line at their interfaces. Basically, to some extent this does not help the heat transfer, as the polymeric jacketing materials definitely have a better heat conductivity than the surrounding atmosphere.

9.2 The heat dissipation of real cables

In reality, the cable designs are more complex than depicted in Figure 12 to Figure 14 above. A general cable design is schematically indicated in Figure 15. Such designs may have cross-webs, in order to space the pairs slightly more apart; they may have an internal profile structure within the jacket, to improve the alien crosstalk; the shape of the jacket may deviate from a circular shape, and this quite substantially. Thus, each new cable design may have to be analyzed individually for the heat transfer properties, if an analytical approach is envisioned.

However, it is much easier to build cable bundles to measure their conductor temperature under the condition that the densest packing structure is feasible.

This last condition is easy to meet for round cable structures, whereas for jacket shapes deviating from a round cross-section, in most cases this is not feasible. To assemble round cables in form of bundles with a better heat dissipation is easy. Though individual cables with a cross-sectional shape deviating from a circle generally have a higher surface area over the jacket, they have better heat dissipation properties than round cables. However, the assembling tight bundles may be a nightmare. As an end result, cable bundles formed in this way are more voluminous, which may be incommodious especially within the equipment rooms, but they also dissipate the heat better into the environment under free suspension conditions.

To summarize the heat dissipation properties of individual cable components based upon their heat conductivity and IR radiation emissivity coefficients, complete cables can be analyzed with respect to their excess heat retention, which in turn is responsible for the conductor temperature increase.

For the purposes of generalization, we consider four pairs enclosed in a jacket, which may contain an overall screen. This screen may be a metallic braid, a laminated composite tape or a combination thereof. In all these cases, the dissipation has to be considered consecutively through each component for each kind of heat dissipation. The overall heat dissipation goes definitely over radiation and convection from the outside of the jacket as long as the cable is at the outside of the bundle, i.e. directly exposed to the surrounding atmosphere.

All the design options covering data grade cables are shown in Figure 8. As this is a generic representation, it covers paired as well as quad-cable designs. All the options in the preceding Sections and bullets are evidently applicable in the appropriate way.

