Preface
Customers for brake resistors often have different requirements for the cables, besides the length and the colour. These requirements are regarding voltage rating and current carrying capacity and the corresponding temperature raise and therefore also a requirement for cable insulation material and conductor surface. For some, also a question of proper shielding technology is required, but how does it all work together? And how should the sizing and dimensioning be done?
AWG or mm²

When it comes to dimensioning, cables are measured according to two different systems. One system is the European metric system, where the other is the American AWG system. Here many conversion tables are found, and many manufactures are naming according to AWG even though they are metric dimensioned.

AWG is short for American Wire Gauge. It is a system for the diameters of round, solid, conducting wire, and it is therefore not representing the actual cable, which consist of multiple strands.

The AWG of a stranded wire is determined by the cross-sectional area of the equivalent solid conductor. Because there are also small gaps between the strands, a stranded wire will always have a slightly larger overall diameter than a solid wire with the same AWG.

The AWG system originated in the number of drawing operations used to produce a given gauge of wire starting with heavy gauge wire having zero drawings as AWG0, and a wire that has been drawn one time is AWG1, two drawing cycles as AWG2. So, very fine wire required multiple drawing cycles.

AWG36 is, by definition, 0.005 inches in diameter, and AWG0000 is 0.46 inches in diameter. The ratio of these diameters is 1:92, and there are 40 gauge sizes from No. 36 to No. 0000, or 39 steps. By each gauge number increment, the cross sectional area increases by a constant factor. Any two gauges have diameters in the ratio B-A of $92^{1/39} = 1.12293$ while for two steps apart, the ratio C to A is a factor 1.12293² = 1.26098.

The cross sectional area of n AWG wire is for 36 to 0 can hereafter be calculated using:

$$A_n(mm^2) = \frac{\pi}{4} \cdot d_n^2 = 0.012668mm^2 \cdot 92^{(36-n)/(19.5)}$$

where $d_n = 0.127mm \cdot 92^{(36-n)/39}$

### Table: AWG to Area

<table>
<thead>
<tr>
<th>AWG</th>
<th>Area (mm²)</th>
<th>Cu Resistance (Ω/km)</th>
<th>UL Amp of Conductor 60°C</th>
<th>NEC Insulated Cu Wire 60/75/90°C</th>
<th>Fusing Current (100s)</th>
<th>Preece (1s)</th>
<th>Onderdonk (32ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.518</td>
<td>33.31</td>
<td>5</td>
<td>58.5 A</td>
<td>149 A</td>
<td>834 A</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.653</td>
<td>26.42</td>
<td>6</td>
<td>70 A</td>
<td>189 A</td>
<td>1.1 A</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.823</td>
<td>20.95</td>
<td>7</td>
<td>83 A</td>
<td>257 A</td>
<td>1.3 A</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.04</td>
<td>16.81</td>
<td>8.5</td>
<td>99 A</td>
<td>300 A</td>
<td>1.7 A</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1.31</td>
<td>13.17</td>
<td>10</td>
<td>117 A</td>
<td>377 A</td>
<td>2.1 A</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.65</td>
<td>10.45</td>
<td>12.5</td>
<td>140 A</td>
<td>477 A</td>
<td>2.7 A</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.08</td>
<td>8.28</td>
<td>15</td>
<td>166 A</td>
<td>601 A</td>
<td>3.3 A</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.62</td>
<td>6.57</td>
<td>7.5</td>
<td>198 A</td>
<td>758 A</td>
<td>4.2 A</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>3.31</td>
<td>5.21</td>
<td>10</td>
<td>235 A</td>
<td>955 A</td>
<td>5.3 A</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>4.17</td>
<td>4.13</td>
<td>15</td>
<td>280 A</td>
<td>126 A</td>
<td>6.7 A</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>5.26</td>
<td>3.27</td>
<td>30</td>
<td>333 A</td>
<td>15 A</td>
<td>8.5 A</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>6.63</td>
<td>2.59</td>
<td>35</td>
<td>396 A</td>
<td>1.9 A</td>
<td>10.7 A</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8.37</td>
<td>2.06</td>
<td>40</td>
<td>472 A</td>
<td>2.4 A</td>
<td>13.5 A</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10.5</td>
<td>1.63</td>
<td>47.5</td>
<td>561 A</td>
<td>3 A</td>
<td>17 A</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>13.3</td>
<td>1.29</td>
<td>55</td>
<td>668 A</td>
<td>3.8 A</td>
<td>21 A</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16.8</td>
<td>1.02</td>
<td>62.5</td>
<td>785 A</td>
<td>4.8 A</td>
<td>27 A</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>21.2</td>
<td>0.81</td>
<td>70</td>
<td>946 A</td>
<td>6.1 A</td>
<td>34 A</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>33.6</td>
<td>0.512</td>
<td>95</td>
<td>1192 A</td>
<td>8.9 A</td>
<td>54 A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>53.5</td>
<td>0.322</td>
<td>N/A</td>
<td>125 / 150 / 170</td>
<td>15.5 A</td>
<td>87.6 A</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the many current charts, it is found which maximum current that can be allowed when a certain temperature rise is allowed. These are for continuously use, but it is not clear whether it is for AC or DC, and at what frequency, and at which kind of standing, but it still gives the basic rule of thumb on how the cables can be loaded.

