Fuse-link protection in the challenging and extreme conditions of HEV environments

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Abstract

With an increase in the commercial acceptance of hybrid and pure electric vehicles (HEV/EV), leading car manufacturers are striving in their efforts to reduce the environmental impact of transportation. In a rapidly expanding low carbon vehicle industry, demands are placed on fuse manufacturers to quickly respond to their challenges of circuit protection with the unique conditions of EV and HEV applications. There are a number of design concepts to producing vehicles with reduced CO2 emissions; many utilise electric storage systems together with electric drive trains. The unique and dynamic environment of the electric vehicle places additional stresses on the fuse-link and often pushes a standard industrial fuse link beyond its design limits. This paper will discuss some of these design challenges and how HEV and EV applications are managed in terms of fuse protection.

Introduction

With an estimated 20 million electric vehicles set to hit the road worldwide by 2020 **[1]** there is an increasing expectation for component manufacturers to respond to the challenging demands placed on them by leading car manufacturers. The last 2 years have seen a remarkable surge in demand of electric vehicles in the UK alone with new registrations of plug-in cars increasing four-fold from over 3500 in 2013 to almost 15,500 in 2014 **[2]**. The unique and dynamic environment of the electric vehicle places additional and often unknown stresses on internal components pushing industrial components beyond their capabilities. Through this paper we will comment on and explore the continued design challenges faced by fuse-link manufacturers as standard industrial fuse-links prove to be unsuitable for the unique EV and HEV applications.

Industrial vs EV applications

Fuse-links have been around since the earliest days of electric telegraph and power distribution protection **[3]**. Since then the fuse-links in general have undergone considerable development to accommodate differing styles of application, from protecting cables, transformers and switches to batteries, Photovoltaic (PV) and Rail systems. With the introduction of EV and HEV applications

the design of these fuse-links must be reviewed with each application request to confirm their suitability to the demanding and frequently changing requirements.
Industrial fuse-links are designed and tested to known standard IEC 60269. The behaviour of fuses in conditions applicable to the standard 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 behaviours or even outside the requirements of the standard itself. In the next section, this paper will discuss some of the key differences to consider when dimensioning fuse-link selection in EV and HEV applications.

1_Voltage Dimensioning

Traditional automotive batteries were mostly lead-acid batteries rated at 12Vdc, 24Vdc or 42Vdc. Today however, EV batteries are moving to Lithium-Ion and can range from 150Vdc to 800Vdc as car manufacturers are pushed to improve the power capabilities of their design **[4]**. In application, electrical fault conditions can reach as high as 950Vdc and components must be able to operate safely at this voltage level. This is a particular requirement for fuse-links which introduces a key challenge. The voltage rating of an industrial fuse-link is 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 because the capability of the fuse-link is dependent on 2 distinct and variable factors:

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 specialized fuse-links and specific application testing become the only option for this DC voltage range. 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. As discussed below, the conditions for current dimensioning are such that the rating of the fuse is often positioned in direct conflict with the requirement to interrupt low level short circuit currents.

2_Current dimensioning

The fuse-link's 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 **[3]**. The well-defined conditions for industrial fuse-links are stated in standard IEC 60269 for the following application conditions:

1) Ambient temperature: Between 10°C and 30°C (lowest temperature conditions specified at -5°C)
2) Current density of busbars: 1.3A/mm^2
3) Open air

4) Steady-state (no cyclic loading)
5) Static conditions (no vibration)

3_Ambient Temperature

In EV applications, conditions can differ considerably from those described in IEC 60269; temperatures have been specified from -40°C to +105°C. Using the standard de-rating curve **[Fig.1],** current de-rating factors can be as low as 0.5, instantly doubling the fuse rating required compared to the continuous RMS of the application. The impact of the ambient temperature is often underestimated when dimensioning the fuse current and therefore misapplied, ultimately reducing the lifetime of the fuse **[4].**