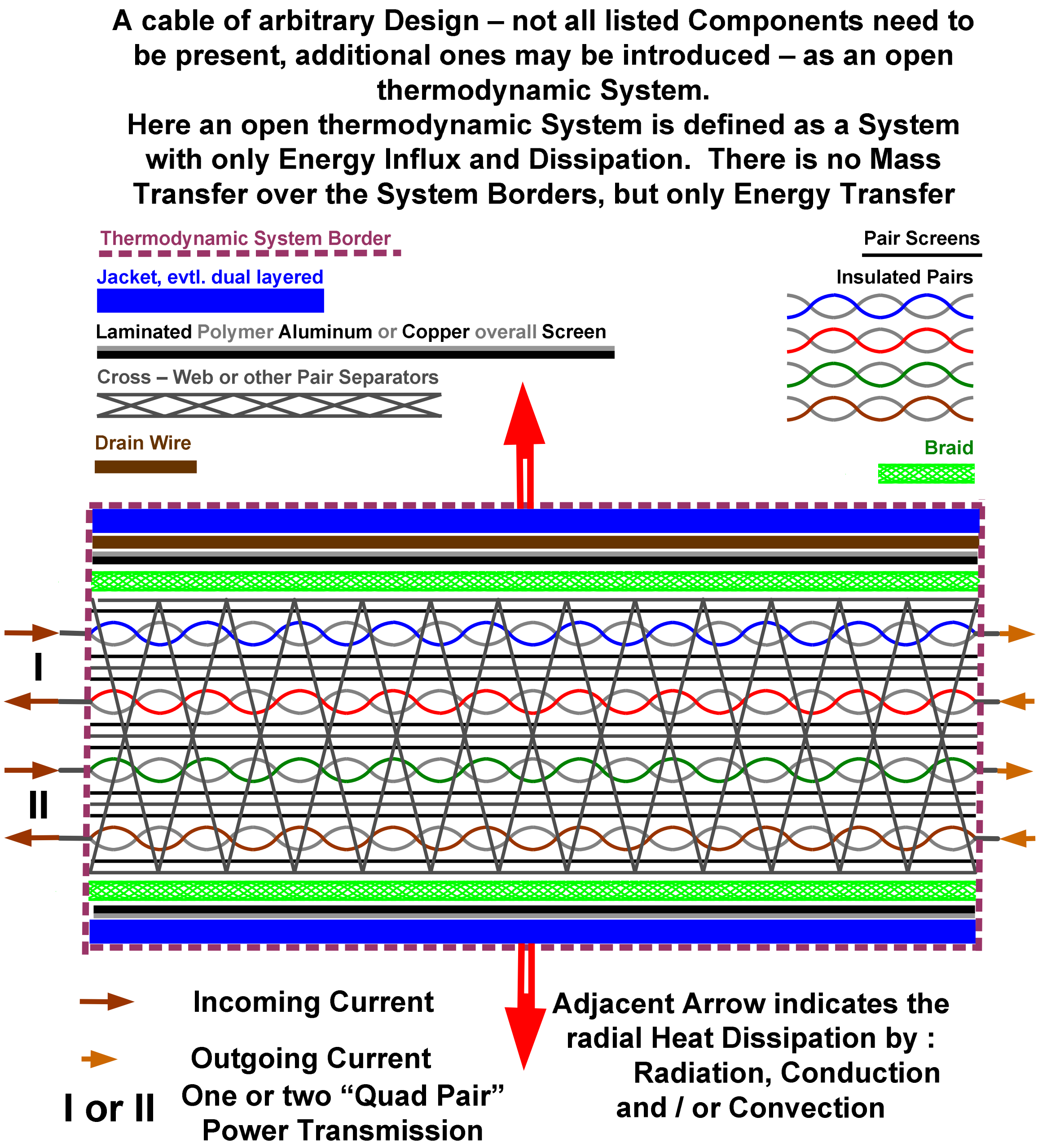


Figure 15 – A data grade cable of arbitrary design

Even between the individual cables, there is a very minor dissipation due to conduction between the jackets of the cables, at they contact on lines which are not compressed by any installation practice and have as such no substantial interface surfaces (obviously, this implies round jacket configurations only and no major deformation of the circumference of each cable due to the pressure by its neighbouring cables.)

NOTE If heat dissipation is considered, then obviously only the heat dissipation once the thermal equilibrium is reached is of importance and discussed here. This PAS definitely does not consider any dynamic processes, but only stabilized processes, i.e. processes in a complete thermodynamic equilibrium.

10 Thermodynamic considerations for a combined experimental and mathematical solution of the heating problem

10.1 Objective

Here some indications are given to more extensively resolve the heating problem of bundled data grade cables. These indications are based towards a combined solution of the heating problem by experimental means, using heating trials on a restricted bundle size, and to extend the obtained results to establish the heat transfer properties of a cable bundle of any size.

However, as already mentioned at the beginning, here only indications are given on how to tackle this problem, without going into the last details, as this falls into the competence domain of SC25.

Such a combined assessment is required as the installation of data grade cables is normally not done in a freely suspended fashion as the test procedure described above, but is normally characterized by relatively limited heat dissipation conditions by insulation materials, restricted air spaces with no air exchange etc.

In these cases, the heating problem can be assessed on short cable bundles, which are appropriately restricted in their heat dissipation capabilities, in comparison to the free suspension.

A mathematical analysis will then allow the determination of the heat transfer properties in a comparative fashion, after having determined the heat generated in the cables under the above- mentioned conditions.

Here will be given only a very short outline on how to proceed, without going through all the mathematical details, as it is not the intent of the present PAS to elaborate on a complete modelling of the heat transfer, and the resulting temperature increase in the center of the cable bundle under installation conditions.

10.2 The cable bundle considered as a layered structure

It has been already mentioned that the interstices within the cables themselves as well as those between the cables in the densest packing configuration, i.e. totally surrounded by other cables, do not allow the heat transfer by convection. In these cases, the heat transfer for the ultimate dissipation into the environment (the surroundings of the cable inside the jacket or the surroundings of other cables) is accomplished only by radiation and conduction.

Hence we have to approximate the air layer, the layer between the interstices of the cables, by a homogeneous circular layer, i.e. by a layer of uniform thickness, corresponding to the average of the thickness.

This is schematically shown in Figure 16 and Figure 17 in comparison. Figure 16 shows a bundle of 37 cables, hence n = 3 and N = 37. Figure 17 schematically shows the equivalent radii of the layers of the bundled cables and the air gaps.