Dealing with switched circuitry and heavy pulse loads from events like inrush due to capacitance or inductive components, this standard table is not sufficient, so it can be necessary to look at some of the fuse current data provided by Preece or Onderdonk. Having in mind that the copper has a melting point at 1085°C and a boiling point at 2562°C

The Onderdonk equation is:

$$I_{fuse} = A_{Cu} \cdot \sqrt{\frac{\log(T_{melt} - T_{ambient}) + 1}{33 \cdot Time}}$$
Conductors with Stranded wire

Several metals can be used as an electrical conductor, and Copper (Cu) is by far the most common due to its relative low cost and very low resistance. Aluminium, steel or mixed strands of copper and steel may offer advantages in strength, weight or flex-life, but they come at the cost of reduced conductivity. The simplest form of conductor is a single, solid strand with the smallest diameter, but such conductors are prone to breaking after just a few bending or vibration cycles. Conductors are therefore most of the times stranded with multiple wires to improve the durability and flexibility. The more wires that are stranded together, the more flexible the conductor gets without breaking. Following stranding types are very common, dependent on their usage:

Concentric Strand - These are having a central wire surrounded by helically laid wires, usually applied in opposite direction of each other. Standard layer numbers are 1, 6, 12, 18 ... (+6) when all strands have the same diameter.

Bunch Strand - The strands are all twisted together in the same direction. This gives a more compact cable, but also very stiff.

Rope Strand - Here the conductor is concentric stranded with multiple stranded groups that forms a rope.

Segmented Conductor - Here the conductor consists of three or four sectors having a tiny layer on insulation for lower AC resistance due to skin effect.

Annular Conductor - This is stranded around a nonconductive material, for lower AC resistance due to skin effect.

Compact Strand - In this type, all the strands has been compressed to eliminate all air that is naturally present when combining circular strands.

Metal platings are often applied to the wire strands to improve solderability, reduce oxidation (corrosion) or improve electrical properties at high frequencies. Tin is the most common plating material, referred to as tin plated or tinned conductors. At higher temperatures, silver is often used despite its high cost, but also for high-frequency applications where it’s excellent conductivity and the skin effect usage reduce the AC resistance. At temperatures above 250°C, nickel is used for protection from oxidation up to approximately 450°C, although it has relatively poor conductivity.

It is uncommon for industry standards to specify plating thickness. The thickness is indirectly controlled through requirements including the continuity, adhesion, electrical resistance and weight. Typically plating thickness is in range of 1µm to 50µm, depending on plating material and the wire size involved. Silver is around 3µm and Tin is closer to 50µm.

