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A STUDY OF CHALLENGES FOR FUSE LINK PROTECTION IN THE NEW GENERATIONS OF ENVIRONMENTALLY FRIENDLY VEHICLES

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Abstract

Electric vehicles are more environmentally friendly than traditional cars using fossil fuels, making them an ideal, real-world response to the challenge of reducing the environmental impacts of transportation. However, a number of key success factors will condition the future of the electric vehicle. Recharging infrastructure, range concern and driver safety are high on the discussion list. Most of these vehicles utilise an electric storage system together with electric drive train. To avoid rapid and uncontrolled discharge of the storage device in the event of an equipment malfunction or vehicle accident, there is a need to provide circuit protection to prevent further damage to equipment or injury to passengers. This paper explores some of the challenges encountered by the fuse world by looking at different configurations of the electric system and the specific requirements that the protective device will have to meet.

Keywords: electric vehicles, hybrid electric vehicles, fuse link, batteries.

1. Introduction

The history of Electric Vehicle (EV) has been documented as early as 1881 in Paris by Gustave Trouvé, five years before the alleged "invention of the automobile" by Benz and Daimler, followed by another tricycle in 1882 by W. Ayrton and J. Perry in England. These were lightweight vehicles, based on bicycle construction. These "first generation" electric vehicles had their heyday in the last decade of the 19th century but were gradually taken over by the development of the Internal Combustion Engine (ICE). These vehicles were more efficient and cost effective to operate.

Now in the 21st century, a new dawn of EV's has arose. This is primarily driven by climate change, shortage of energy as well as economic reasons.

The automotive industry continues to investigate reducing its impact on the environment despite the current economic crisis. At the 2010 Clean Energy Ministerial in Washington D.C., ministers reaffirmed their commitment to previously announced targets for the deployment of EV. The International Energy Agency (IEA) estimates 20 million electric vehicles will be on the road worldwide by 2020 [1].

In UK, electric vehicles alone provide 19% of the 26% assigned to road transport, contributing to the overall carbon commitment targets for 2020 [2].

However, there are still numerous limitations to be resolved before the mass production of EV's can be rolled out. In particular, the issues with energy / power density, lifetime performance, system costs and safety are still very much in debate. The electrical subsystem will also need to be revolutionised for reliability, space and cost.

Over current protection devices are essential in automotive electrical systems to limit the threat to human life and vehicle damage. The battery in conventional ICE vehicles, use the chassis for ground, which means that the current path actually passes through the body of the car. Battery packs in an EV, can be considered "a floating system" i.e. is completely electrically isolated from the chassis. Therefore, it is important that the EV has various safety disconnects built in. These include main contactor, circuit breaker, and fuse links. All of these can be used to manually disarm the electrical system, or operate automatically in the event of a short circuit, collision damage, or some other situation that causes a surge of current. This paper studies the present status of automotive and industrial fuse links and explores the challenges posed by the EV.

2. Main System

EV is a generalised term for "electrically propelled vehicle". Other terms used are, battery electric/all electric (BEV), hybrid electric (HEV), plug-in hybrid electric (PHEV) and fuel cell electric vehicles (FCEV) – examples in Fig 1.

The advancements in Lithium Ion battery technology coupled with increasing oil prices, has made the EV more appealing. Drive or propulsion is provided by the chemical energy stored in such batteries together with electric motors and controllers. This is the equivalent of the ICE. The battery is typically re-charged by plugging it into an electricity supply. The method of connection is another top topic under discussion.

HEV's typically operate in a charge-sustaining mode which uses both electric and ICE power sources as efficiently as possible such that the battery does not deviate outside a set parameter. HEV batteries can only be charged by the ICE generator or through regenerative braking.

PHEV's also has a charge-depletion mode. In fact, there are several options which vary the amount or timing of battery discharge with the aim to improve fuel economy. PHEV batteries have the added advantage of being able to charge by external means.

FCEV's typically utilise a hydrogen fuel cell to produce electricity and power the electric motor. Not surprisingly, this is a less attractive option for the EV due to the present costs and efficiencies of extracting and storing hydrogen. However, it is expected to expand significantly once the fuel cell technology advances to the next level.