Fig.1

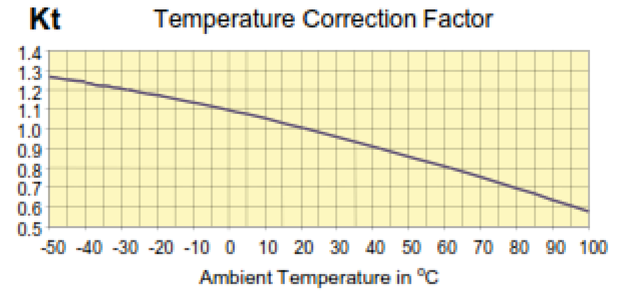

Fig 1 Influence of ambient temperature on current-carrying capability of the

In addition to high ambient temperatures, requirements for testing also put fuse-links under new and unknown stresses. Fuse-links are now also required to survive temperature shock and load tests – a requirement not normally applicable to standard industrial fuse-links. Thermal load tests are considered to be extremely onerous for industrial fuse-links and careful design of the internal element structure must be revised. Under thermal load testing conditions fuse-links are subjected to extreme steady-state temperature conditions (-40°C to +105°C) and pulsed with a defined current at each extreme, depending on application parameters. The mechanics of the element behaviour under these conditions are explained further in section 2.2.4 Steady State.

4_Thermal Connection

The minimum current density of the busbars on which the fuse-links are normally mounted to should be 1.3A/mm^2 **[3]. [Fig.2]** shows the level of derating required should the cross sectional area of the busbars be less than that required to carry 1.3A/mm^2. Car manufacturers are under extreme pressure to reduce the footprint of the battery designs resulting in smaller cabling and the cross sectional area to the fuse is often smaller than the requirement for the current density. Often the busbar or cable is only 50% of the required size, increasing the current dimensioning of the fuse by a further 25% in respect of the application RMS.

Fig. 2

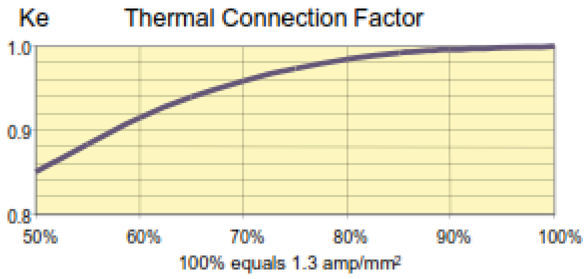

Fig 2 Influence of thermal connection factor compare to IEC con-

5_Open Air

Fuse-links mounted inside a box or enclosed space will reduce convection cooling compared to IEC conditions, increasing the effect of the high ambient temperatures. In EV and HEV applications there is often no space or consideration for additional cooling effects, encouraging further derating of the current dimensioning. A derating factor of 0.8 should be considered, increasing the current dimensioning again by a further 25%.

6_Steady State

The fuse-link's rated current is defined under steady-state conditions. In industrial applications, the load condition is often defined, predictable and easily considered in fuse-link selection. However, EV and HEV applications are very different. Considerations must be included for battery charging and any cyclic load incurred by differing driving styles – in addition, the current drawn from the battery at different speeds or accelerations varies extensively depending on the battery characteristics **[4]**.

When fuse-links are subjected to regular or irregular changes in load current (current pulses) temperature rise of the elements initiates thermal strain due to thermal expansion. *X.Z. Meng et.al* discusses the theory of "thermal buckling" where thermal strain leads to thermal stress and the fuse element leaves its original position when thermal stress reaches a threshold value **[5]**. It was concluded that the thermal strain induced in the notch region (restriction) of the fuse element due to a current pulse is proportional to the temperature rise. In order to address this theory careful consideration must be taken to ensure there is an appropriate safety margin of ΔT across the restriction for the selected fuse-link. This is one of the biggest challenges faced by fuse-link manufacturers – how do we define an appropriate safety margin?

S.Arai **[6]** argues that the repeated expansion and contraction of the fuse-link element coordinates compressive and tensile stresses leading to element fatigue. It can be argued that the more often the cycles are repeated the less the element cools down and the tensile stresses caused by contraction are reduced. On the contrary, if load pulses are such that the fuse element is allowed to heat and cool completely the stresses on the element could be argued to be at their maximum. By this conclusion it is proposed that reducing ∆T across the element restrictions reduces the effect of fatigue and the lifetime of the fuse can be protected.

A number of Duty Classes have been defined for typical industrial load profiles **[Fig.3].** As already discussed the load profile of EV applications is impossible to define, and as a general rule, a safety margin must be considered after analysis of the individual applications. However, in general, it can be argued that the nature of the cyclic loading is such that the elements are never cooled completely and a safety margin of G=1.3 can be considered (where Ib > Irms*G, and Ib is the maximum permissible load current of the fuse-link).