<table>
<thead>
<tr>
<th>Plating Material Properties</th>
<th>Tin Plated Copper (TPC)</th>
<th>Silver Plated Copper (SPC)</th>
<th>Nickel Plated Copper (NPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Operating Temp.</td>
<td>150°C</td>
<td>250°C</td>
<td>450°C</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>15% IACS</td>
<td>105% IACS</td>
<td>25% IACS</td>
</tr>
<tr>
<td>Crimp Contact Resistance</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Solderability</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Requires active flux</td>
</tr>
</tbody>
</table>

International Annealed Copper Standard
Jacket Materials

Cable insulations are made of different polymer materials depending on the requirements for protection.

Polyethylene (PE) is the most common plastic. The annual global production is approximately 80 million tonnes, having the chemical formula \( (\text{C}_2\text{H}_4)_n \).

Polypropylene (PP) is a thermoplastic polymer, made from the monomer propylene \( (\text{C}_3\text{H}_6) \). It is rugged and unusually resistant to many chemical solvents, bases and acids.

Polyvinyl chloride (PVC) is the third-most widely produced synthetic plastic polymer, after polyethylene and polypropylene. Flexible coatings has been stabilised with lead, but these are being replaced, with calcium based systems due to the ROHS requirements.

Ethylene-vinyl acetate (EVA) is a copolymer of ethylene and vinyl acetate. It is low-temperature tough, stress-crack resistant, hot-melt adhesive, and has waterproof properties, and resistance to UV radiation.

Fluorinated ethylene propylene (FEP) is a copolymer of hexafluoropropylene and tetrafluoroethylene. FEP differs from PTFE because it can be used in melt-process and therefore applicable for injection moulding and screw extrusion techniques.

Polytetrafluoroethylene (PTFE) is a synthetic fluoropolymer of tetrafluoroethylene. It is a high-molecular-weight compound consisting wholly of carbon and fluorine. The best known brand name is Teflon by DuPont Co., which discovered the compound. PTFE is hydrophobic, non-stick, and has one of the lowest coefficients of friction against any solid. It is cold flowing and exhibit high strength, toughness, and self-lubrication. It is very non-reactive due to the strength of carbon–fluorine bonds; hence it is used in containers and pipework for reactive and corrosive chemicals.

Perfluoroalkoxy alkanes (PFA) are fluoropolymers with properties similar to PTFE. They are copolymers of tetrafluoroethylene \( (\text{C}_2\text{F}_4) \) and perfluoroethers \( \text{CF}_2\text{F}_3\text{OR}_f \), where \( R_f \) is a perfluorinated group such as trifluoromethyl \( (\text{CF}_3) \). The big difference is that the alkoxy substituents \( (\text{CH}_3\text{O}) \) allow the polymer to be melt-processed like the FEP.

Fluoropolymers are high performance insulation and sheath materials which cover a very wide temperature range.

Other characteristics of these materials are an excellent resistance to chemicals and other aggressive media and remarkable electrical and mechanical properties.
**Halogen freedom**

Halogens are the non-metallic elements found in the 7th row of the periodic table; fluorine, chlorine, bromine, iodine and astatine. Most network cables are insulated with PVC or thermoplastic polyurethane (TPU). Halogens make cable insulation highly flame retardant, but when the insulation reaches its burning point, the chlorine-containing material releases hydrogen chloride. This forms hydrochloric acid with water, also seen as a thick toxic smoke which is corrosive. That is why the industry is now focusing on the types without, and instead adding metal hydrates, which releases steam when heated.

Low Smoke Zero Halogen or Low Smoke Free of Halogen (LSZH, LSOH, LS0H, LSFH or OHLS) is a material classification typically used for cable insulation. These materials emit limited smoke and no halogen when exposed to high sources of heat, but halogen-free cables made with metal hydrates are not as fire-resistant, and when the metal hydrate is exhausted, the insulation burns freely. Due to the max temperature of 90-110°C they cannot be used for brake resistors.

Teflon or PTFE cables are high temperature cables based on a halogen (fluorine), where no replacement can be found without halogen. So the standard rules for having halogen-free cabled does simply not comply brake resistors.