Unlike conventional ICE vehicles, each of the above EV categories employs different control and electrical systems. As a consequence, this has an influence to the problem of revolutionising the sub components including over current protection devices.

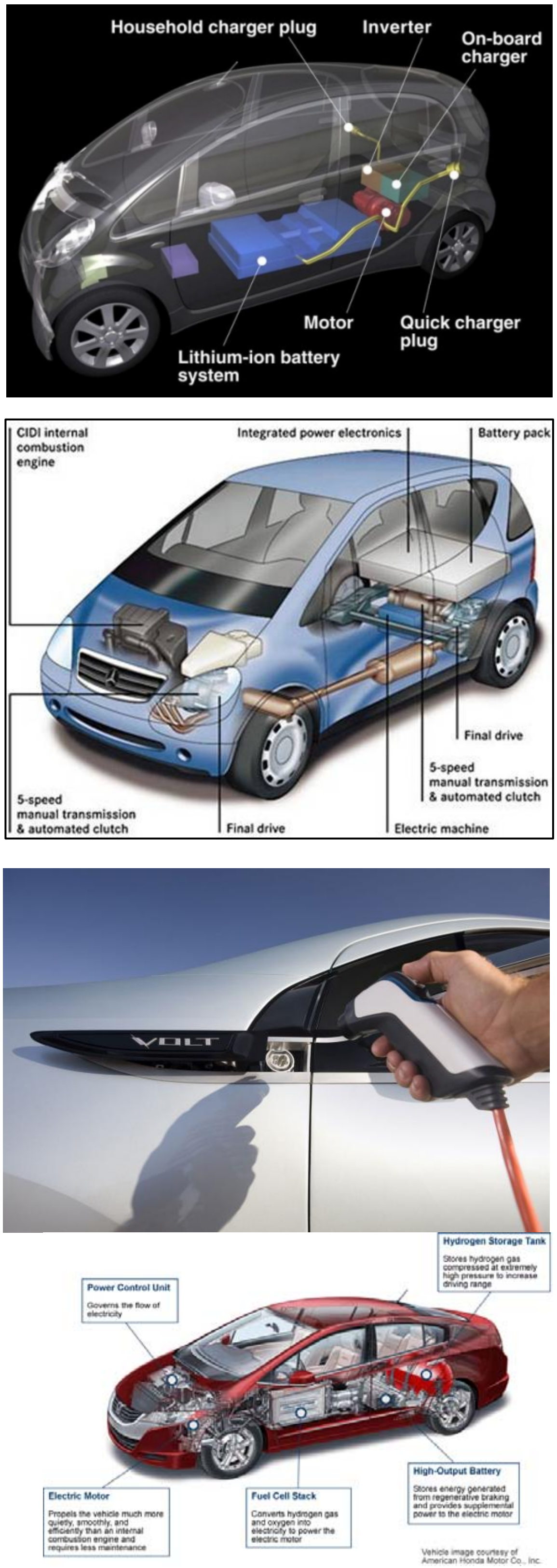


Fig. 1: From top to bottom. (i) BEV - generic; (ii) HEV – Mercedes-Benz concept; (iii) PHEV – Chevy Volt; (iv) FCEV – American Honda Motor Inc.

3. Protection Challenges for EV's

The use of an over-current protection device should be considered for the battery, charging module, cables, HVAC, heater, etc - see Fig. 2.

In general, apart from the emergency safety protection such as a Pyrotechnic Safety Switch, the most common form of over current protection device used in the EV is the fuse.

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. Many conditions can affect the current carrying capability of a fuse link and all aspects need to be considered to ensure continued and safe operation.