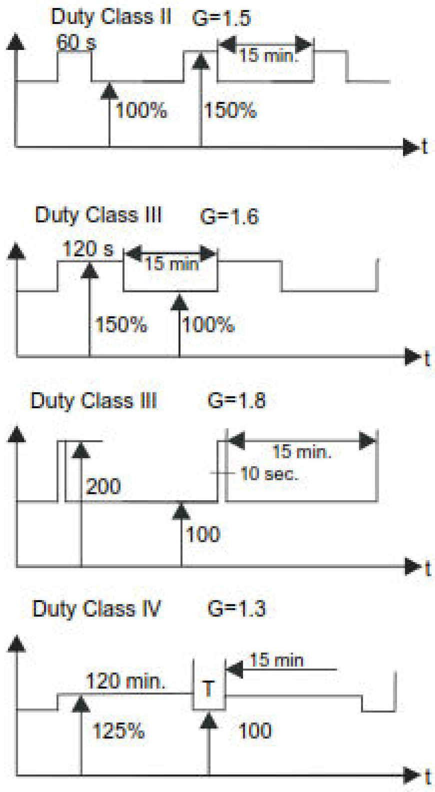

Fig 3 Duty Cycles for defined industrial applications

In addition, *S.Arai* **[6]** also proposes that the thermal expansion of bent elements distributes evenly along the element making the strain distribution uniform along the element and not confined to the element restrictions. In this case, it can also be argued that using bent elements in place of straight elements can aid in protecting the lifetime of the fuse in given applications.

Testing requirements for automotive approval are often much more onerous than the conditions of the “real-life” application. The continuous heating and cooling of the ambient temperature in thermal load tests (-40°C to +105°C) causes the ceramic body and the element to expand and contract at differing rates increasing the stress and strain on the elements at each temperature extreme.

Coupled with the expansion and contraction under conventional heating due to current pulses, it becomes increasingly complex to design the elements such that the effect of these conditions is minimal. Allowing the elements to flex is a necessity however defining how specific design changes affect the lifetime of the fuse is an ever-growing problem. To date, not enough investigation or analysis has been done to allow fuse-link manufacturers to state a defined life-time of the fuse. However, car manufacturers are continuing to question the performance quality of the fuse-link and demands are reaching up to a 30 year lifetime guarantee.

Fuse-link manufacturers must respond to these requests and while reflective acceptance is in a replicable 30 year real life-time test, it is neither cost nor time effective. This encourages a sought-after and reliable life-time simulation model that can be utilised to predict the number of load pulses any given fuse can withstand during its lifetime.

7_Static Conditions

Typical industrial applications tend to be static and have no requirement for shock or vibrational testing. As such there is little understanding of how such severe conditions can affect the performance of the fuse. It is understood however that there is no universal acceptance of shock and vibration testing and car manufacturers issue their own requirements **[4]**. To date, Eaton has not experienced any design challenges with regards to the effect of shock and vibrational testing but highlights the increasing need to test each fuse-link selection to the specifics of each application.

8_Coordination

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. Fuse-links are often in a conflict situation whereby the requirement to break a minimum short circuit current is too low compared to the considered rating of the fuse. There is often a narrow band between the requirement of the fuse-link to operate and the requirement of the fuse-link to survive at a given overload. Demands are such that the relay or breaker should be space efficient forcing the fuse-link to break even lower current levels. Such high demands often lead car manufacturers to require fuse-links to perform in unmanageable ways and fuse-link manufacturers are faced with a battle to convince car manufacturers to compromise. Meeting these demands and also guaranteeing a 30 year life-time breaks the laws of physics and cannot be achieved.

While car manufacturers look for the smallest footprint they tend to opt for cylindrical fuse-link designs. However, with increasing power requirements cylindrical designs do not always offer the most space efficient solution and fuse-link manufacturers looks to offer square body fuse-link designs. Size and weight is the most obvious compromise and is essential if all other requirements are to be considered.

Fuse-link manufacturers therefore urge car manufacturers to consider square body fuse-links in their future designs.

Automotive standards

Adding to complexity, there is currently no unified or determined standard applicable to automotive certification. Suggested standards include AECQ200, JASO D622, SAE J2781, ISO8820-1 and ISO8820-8; however these do not always cover the more onerous test requirements that are put on component manufacturers. In fact, standard industrial fuse-links often pass the testing requirements of JASO D622, ISO8820-1 and ISO8820-8 in particular but do not survive the more onerous test conditions of the thermal load tests. Early awareness of the car manufacturer's test specification is essential for accepted fuse dimensioning and presents an additional challenge that fuse-link manufacturers face – working with Tier One's not only adds a layer to communication but also makes it much harder for fuse manufacturers to access all of the information that they need. Car manufacturer's and fuse-link manufacturers should adopt an approach to work directly in the first instance to ensure that the fuse-link is designed as specified.