The rule (having halogen free cables or low-smoke cables) is made for protecting people during a fire in a building (or train in a tunnel) where kilometres of cables are present in large bundles, but for a break resistor with box-solution having 2x20 cm of Teflon-cables inside, there is no such risk. The rule is a part of the Building Materials Construction Products Directive, hence it applies building installations – not equipment.

Alternatively – Silicone cables can be used.

Silicones, or polymerized siloxanes / polysiloxanes are mixed inorganic-organic polymers with an inorganic silicon-oxygen backbone chain with organic side groups, such as methyl, ethyl, or phenyl, attached to the silicon atoms, which are tetravalent.

Synthetic rubber, is any type of artificial elastomer mainly synthesised from petroleum by-products. Where an elastomer, is a material with the mechanical property that it can undergo elastic deformation under stress and return to previous size without permanent deformation.

Hypalon is a trademark for chlorosulfonated polyethylene (CSPE) a synthetic rubber (CSM). It is noted for its resistance to chemicals and ultraviolet light.

Ethylene propylene rubber (EPR), sometimes called (EPM), is a copolymer of ethylene and propylene whereas Ethylene propylene diene monomer (EPDM) rubber is a terpolymer of ethylene, propylene and a diene-component. M refers to its classification in ASTM. Diene is a hydrocarbon that contains two carbon double bonds.

<table>
<thead>
<tr>
<th></th>
<th>Halogen Content [%]</th>
<th>Oxygen Content [%]</th>
<th>Corrosion Constant (µm/h ppm)x10</th>
<th>Dielectric Constant εr</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>22-29</td>
<td>38-42</td>
<td>0.073</td>
<td>3.3-8</td>
</tr>
<tr>
<td>PE</td>
<td>none</td>
<td>20-23</td>
<td>-</td>
<td>2.3</td>
</tr>
<tr>
<td>PP</td>
<td>none</td>
<td>-</td>
<td>-</td>
<td>2.2</td>
</tr>
<tr>
<td>CSPE</td>
<td>16-26</td>
<td>34</td>
<td>0.0092</td>
<td>8-10</td>
</tr>
<tr>
<td>EVA</td>
<td>none</td>
<td>32-35</td>
<td>-</td>
<td>3.8</td>
</tr>
<tr>
<td>CPE</td>
<td>none</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
</tr>
<tr>
<td>EPR</td>
<td>9-14</td>
<td>-</td>
<td>0.076</td>
<td>3.2</td>
</tr>
<tr>
<td>SIL</td>
<td>none</td>
<td>-</td>
<td>0.059</td>
<td>3-4</td>
</tr>
<tr>
<td>FEP</td>
<td>76</td>
<td>80</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>PFA</td>
<td>75</td>
<td>93</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>PTFE</td>
<td>67</td>
<td>80</td>
<td>0.293</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Silicone contamination

Outgassing, or offgassing, when in referenced to indoor air quality, is the release of particles by sublimation and evaporation, as well as desorption and seepage from cracks and internal volumes. Volatile outgassing is a slow chemical reaction or a so called phase transitions from substance to gas phase. Here thickness is not a controlling factor and therefore has a minor effect. At high temperatures and low pressure, outgassing from silicone elastomers is inevitable, but post-curing is one of the principal tools to mitigate outgassing. A process carried out at a temperature greater than the service temperature for the component, where the volatiles are removed at increased reaction time due to diffusion and evaporation. After 4 hours of post cure, a substantial amount of more than 40% is still remaining though.

Silicone oils are present in all silicone compounds as either a precursor or incorporated as an ingredient.

Silicone contamination, where the released aerial particles contaminate adjacent surfaces, is resulting in unexpected bond process failures – leading to manufacturing activity stop. It is known to have a negative impact on processes such as soldering, coating, wire-bonding and adhesive bonding. All process that requires the high surface energy of metal to allows adhesive to wet its surface.