In general, the required rating of a fuse link, I_n, is governed by the following equation [3]:

$$I_n \geq \frac{I_{RMS} \times G}{K_t \times K_e \times K_v \times K_f \times K_a \times K_b}$$

I_{RMS}: Load RMS rating
I_n: Rated current of a given fuse
K_t: Ambient temperature correction factor
K_e: Thermal connection factor
K_v: Cooling air correction factor
K_f: Frequency correction factor
K_a: Correction for high altitude
K_b: Fuse load constant
G: Cyclic load factor

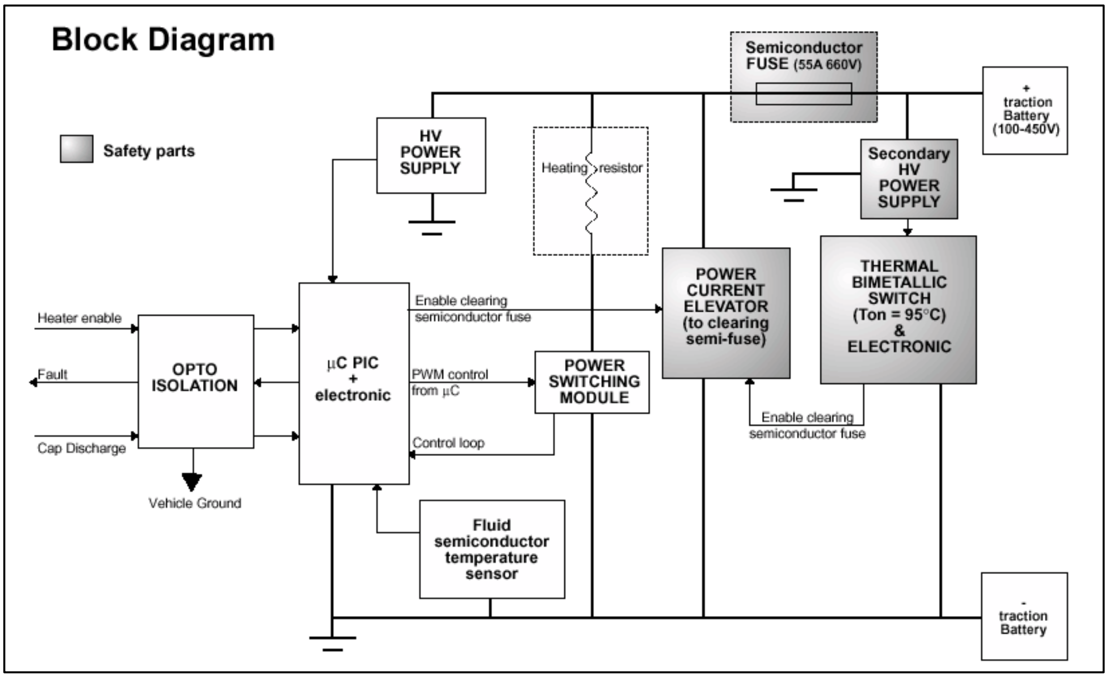


Fig. 2: Fuses requirement in the EV circuit

In the following, we will analyse the areas posed by EV's that will affect the above factors, directly or indirectly.

3.1 Voltage Level

Traditional automotive batteries were mostly lead-acid batteries and were 12Vdc, 24Vdc (heavy vehicles) or 42Vdc. This provided power for the starter motor, ignition system, lights and even the power steering.

With the expansion of EV's, the tendency is to go to a higher voltage, allowing higher power without drawing excessive currents. A comparison of motor efficiency showed an improvement; in particular, commutator losses at the brush decrease with higher voltages.

Whilst some cars have an independent lead-acid 12/24Vdc battery for the auxiliary system or a DC/DC converter for stepping down the voltage to a lower level for auxiliary supplies, many retain the same battery output voltage throughout to minimise the cable size and losses.

EV batteries can range from 150Vdc up to 800Vdc whereas the traditional automotive fuse links are only rated at 32Vdc and 58Vdc.

This means the traditional automotive fuse links cannot be used in most cases on EV's. Industrial fuse links or more specialised fuse links become the only available options for this voltage range.

3.2 Ambient Temperature

This variable is extremely crucial and is often underestimated when deciding the fuse selection. Increases in ambient temperature will reduced the life cycle of the EV battery and has a similar effect with the fuse. Normal ambient temperatures as per IEC 60269 for a fuse link, is up to 40°C (average of 35°C in a 24hr period and less over one year). However, today, EV ambient temperatures have been specified from as low as -40°C up to +105°C. As such, utilising Fig. 3, a fuse link temperature de-rating factor, Kt, could be as low as 0.5 which will have a serious impact on the selected fuse type.