In Figure 16 are also indicated the cables which are subject to a slightly higher heat dissipation on the main diagonal of the hexagonal structure. The reason for this is that in each layer they are only in direct contact with one cable of the underlying layer. Obviously, the cables in the first layer would have all the same heat dissipation, if the bundle size would be only 7. The case of 19 cables in the bundle shows that also the to the main diagonal adjacent cables are having a slightly better heat dissipation than those in bigger bundle sizes, when the cables approach an orthogonal position relative to the sides of the hexagon. However, a detailed analysis allows nevertheless the assumption of uniform heat dissipation over the entire cable layers.

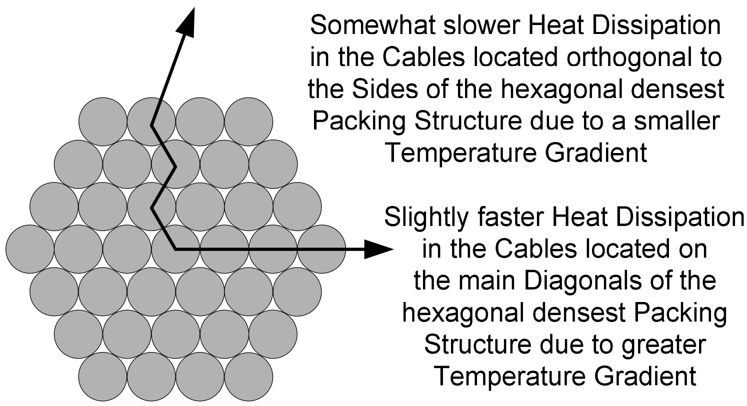


Figure 16 – Bundled cables indicating the air spaces between the cables

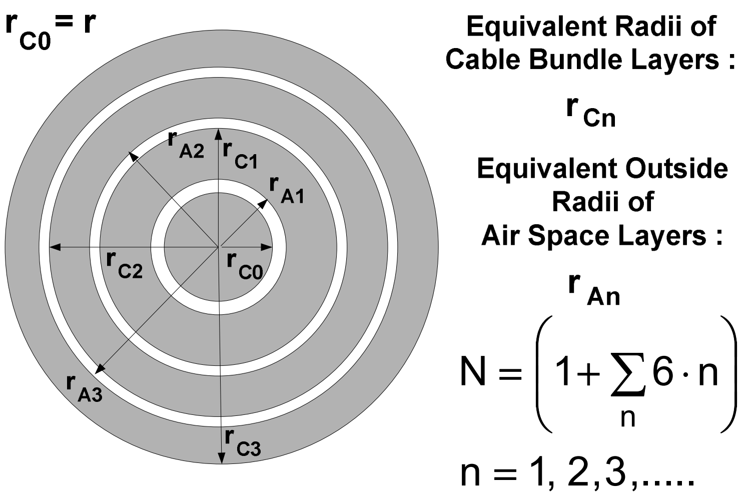


Figure 17 – The thermodynamic equivalent layered structure of the cables and air gaps

This allows then the calculation of the radii of the air gap and cable layers in the bundle. The outside radius of the equivalent air gap layer $r_{A\,n}$, starting with the one directly over the center cable is then:

$$r_{A\,n} = r \times \sqrt{1 + 6 \times \left[\left\{ \sum_n (n-1) \right\} + \left(\frac{\sqrt{3}}{\pi} - \frac{1}{2} \right) \times \left\{ \sum_n (2 \cdot n - 1) \right\} \right]} \tag{23}$$

$n = 1, 2, 3, \ldots\ldots$

As the outside layer radii of the equivalent air gap are identical to the inside radii of the equivalent cable layers, it is only required to calculate the outside radius of the equivalent cable layer radii. This is given in Equation (24), starting with the radius $r_{C\,n}$ of the first cable layer consisting of six cables:

$$r_{C\,n} = r \times \sqrt{1 + 6 \times \left[\left\{ \sum_{n} n \right\} + \left(\frac{\sqrt{3}}{\pi} - \frac{1}{2} \right) \times \left\{ \sum_{n} (2 \cdot n - 1) \right\} \right]} \qquad (24)$$

$n = 1, 2, 3, \ldots\ldots$

The air layers are characterized by a heat transfer by conduction and radiation from the inner cable layer to the outer cable layer. Hence the heat conduction of air has to be used in these cases. There is no heat generated inside these layers.