Implications for car manufacturers

With the UK Government's vision to include another £500m funding to support low carbon vehicles over the next 5 years **[7]**, the demand for guaranteed lifetime and longevity is extreme. This paper has described the various parameters that must be considered in order to protect the life-time of the fuse-link which often sits in direct conflict to the requirement for reduced footprint. Considering the infrastructure of Electric Vehicles **[Fig 4]** it is easy to understand why longevity is such a high requirement – the battery is situated at the heart of the engine and access to the fuse-link is both labour intensive and complex. Nuisance operation would not only be inconvenient but also costly for the owner of the vehicle and requirement to change the fuse-link should be driven by circumstance of a true electrical fault.

Today, protection goes beyond classic battery protection – car manufacturers are also asking for auxillary fusing, protecting other power conversion systems such as lighting, heating, and air conditioning units. This adds variety to the vast application parameters and each fuse-link selection should be considered independently.

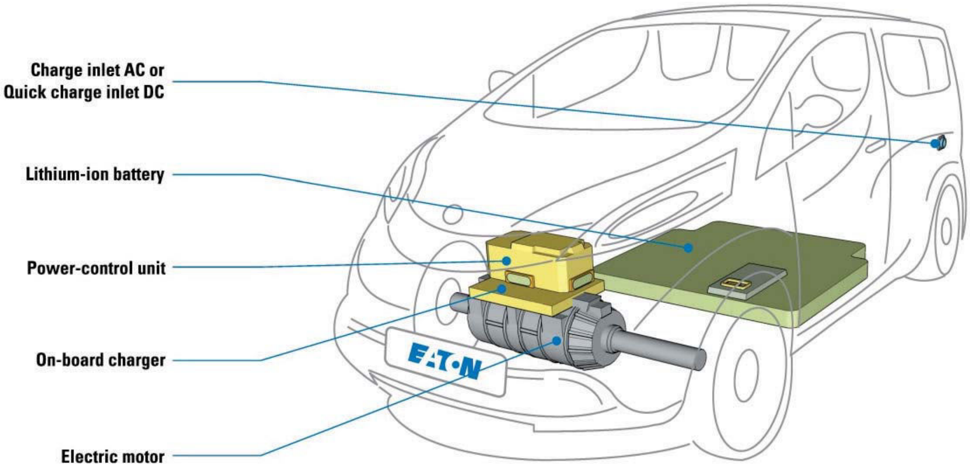

Fig 4 Typical fuse applications in an Electric Vehicle

Conclusion

Owing to the fact that the selection criteria for fuse-links in EV applications conflicts many demands from car manufacturers it becomes more important for fuse-link manufacturers to influence the selection in the early stages of design. It also becomes increasingly important for car manufacturers to understand the challenges of fuse-link design and adapt their models to limit the conflicts.

With the increasing demands for guarantee on life-time fuse-link manufacturers must find a method to predict the life-time of their specific designs in any given application. In this early stage of the market there has not been enough focus on life-time testing or influence of EV environments on key element designs and Eaton proposes to start life-time investigations in particular response to common requests stipulated by car manufacturers. Designing a simulation model to replicate the defined applications would be the most efficient way to analyse and understand the physics of the internal workings, however a vast amount of testing should be concluded first. Car manufacturers and fuse-link manufacturers should work together to define to most appropriate testing method of accelerated life-time predictions.

References

- [1] Phil Skipper, “Electro mobility – The opportunity”, BEAMA Low Carbon Living Conference, Mar 2011
- [2] www.nextgreencar.com/electric-cars/ (July 2015)
- [3] A. Wright and P.G. Newberry, “Electric Fuses”, 3rd Edition (2004)
- [4] Craig Rice, Nigel Nurse, Steffie Cheong, “A Study of Challenges for Fuse Link Protection in the New Generations of Environmentally Friendly Vehicles”, ICEFA 2011
- [5] X.Z. Meng, J. G. J. Sloot, H.U. Haas, “Ageing mechanism of fuses for semiconductor protection”, ICEFA 1995
- [6] S. Arai, “Deterioration and cycles to failure of H.V current limiting fuses subjected to cyclic loading”, ICEFA 1984
- [7] “Low Carbon Vehicle engineering” LCV 2014 Show Issue

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