This has the initial implication of doubling the fuse link's current rating before other factors are taken into consideration.

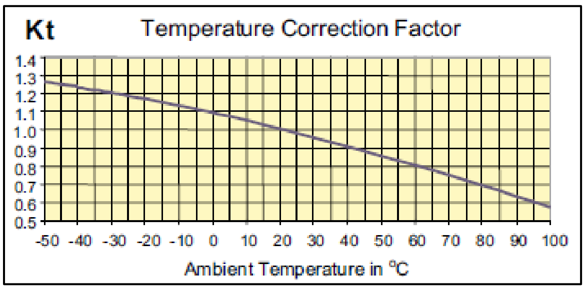


Fig. 3: Fuse link's temperature de-rating factor curve

3.3 Thermal Connection

Fuse links are generally mounted/connected using busbars or cables. The current density of the busbars/cables is defined in IEC 60269-4 and should be between 1 - 1.6A/mm^2. If the connection carries a current density less than this, then the fuse link should be de-rated as per the following graph [3].

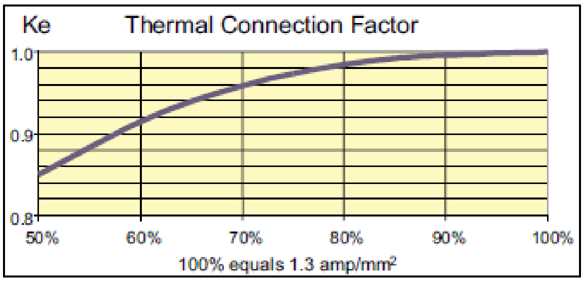


Fig. 4: Fuse link's thermal connection factor curve

In order to keep the weight, space and cost to a minimum, the automotive industry tends to opt for using small cabling.

A typical battery cable size is around 35mm^2 for a 200A continuous loading; a 27kW motor cable is around 25 mm^2; the auxiliaries such as HVAC, steering pump, heaters range from 2.5 mm^2 to 4 mm^2.

A thermal connection factor (Ke) of 0.8 can be applied (which is equivalent to around 15% of the IEC required cross sectional area for the fuse).

3.4 Cyclic Loading and Overload

When fuse links are subjected to current pulses (i.e. regular or irregular changes in load current), cyclic stress is induced owing to temperature variations. Degradation of the fuse elements can gradually accumulate and this may show as an increase in resistance. Consequently, current-time characteristics shift causing premature fuse fatigue and early operation during normal service. Under such circumstances, the intended protection will not be achieved. In order to avoid this condition, consideration has to be taken to ensure that there is an appropriate safety margin for the selected fuse.

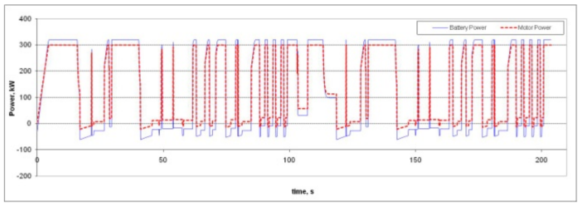
Unlike a PV system where the load profile is quite predictable, EV's have a very large and unpredictable cyclic load profile. Variables include geography, driver's style and specification of the car.

Depending on the battery characteristics, the current drawn at different speed / accelerations varies extensively.

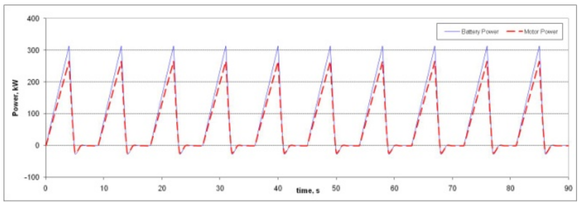
For example, using a VX1 battery,

At 20 Mph on a level road current drawn = 10 Amps
At 30 Mph on a level road current drawn is 15Amps
At 40 Mph on a level road current drawn is 25Amps
At 50 Mph on a level road current drawn is 40 Amps
At Maximum Power on an incline from standing start and full 'throttle', current drawn is 106 Amps.