The cable layers are characterized by a heat conduction passing some of the heat generated in the inner layers towards the outside of the bundle, while an additional amount of heat is generated within these layers.

At the outermost cable layer, the heat is dissipated by convection and radiation under free suspension conditions, as described in 4.3.

If the bundle is subjected under restricted heat dissipation conditions, i.e. if it is surrounded for instance by insulation material or embedded in a duct, then the outermost cable layer dissipates the heat by conduction and radiation.

10.3 The heat transfer through the layered structure

If the heat conductivities of the cable and the air are k_C and k_A, respectively, the heat transfer through each of these layers, starting with the first layer of air over the centre cable is, according to Fourier's equation, applied to a circular tube:

$$q = -k \cdot F \cdot \frac{dT}{dr} \qquad (25)$$

where

k is the heat transfer coefficient.

NOTE The heat transfer coefficient is for solids normally temperature dependent according to the following equation:

$$k = k_o \cdot [\, 1 + \kappa \cdot (\, T - T_o \,) \,]$$

Within the temperature ranges considered here, the temperature dependence of the heat transfer coefficient of the cables k_C is neglected, i.e. it is assumed here that $\kappa \approx 1$. The heat transfer coefficient k is normally negative for good heat conductors and negative for insulating material.

The heat transfer coefficient of air is:

$$k_A = 0.02142 \cdot \left[1 + 3.1 \cdot 10^{-5} \cdot (T - T_R) \right] \qquad \left[\frac{\text{kcal}}{\text{m} \cdot \text{h} \cdot {}^{o}\text{C}} \right] \qquad (26)$$

The heat transfer coefficient can be obtained by two to approximately three or four consecutive heating trials on the same cable bundle while changing the heating pattern of the cable layers according to Figure 7. If in the first trial all the cables are heated, then in the consecutive trials the consecutive cable from the outside on should be cut off from any heating, while maintaining the temperature measurement over the resistivity. This allows then a consecutive extrapolation of the heat transfer coefficient for a very high number of unheated layers, while taking also the air layer into account. Thus, several results yield an approximation by extrapolation to the ambient temperature as a function of successive large number of unheated air / cable layers.

We get then for a plane wall:

$$q = \frac{k \cdot F \cdot (T_i - T_a)}{(r_a - r_i)}$$

(27)

Then Equation (25) yields after separation of the variables and integration, applied to the present problem:

$$Q_{A\,n} = \frac{2 \cdot \pi \cdot \ell_B \cdot k_A \cdot (T_i - T_a)}{\ln\left(\frac{r_{A\,n}}{r_{C\,n}}\right)} = \frac{k_A \cdot \Phi_{A\,n} \cdot (T_i - T_a)}{(r_{A\,n} - r_{C\,n})}$$

(28)

where

$Q_{A\,n}$ is the heat transferred through the air n^th air layer;

T_i is the temperature at the outside of the centre cable or of the individual n cable layers;

T_a is the temperature at the outside of the individual n air layers;

k_A is the heat conductivity coefficient of the air;

l_B is the length of the cable bundle.

with

$$\Phi_{A\,n} = \frac{2 \cdot \pi \cdot \ell_B \cdot (r_{A\,n} - r_{C\,n-1})}{\ln\left(\frac{r_{A\,n}}{r_{C\,n-1}}\right)} \qquad \text{for } n \geq 1$$

$$\Phi_{C\,n} = \frac{2 \cdot \pi \cdot \ell_B \cdot (r_{C\,n} - r_{A\,n})}{\ln\left(\frac{r_{C\,n}}{r_{A\,n}}\right)} \qquad \text{for } n \geq 1 \tag{29}$$

The heat transferred through the cable layers, starting with the centre cable, is then correspondingly:

$$Q_{C\,n} = \frac{2 \cdot \pi \cdot \ell_B \cdot k_C \cdot (T_i - T_a)}{\ln\left(\frac{r_{C\,n}}{r_{A\,n}}\right)} = \frac{k_C \cdot \Phi_{C\,n} \cdot (T_i - T_a)}{(r_{C\,n} - r_{A\,n})} \tag{30}$$

However, here the heat generated additionally within each layer is not yet added.

