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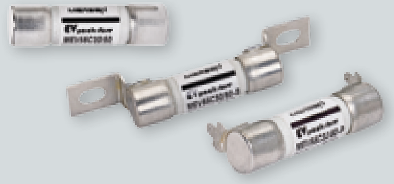
E-MOBILITY OVERCURRENT PROTECTION GUIDE

M-fuse®

EVpack-fuse®

Xp series®

Xs series®



OVERCURRENT PROTECTION FOR DC BATTERY APPLICATIONS

FAULT CLEARING OF DEMANDING DC CURRENT APPLICATIONS

The increase of voltage, current and power in E-Mobility creates a significantly more complex system and new challenges to attain a proper overcurrent protection.

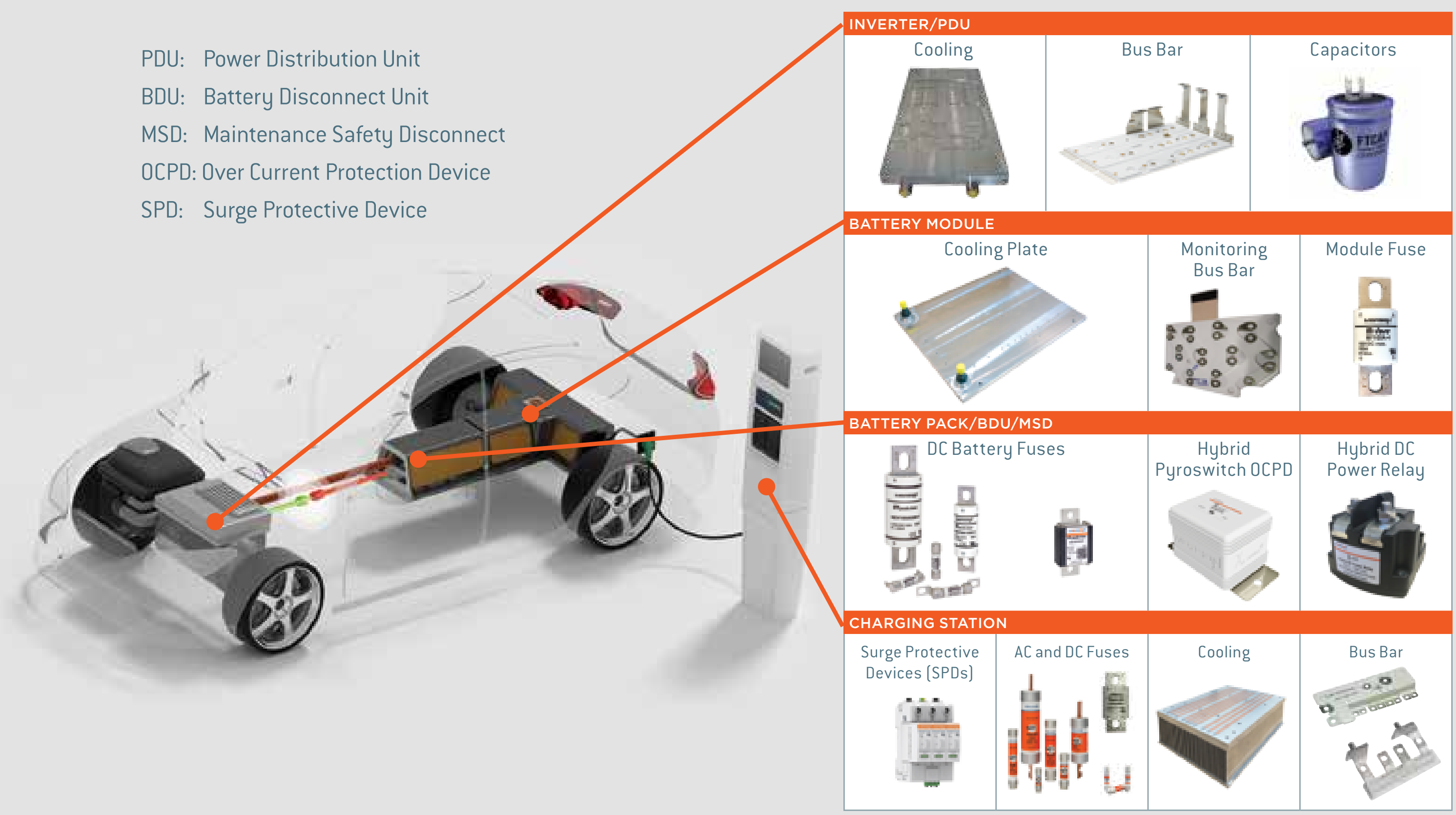
E-Mobility transportation means are now being mass-marketed; safety and reliability are the most important priorities for the vehicles and their occupants. For all variations of Electric Vehicle: Hybrid (HEV), Plug-In Hybrid (PHEV) or Battery Electric Vehicles (BEV), the motor is powered by the battery either intermittently or continuously. And wherever there is a power source, electrical components such as the Battery, DC Contactor, Power Distribution Unit, or Auxiliary Circuits must be protected by Over Current Protection Devices (OCPD).

The process of selecting a proper OCPD for a specific application may seem simple at first: one must select a fuse suitable for the application's system voltage and current requirements while being capable of withstanding a wide range of conditions.

