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Fuses for Hybrid and Electrical Vehicle Application

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Abstract

Electrical fuse links have been in use since the earliest days of electric telegraph and power distribution. The arrival of HEV applications brings with it new set of design challenges for fuse links. This paper discusses, the fuse link selection criteria and other aspects for fuse selection in electric vehicles applications.

Keywords: Co-ordination, Dimensioning, Electrical Vehicle, EV fuse, Selection

1. Introduction

With an estimated 20 million electric vehicles set to hit the road worldwide by 2020[1,2] there is an increasing expectation for component manufacturers to respond to the challenging demands placed on them by leading car manufacturers.

As market acceptance of electrified vehicles builds, industry experts as well as OEM platform forecasts are predicting strong growth in vehicle sales leading up to 2020. Figures show that in EMEA alone there will be more than 800,000 vehicles built to satisfy this changing demand[3]. The unique and dynamic environment of the electric vehicle places additional and often unknown stresses on internal electrical components pushing industrial components beyond their capabilities.

Through this application guide we will explore the continued design challenges we face as we continue to see flaws in the use of industrial fuse links in Hybrid and Electric Vehicles (HEV) applications.

Keywords: Electrical Vehicle, EV fuse, Dimensioning, Selection, Co-ordination

2. Electrical Vehicle Fuse Requirement

Electrical fuse links have been in use since the earliest days of electric telegraph and power distribution protection. Since their conception electrical fuse links have been subject to ongoing development to meet the ever-changing application uses, for example cable protection, transformer protection to switches, batteries, Photovoltaic (PV) and rail systems. The arrival of HEV applications brings with it new set of design challenges for fuse links, with each application having varying requirements, an in-depth understanding of the environmental parameters and typical drive cycle profile is key to selecting a suitable fuse link for such a demanding environment.

3. Industrial vs EV Application

Industrial fuse links are designed and tested to known standards IEC 60269 and UL 248.

The behavior of fuse links in conditions applicable to these industrial standards have been researched and understood drawing conclusion to derating considerations in environments where fuse links are subject to conditions differing from the standard. The challenge in EV applications is that the conditions are often outside the researched behaviors or even outside the requirements of the standard itself

Fuse products for EV/ HEV applications are relatively new in the industry, they could be regarded as a crossover product between low voltage fuse and automotive fuse. As of current there are no certification standards or industrial regulations defined yet.

For our EV fuse designs we take references from following industry standards:

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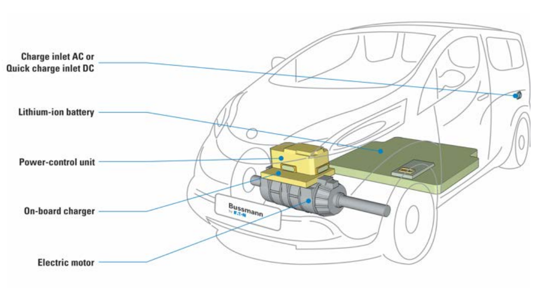
ISO88208; ISO88201; AECQ200; SAE J2781; JASO D622 – Japan

4. Industrial vs EV Fuse

The process of developing EV fuse link is as same as the process of industrial fuse links. However, to withstand the thermal shock & vibration cycles and also to current cycling the links designs have to be modified. To ensure fuse-link element to tolerate the thermal contraction & expansion due to temperature various say -40 to 90 deg, mechanical vibration & varying current cycling, the fuse-link element shall have shape/forming than the flat element being used in industrial fuse.

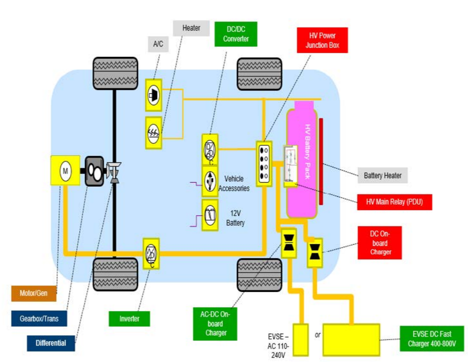
Also the fuse-link element material selection should be very vital. Considering the above requirement, fuse-link element should be soft silver with hardness sufficient enough to support the element profile punching process.