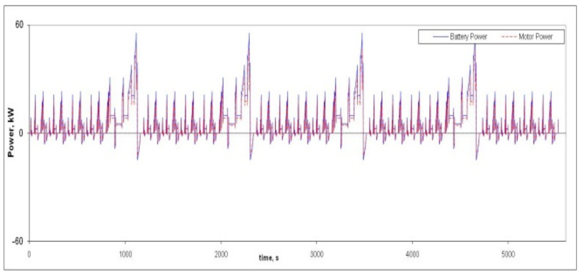
The following examples show the variation of loading under different situations. The profiles are from a high performance EV/supercar.



(i) A single cycle representing a standing start lap and one flying lap of the test track



(ii) Traffic light test



(iii) Profile over 30 mile range

Fig. 5: Load profiles of a 'supercar' prototype

The examples in Fig. 5 show how intense the loading can be and as such, a large cyclic loading de-rating factor (G) - up to 1.8 times - may need to be applied when determining the fuse link. Less arduous loading will incur a lower G factor.

The challenge here lies in the fact that whilst it is possible for the industry to provide the load profile of say an Electric Bus (predefined route and timetable), it is difficult to predict the "normal" current loading of an EV.

In addition, during the recharge state, there will be an overload condition for a pre-defined time for the motor-controller. It is important to ensure that the fuse is able to withstand this overload condition without melting and causing pre-mature fatigue.

Fig. 6 shows the profiles during pre-charging under different test conditions. All exhibit very high overload and cyclic loads, which can significantly affect the thermal stress of the fuse element.

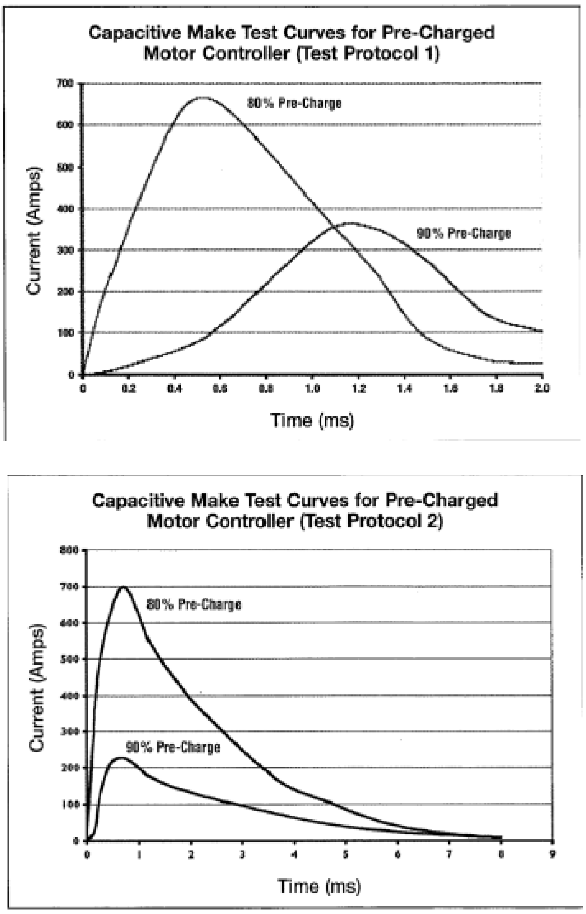


Fig. 6: Charging profiles

3.5 Weight and Space

Space and weight are premium in vehicles. Whilst traditional automotive fuse links such as blade fuses are tiny, industrial fuses are significantly bigger in both weight and size. However, with the voltage level requirement increasing, present day industrial fuse links or specialised fuse links seem to be the only available options.

Battery packs do not solely consist of battery cells, but also other subcomponents such as Battery Management System (BMS), contactors for switching, fuses, connectors, etc [4]:

- 10% of a battery volume and weight is BMS and HV components
- Another 5 – 10% is taken up with wiring and bus-bars
- 15 – 20% is in the housing and support structure
- 25 – 35% of battery weight is non cell content

Therefore, it is desirable to have the fuse link as small as possible.

However, when considering the variables such as high ambient temperature and cyclic loading, this will require up-rating the fuse link which may impact size and space. This is something that the automotive industry is now beginning to recognise.