10.4 The heat transfer through the bundle in layered structure with internal heat generation

It is assumed that all cables in each layer are used for power transmission. That means, each of the cable layers is also internally generating a heat, which has to be added to the heat transferred from the inner layers. This of course also affects the temperature of the conductors in these cables. According to Equation (30) and Equation (29), the heat in each cable layer is then:

$$Q_{Cn} = \frac{2 \cdot \pi \cdot \ell_B \cdot k_C \cdot (T_i - T_a)}{\ln\left(\frac{r_{Cn}}{r_{An}}\right)} + Q(n) = \frac{k_C \cdot \Phi_n \cdot (T_i - T_a)}{(r_{Cn} - r_{An})} + Q(n) \qquad (31)$$

where

Q (n) is the additional heat generated in each cable layer.

It should be noted that in the temperature ranges expected here, i.e. with a minimum temperature of 0 °C and maximum temperatures reaching 60 °C, the heat transfer coefficient is considered to be constant over temperature. The value of Q (n) can be then calculated, under the assumption that each cable in each layer has the same thermal properties. Thus the generated heat for the centre cable and for each layer is as follows:

$$\begin{aligned} Q(0) &= I^2 \cdot R \cdot t && \text{for the centre cable} \\ Q(n) &= 6 \cdot I^2 \cdot R \cdot t \cdot n && n = 1, 2, 3, ... \quad \text{for each layer n} \end{aligned} \qquad (32)$$

The conductors of the cables used for power transmission form generally pairs of a quad, with a quad twist lay corresponding to the strand lay of the pairs used for data transmission. This renders the temperature across each cable within the layer slightly variable within the longitudinal direction, as the radial distance, responsible for the heat transfer is helically varying. Therefore, here the logarithmic average of the temperature gradient within the cable layer is to be used for a reasonable approximation of the conductor temperature for the heat generation. The logarithmic mean temperature across the cable layer yields:

$$T(n) = \frac{(T_i - T_a)}{\ln\left(\frac{T_i}{T_a}\right)} \qquad (33)$$

where

T (n) is the logarithmic mean temperature over the temperature gradient prevailing in the cable layer n.

Equation (32) yields then together with Equation (9) and Equation (15) for the centre cable and for each consecutive cable layer, using the result of Equation (33):

$$\begin{aligned} Q(0) &= I^2 \cdot R\left[1 + \alpha \times \left(T(n) - T_{Ambient}\right)\right] \cdot t && \text{for: } n = 0 \\ Q(n) &= 6 \cdot I^2 \cdot R\left[1 + \alpha \times \left(T(n) - T_{Ambient}\right)\right] \cdot t \cdot n && \text{for: } n \geq 1 \end{aligned} \qquad (34)$$

This equation simplifies if we assume an inside heat transfer coefficient from the cable to the first air layer is identical to the one between the cable layers. However, the heat transfer coefficient for the outside of the cable bundle is different. This is due to the fact that the heat is dissipated either by free convection or by conduction or a combination thereof. This will be the predominant condition of any installation, as the cable bundles cannot be freely suspended in any realistic installation. In cases where the heat dissipation is restricted, the transfer coefficient is definitely different, but can be assessed as indicated further down.

Then the heat flowing through each air layer may be written In a similar way as in Equation (31):

$$Q_{A\,n} = \frac{k_A \cdot \Phi_{A\,n} \cdot \left(T_{Cn} - T_{An}\right)}{\left(r_{A\,n} - r_{Cn}\right)} \tag{35}$$

Hence the heat transferred through multiple layers can be simplified for easy computation to:

$$\begin{aligned} Q(N) &= \sum_{n=0}^{N} \left(Q_{C\,0} + Q_{C\,n}\right) \\ &= \frac{\left(T_{C0} - T_{CN}\right)}{\dfrac{1}{k_A \cdot \Phi_{C\,0}} + \left\langle \left\{ \sum_{n=1}^{N} \left(\dfrac{\left(r_{A\,n} - r_{Cn}\right)}{k_C \cdot \Phi_{Cn}} \right) \right\} + \left\{ \sum_{n=1}^{N} \left(\dfrac{\left(r_{C\,n} - r_{An}\right)}{k_A \cdot \Phi_{An}} \right) \right\} \right\rangle} \end{aligned} \tag{36}$$

The summations in Equation (36) have to be carried out in a synchronized manner, and can be adapted to obtain the heat transfer coefficient of the cables by extrapolation according to Equation (26).

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