5. Configuration of EV Vehicle



Typical fuse applications in an electric vehicle

	Battery Electric Vehicle
Voltage	200 - 800V
Electric Range	80 - 500 km
Power of Electric Motor	50 - 150 kW



Technology	Description
Power Concersion	Converts power type SC-DC or DC-AC and/Or power voltage
Power Protection	Distribution of power to traction and accessory loads. Swithcing control and protection of electrical current
E-Motors & Drives	High Voltage traction motors, low voltage accessory drive, hybrid drive motors
Driveline	Mechanical systems to transfer power from traction motor output shaft to wheels
Energy Storage	Batteries, Battery Management system and Supercapacitors
Thermal Management	Traditional HVAC, power electronics cooling, battery heating and cooling

6. Voltage and Current Dimensioning

6.1 Voltage Dimensioning

Traditional automotive batteries were mostly lead-acid batteries rated at 12 V d.c., 24 V d.c. or 42 V d.c. Today however, EV batteries are moving to Lithium-Ion and can range from 150 V d. c. to 800 V d.c. as car manufacturers strive to improve their vehicles power, range and charging time. In EV applications, electrical fault conditions can reach as high as 950 V d.c. and components must be able to operate safely at this voltage level. This is a particularly important requirement for a fuse link, which must be able to safely interrupt the maximum system voltage when a fault occurs. The voltage rating of an industrial fuse link is usually defined in AC RMS voltages, and few industrial fuse links have an assigned DC rating.

DC faults are notoriously more difficult to clear than AC faults, the sinusoidal nature of alternating current assists with extinguishing the arcs inside the fuse during operation, this is not the case within a DC system where the voltage remains constant. Two variables should be considered in a DC system:

1) Fault circuit time constant (L/R)

2) Minimum prospective short-circuit current

It is not possible to define one DC voltage rating to cover considerable varying fault conditions and therefore specialised fuse links and specific application testing become the only option under DC conditions. Typically, the time constant of the fault conditions is < 5ms limiting the complexity of design, however the short-circuit level is variable depending on the state of the battery during a fault and the minimum prospective short-circuit current level can often be very low.

6.2 Current Dimensioning

The fuse link rated current is the RMS current it can continuously carry without degrading or exceeding the applicable temperature rise limits under well-defined and steady-state conditions. The well-defined conditions for industrial fuse links are stated in standard IEC 60269 for the following application conditions:

1) Ambient temperature: Between 10oC and 30oC (lowest temperature conditions specified at -5oC)
2) Current density of busbars: 1.3 A/mm2
3) Open air
4) Steady-state (no cyclic loading)
5) Static conditions (no vibration)

In an automotive environment however, these parameters tend to differ significantly, and as such the fuse's rating needs to be reassessed for each specific application to ensure that the selected fuse link is not run beyond its current carrying capabilities; as this will lead to premature aging of the fuse and will cause it to nuisance operate.

7. Fuse Link Selection Criteria

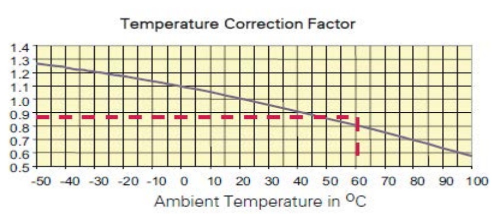


Figure 1. This Curve shows the influence of the ambient temperature on the fuse link's current carrying capability.

1. Basic selection
2. Temperature derating
3. Thermal connection derating
4. Cooling air correction
5. High altitude derating
6. Enclosure correction factor
7. Cyclic loading
8. Influence of overloads
9. Coordination with relays and other protection components
10. Fuse selection
11. Worked example

7.1 Basic Selection

This part covers the basic selection criteria for only the fuse link's rated current and not the influence from overload and cyclic loading. The actual RMS steady-state load current passing through the fuse link should be lower or equal to the calculated maximum permissible load current called Ib.

Irms = In x Kt x Ke x Kv x Ka x Kx

Irms: The max permissible continuous RMS load current

In: Rated current of a given fuse link

Kt: Ambient temp. correction factor as per Figure 1

Ke: Thermal connection factor per Figure 2

Kv: Cooling air correction factor per Figure 3

Ka: High altitude derating factor

Kx: Enclosure correction factor

7.2 Temperature Derating - Kt

Current ratings are valid for ambient temperature of ~ 20˚ C

Higher ambient air temperature will impede the fuses ability to dissipate heat by convection. Typically, EV fuses are placed in environments where temperatures are specified to reach a maximum of 60 - 800˚C. For ambient temperatures higher than 20˚C, it is important to consider the derating factor Kt.