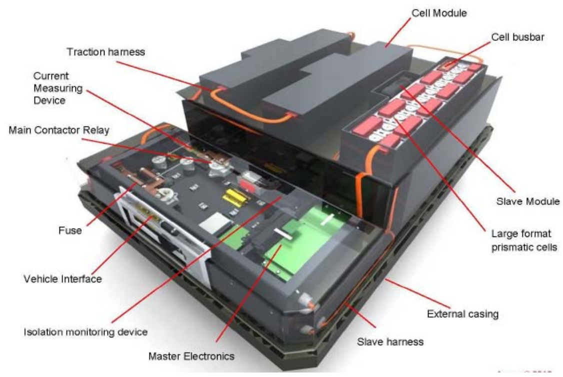


Fig. 7: Battery pack components [4]

3.6 Shock and Vibration

Harsh environments as seen in automotive applications, can be very demanding on larger components which are exposed to severe shock and vibration.

The car manufacturers normally issued their own shock and vibration specifications. However, these are generally in line with IEC 60068-2-6 for sinusoidal vibration excitation and IEC 60068-2-64 for wide band vibration excitation. For the mechanical shock requirement, this will normally be in line with IEC 60068-2-27 and IEC 60068-2-29.

It should be noted there is no requirement in IEC 60269 for shock or vibration testing of a fuse link. Although high speed fuses are expected to be better in terms of shock and vibration-withstand capability due to their very compact construction, it is important to test the fuse links, when installed under the specific application. Very often, it is not just the fuse links itself, but a combination of using good anti-vibration components and known processes/ procedures.

3.7 Automotive Quality Requirement

Today's existing automotive fuse links are made to automotive quality management system standard, ISO/TS 16949.

It is highly unlikely that the proposed solutions using larger fuse links in an EV application, will have been made/tested to this specification.

The automotive industry typically demands less than 10 Parts-Per-Million (PPM). The question for fuse link manufacturers is,

"Is this realistic or achievable?

4. Standards

At the time of writing, it can be said there is no complete, unilateral standard covering EV's.

It is globally recognized to have such standards which protects consumers, defines development, discourages the imposition of market barriers and establishes common components and systems used in EV's. Standards currently applicable to EV's are mostly for lead-acid batteries and nickel-metal hybrid batteries (NiMH).

Motor voltage, battery size, charging and discharging rate can vary significant from car to car. This poses problems to the component suppliers as each of these could be a custom solution - applicable only to one model.

Battery tray sizes, charging infrastructure, voltage level, protection, etc have been targeted for standardisation.

The European Commission has issued a legislative proposal for a common safety standard for EV's. This proposal is part of the wider European Strategy on Clean and Energy Efficient Vehicles which sets into action, the first part of the European Commission's roadmap on regulations and standards for EV's.

The proposed legislation aims to:

- Bring EU legislation in line with the United Nations Economic Commission for Europe (UNECE) legislation on approval of battery electric vehicles and their construction and safety requirements.
- Ensure that all vehicles marketed within the EU are constructed under a common safety standard for electric vehicles.
- Protect vehicle users from getting into direct contact with high voltage parts of the vehicle.
- Harmonise testing requirements in order to simplify approval of electric vehicles. Under the new type-approval system, automotive manufacturers will only need to obtain approval for a vehicle type in one Member State.

Whilst traditional automotive fuse links are built according to ISO 8820-3 (32Vdc or 58Vdc), this standard has not been updated to reflect the changes and requirements of the EV electric circuit.

The establishment of standard(s) for an EV will have far reaching implications and will impact everything from components and subsystems to charging infrastructure and national grid development.

5. Conclusion

This paper has attempted to address the major challenges posed to the fuse world in the EV market. Most of the current automotive manufacturers are using standard fuses, but it is clear that development is needed if trying to reduce size whilst maintaining the environmental, reliability and safety requirements.

Once international or global standards are approved, the focus will then turn to suppliers and manufacturers to provide a range of EV compliant products. There are several international committees reviewing the requirements - many have specific considerations. However, this "indecision" has not deterred automotive manufacturers from launching their EV's, but could, at a later date, impact those in general circulation.

The opportunity is huge. Pure electric vehicles are the future, but hybrids are gaining in popularity now - it can only get better as costs come down.

Watch this space!

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