Due to the oils ability to wet nearly any surface and it’s very low surface energy, the silicone particles wets extremely well – and becomes extremely difficult to any cleaning effort. Even harsh dissolving-chemicals and abrasive blasting leaves back a contaminated surface. The silicone contamination is furthermore hard to identify – Scanning Electron Microscopy (SEM) is needed to determine the particle types, and the source of contamination is impossible to locate, since droplets airflow is invisible and not traceable.

Humans also represent a potential source of silicone contamination due to creams, cosmetics, hair products, antiperspirants, soft tissues, shoes, wrist watches, cell phone covers, chewing gum and several food types, which all containing silicone oil.

Environmental conditions

Silicone (SIL) is soft and very poor regarding abrasion and chemical resistance. Some of these cables are therefore reinforced with embedded fibre braid or has a braided jacket. But silicone cables also perform outstanding at high temperatures and in though weather conditions.

Strain relief

Standard cable glands made of nickel-plated brass, offering IP54 degree of protection is widely used. These types can also be procured with integrated strain relief which is standard for brake resistors with box.
Shielding

Some customers also need to apply means of shielding, and this can serve different purposes. It can be applied for mechanical, electrical and magnetic protection. The purpose has to be understood, and it has to be implemented correctly, also by the end user – which requires a basic knowhow regarding EMI/RFI.

A disturbance generated by an external source is called electromagnetic interference (EMI), or radio-frequency interference (RFI), when it affects an electrical circuit in the radio frequency spectrum. EMC conditions also take into the aspect whether the signal noise from the cable disturbs auxiliary equipment. The disturbance can be of three types:

- electromagnetic induction
- electrostatic coupling
- conduction

The shielding or screening, functions differently at high and low frequencies, it also has different effects for electric and magnetic field coupling. But equipment is also different. Here are a standard EMI-gland and a HF EMI-gland with brushes.

Braided shields of Tin Plated Copper (TPC) wires protect better at lower frequencies, where a large amount of copper is conducting better, and the large waves is shorted by the mesh. The thin Aluminium/Polyester foil provides 100% coverage, which is better at higher frequencies. A standard braided shield is in excess of 70% coverage, where optimised braided shields (two layers of braided wire in different arrangements) have coverage of more than 90%.

When the cable length reaches a quarter of a wavelength at the frequency of interest, stray capacitance allows screen currents to flow. The performance is expressed in surface transfer impedance (STI) unit mΩ/m. At higher frequencies (>100kHz) the STI is dominated by the effect of mutual inductive and capacitive coupling between the screen and the inner conductor. At low, it is close to DC resistance. For the screen to be successful, it must be connected to ground at both ends to conduct the energy away from the internal circuit (dZ).

A pigtail connection is where the shield braid is reduced to a single wire. It is often seen connecting the screens, but it provides as bad as no connection because of the pigtail inductance, which gives a voltage drop when EMI currents flow down the screen to the ground connection. A pigtail connection, must be as short as possible, and as wide as possible all the way down to the terminal.
Conclusion
Selecting the right cable can be a tricky task. In general the very hot inside of the brake resistor is the driving factor for the temperature rating, and the special cables can therefore be heavily loaded compared to standard installation cables. This is why it is seen that the sizes of the brake resistor cables are somewhat smaller than many electricians are used to work with.

<table>
<thead>
<tr>
<th>Current de-rating factors for installations</th>
<th>Spaced</th>
<th>From Surface</th>
<th>On Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Conductors</td>
<td>0.92</td>
<td>0.89</td>
<td>0.72</td>
</tr>
<tr>
<td>Three Conductors</td>
<td>0.89</td>
<td>0.75</td>
<td>0.69</td>
</tr>
<tr>
<td>Three/Four wire cable</td>
<td>0.71</td>
<td>0.65</td>
<td></td>
</tr>
</tbody>
</table>

Calculations on the allowed installation very much depend on the actual use. In the end, the brake resistors must be evaluated with respect to the end users voltage system and EMC conditions, as well as the ambient temperature and how much the cable can be allowed to heat the surroundings.

This is why the datasheets from the Danotherm standard program are only guidance according to the maximum allowed power. Customized designs can always be made with simulations on all kind of brake resistor products when the system details are known.

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