See example: Ambient 600 ˚C, Kt = 0.8

7.3 Thermal Connection Derating – Ke

The busbar and cabling attached to the fuse link help conduct heat away from the fuse and allow it to run cooler. It is important to consider that when the cross-sectional area of these conductors reduces in size, heat is not transferred as effectively.

To reduce weight and size, smaller light weight cabling is favored by vehicle manufacturers. This will however significantly differ from the conductor size used when testing the fuse under IEC conditions. As such the derating factor, Ke should be observed.

=> The maximum current density of the busbars on which the fuse links are mounted should be 1.3A/mm2 (IEC 60269 part 4 defines 1.0 to 1.6A/mm2). If the busbars carry a current density more than this, then the fuse link should be derated as per the graph Figure 2.

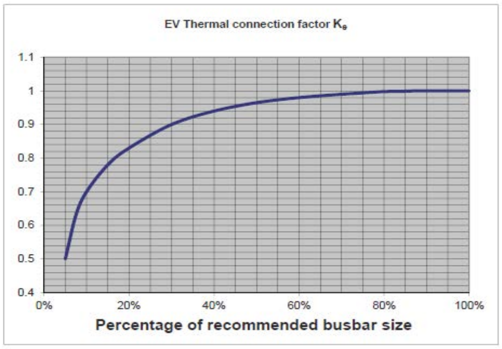


Figure 2. Graph of Thermal connection factor.

7.4 Cooling Air Correction – Kv

EV fuse links may be mounted in a vented enclosure, with additional cooling provided by an electric fan to help dissipate heat.

Please note that the airspeed is measured across the fuse link and not the across the fan.

If forced air cooling is used, then the influence of this cooling has to be taken in to account while calculating the fuse rating. The following curve gives the factor to be considered when forced cooling is used.

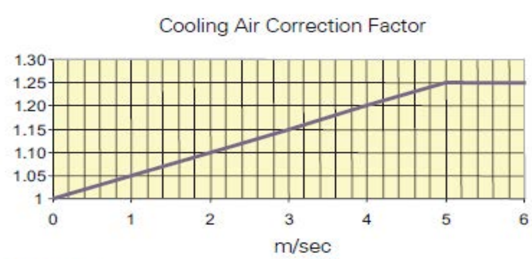


Figure 3. Graph of Cooling air correction factor.

7.5 High Altitudes Derating –Ka

When fuses are used at high altitudes, there is a reduced cooling effect on the fuse as the density of the atmosphere reduces.

$$K_a = 1 - \left(\frac{h - 2000}{100} \times \frac{0.5}{100}\right)$$

Correction factor Ka should be applied to the fuse's continuous rating when the application is above 2000m:

7.6 Enclosure Correction Factor – Kx

High speed fuses are given their current rating in an open air environment. In automotive applications the fuse is often mounted in a small enclosure with no ventilation which will cause the fuse to run a lot hotter. We advise you apply a 0.8 enclosure factor to ensure the fuse does not run too hot.

7.7 Cyclic Loading

Cyclic loading that leads to premature fuse link fatigue is defined as regular or irregular variations of the load current, each of a sufficient size and duration to change the temperature of the fuse link elements in such a way that the very sensitive restrictions (necks) will fatigue. In order to avoid this condition, calculations can be made to ensure there is an appropriate safety margin for the selected fuse link.

Most fuses used on electric vehicles will see these cyclic conditions, the main pack fuses connected between the drives and battery will see varying levels of current, as the power demands of the vehicle is constantly changing. Vehicle manufacturers will usually provide numerous drive profiles that simulate typical driving conditions. These drive profiles can be used as a basis to select the correct current rating of fuse.

While using the following empirical rules will cover most cyclic loading conditions, it is impossible to set up general rules for all applications, so Eaton recommend considering the following

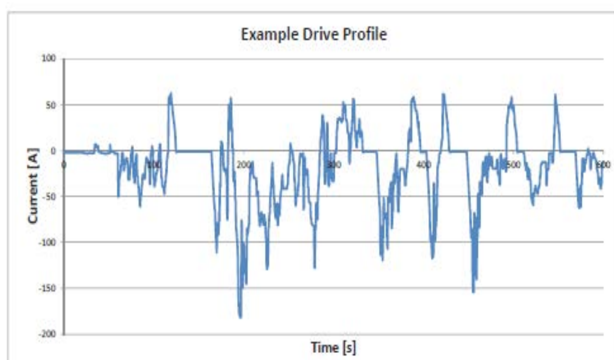


Figure 4. High altitude derating factor.

- Regular or irregular variations of the load current
- Causes the temperature to fluctuate
- Heavy thermal cyclic loading leads to mechanical stress premature aging/fatigue

- Solution: Reduce ΔT of the fuse link by selecting a higher rated fuse link
- Use 'G-factor' to apply a safety margin in the fuse link selection
- 1.6 in typical general industrial application
- 1.3 in EV applications - irregular but not generally high overloads (average temperature of elements)
- In > IRMS * G

7.7.1 Cyclic loading – G Factor

We would consider the effect of G = 1.3 type of heating on elements in EV cyclic loading

$$I_n \geq \frac{I_{rms} \times G}{K_t \times K_e \times K_v \times K_a \times K_x}$$

7.7.2 B Factor

Once a fuse has been selected using the above criteria, a check is required to see if the individual load pulses (each expressed in

Ipulse, tpulse coordinates) have a sufficient safety margin B in relation to It of the fuse's melting curve. It is the melting current of the fuse corresponding to the duration of the pulse (t = tpulse), and B to be found per Figure 5.

Ipulse< It * B

This should ensure a sufficient lifetime of the fuse when subject to the given loadings

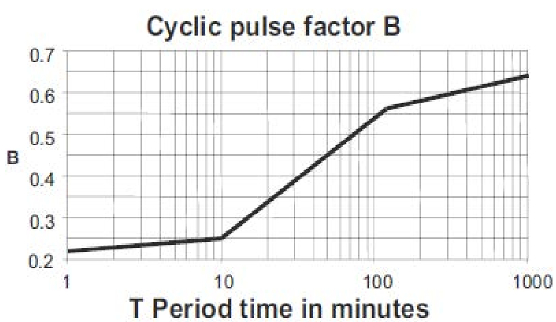


Figure 5. High altitude derating factor.

7.8 Influence of Overloads

After the current rating has been selected using factors 1 to 7, it is important to check the influence of short term overloads on the fuse.

In EV applications the overload condition should not come within 50% of the current required to melt the fuse in that time. This can be reviewed on the selected fuse's time current curve.

Imax< (50%) x It

Where:

Imax: RMS current of the overload [A]

It: melting current corresponding to the time t of the overload duration, as read from the time current curve of the fuse.

Influence of overloads example

A 200 A fuse link has been selected and is subjected to temporary overloads of 300 A rms for 5s. From the time current curve of the fuse It is found to be 650 A for 5 seconds.

Imax< 50 % x It = 50 % x 650 = 325 A

This means that the 200 A fuse selected is able to withstand the temporary overload of 300 A for 5 seconds, as the above equation is fore filled.

7.9 Coordination with Relays and other Protection Components

Unlike industrial applications, EV applications often hold specific requirements to coordinate with a relay or breaker to cover all fault conditions – low and high short circuit currents. Typically, the relay deals with the low overload currents and the fuse-link deals with high magnitude short circuits.

The fuses as part of a larger system will have to meet coordination requirements such as the selective coordination between multiple fuses in the circuit as well as between the contactor/relay. The latter, in our experience, can be rather challenging. Once the fuses have been selected as individual components based on the current carrying capability, they more often than not have to coordinate with the contactor/relay during a fault scenario. The challenge is that the fuses will have to be quick enough to operate well before the contactor would either overheat or exceed its breaking condition, but the fuses also have to be slow enough to survive currents due to the rigorous driving profiles.

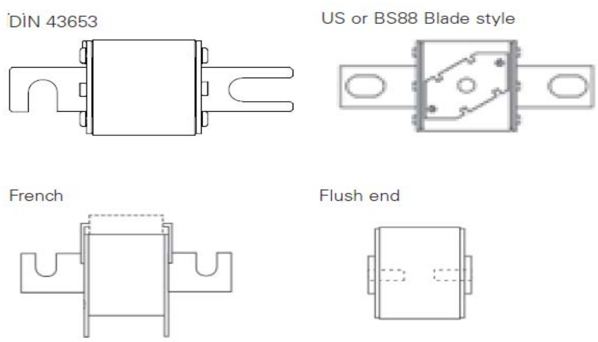
7.10 Fuse SELECTION

7.10.1 Factors Affecting Fuse Link Selection

- DC voltage capability

- Current de-rating
- Physical size and type

7.10.2 Common End Tag Options (square body)



7.10.3 Internal Design Modification

Care must be taken when selecting product for electric vehicle applications.

Industrial designs are often modified to accommodate for the harsh environments experienced in EV applications. There are many factors to consider including thermal shock, vibration, high relative humidity and high ambient temperatures.

Mechanical fuse link packages can be used as a base design, where internal modifications are made. The finalised design is then tested in accordance to the specific OEM requirements.

7.11 Worked Example

EV Fuse is required to protect an EV battery system. A number of typical drive profiles are given for the application, all of which are cyclic, the rms current over each cycle is calculated and the most onerous profile is determined to be 300 A rms. The starting ambient air temperature is 50 °C and the fuse is mounted in a small enclosure with no ventilation. It is decided that the cabling used to electrical connect the fuse will be 130mm2. It is also specified that the vehicle needs to function up to 2500m above sea level.

First of all we calculate the minimum required current rating as per the below equation:

$$I_n \geq \frac{I_{rms} \times G}{K_t \times K_e \times K_v \times K_a \times K_x}$$

Irms = 300 A

Kt = 0.85 Figure 1 for 50 °C ambient temp

Ke = 0.97, Figure 2 for 56% x IEC

$$100\ \%\ \text{IEC Cable size} = \frac{\text{RMS Current}}{1.3\ A/mm^2} = \frac{300}{1.3} = 230.8\ mm^2$$

The cabling being used is only 130mm2, which is 56% of the IEC cable size.

Kv = 1, the fuse isn't cooled by a fan

Ka = 0.975

2500m above sea level gives:

$$K_a = 1 - \left(\frac{2500 - 2000}{100} \times \frac{0.5}{100}\right) = 0.975$$

KX = 0.8, the fuse mounted in a small enclosure with no ventilation

$$I_n \geq \frac{300 \times 1.3}{0.85 \times 0.97 \times 1 \times 0.975 \times 0.8}$$

$$I_n \geq 606\ A$$

G = 1.3, the drive profile is not a steady state load current, it is cyclic

The minimum required current rating is 606 A, so the next available IEC current rating is chosen: 630 A.

Secondly, we need to check the short term overloads to ensure they do not damage the fuse selected and cause it to prematurely age, one overload condition identified as particularly onerous in the drive cycle is 1000 A for 3 seconds. We need to plot this on the selected fuse's time current curve to make sure the below equation is satisfied.

$$I_{max} < (50\%) \times I_t$$

Imax = 1000 A

It = 3800 A @ 3s

Imax is only 26% of It.

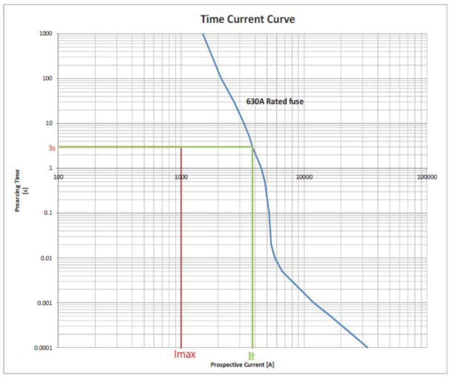


Figure 6. Time current curve.

So the overload of 1000 A for 3s is acceptable as it does not come within 50% of the current required to melt the fuse in that time.

Automotive Standards and Qualification

- No global standards for Electric Vehicles
- AECQ200
- JASO D622 - Japan
- SAE J2781
- ISO 8820-1
- ISO 8820-8
- No standards cover fuse links > 500 V d.c.
- Solutions are fully catered to accommodate each OEM Requirements
- In-house testing capability within Eaton
- DC Capability
- Shock and vibration
- Cyclic loading

Early awareness of OEM test spec. is essential for fuse link selection.

8. References

1. Eaton Bussmann series Hybrid and Electric Vehicle application guide.
2. ISO 8820-1 & 8, JASO D622 and other EV OEM specification for Test requirements.