However, the need for protection of power components in the automotive world relying on DC battery power has introduced a whole set of new challenges. Fuses being applied to DC battery applications in E-Mobility must guarantee fast protection for a wide range of fault currents; withstand a sequence of charging and discharge cycles, accelerations, regenerative braking; all the while being subjected to environmental conditions such vibrations, and wide variations in surrounding ambient temperature.

Although each vehicle's power system is unique; a set of guidelines can be applied for selecting a fuse ensuring proper protection and long-term reliability. The purpose of this document is to guide the reader through the process of selecting the appropriate OCPD for their DC Battery Related systems in an E-Mobility application.

PDU: Power Distribution Unit
BDU: Battery Disconnect Unit
MSD: Maintenance Safety Disconnect
OCPD: Over Current Protection Device
SPD: Surge Protective Device



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1. Adjusting the fuse rated current to allow for real-world working conditions

The current rating of a fuse is based on specific type-tests defined by standards and performed in controlled laboratory conditions. However in real-world applications, the working conditions in the equipment where fuses are installed are rarely the same as those conditions used during type tests. Fuses are thermal devices: anything that changes how they dissipate heat changes the continuous current carrying capability. To account for the differences between operational and test conditions, an array of correction factors are used to ensure a fuse with adequate current carrying capability is selected.

- Thermal Factors:
  - A_1: Ambient Temperature
  - B_v: Air flow passing across the fuse
  - C_1: Connections
- Life Requirements:
  - A'_2: Current Cycling
  - B'_2: Repetitive Overloads

Taking everything into account, the following equation is used to calculate the proper fuse rating:

$$I_{fuse} \geq \frac{I_{RMS}}{A_1 B_v C_1 A'_2 C_{ALT}}$$

As well as the following conditions:

- $I_1 \leq B'_2 I_{melt}$
- V_{nDC} @ $L/R_{fuse} \geq V_{DC\ MAX}$ @ L/R_{system}
- Fuse MBC $\leq I_{fault\ min.}$

Terminology	Definition
A	Ampere
V_{DC}	DC Voltage
L/R	Time Constant
IR	Fuse Interrupting Rating
MBC	Fuse Minimum Breaking Capacity
I_{rms}	Heating effect of transient or non-continuous current
I_{fuse}	Calculated fuse rated current
$V_{DC\ max}$	System Maximum Voltage
V_{nDC}	Fuse DC Voltage Rating
I_1	Overload Current
$I_{fault\ max}$	Maximum Fault Current
$I_{fault\ min}$	Minimum Fault Current
I_{melt}	Fuse Melting current at given time t
I_n	Fuse Rated Current

This application guide is a simplified version of the fuse selection process for EV protection. Evaluating fuse performance and cycling profiles can be complex. A more detailed study of your application is likely required. Please contact our Technical Service Engineers for guidance on your fuse selection.

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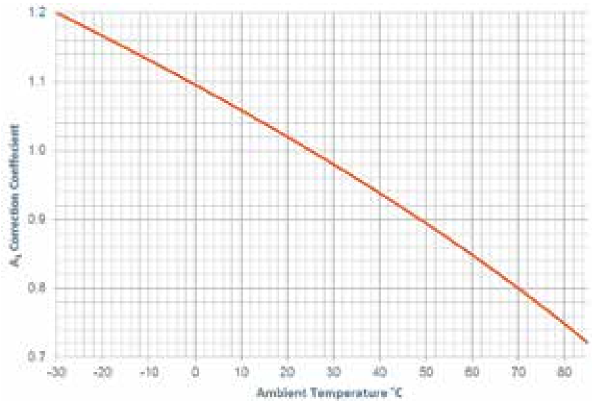
2. Thermal related factors to consider

a. Ambient temperature: A_1 coefficient For most E-Mobility applications, the ambient temperature surrounding the fuse ranges from 50˚C to 85˚C due to heat dissipation from nearby components or environmental conditions. Fuse current rating is established by standard type tests at 25˚C or 30˚C ambient. Higher ambient temperatures decrease the current carrying capability of the fuse. Consequently, we must apply a corrective coefficient to account for the difference in surrounding ambient temperature.

Temperature correction coefficient graphs are published to quickly find the correction factor for the expected ambient temperature inside the enclosure where the fuse is installed:



Graph 1: Temperature Correction

b. Air cooling: B_v coefficient If the application uses forced air to cool the fuse, this will benefit the current carrying capability of the fuse. The current correction coefficient will increase linearly until an air speed of 5 m/s after which further cooling cannot be achieved (see Graph 2).

Graph 2: Air Cooling Corrective Coefficient

c. Terminal connections size: coefficient C_1
In actual applications, the cable/bus bar sizes are typically smaller than those used in standard type tests. Since heat is conducted away from the fuse through the conductor connection points at the fuse terminals, using a smaller size cable will have a negative impact on cooling the fuse. The corrective coefficient C_1 is used to compensate for this effect. For Mersen's **EVpack-*fuse*** range, the following can be used:

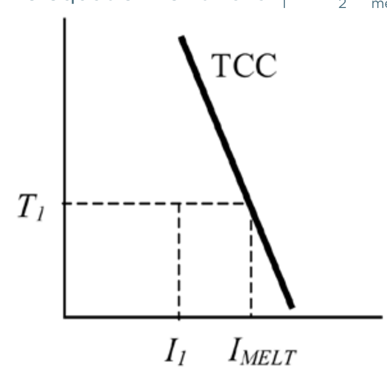
Voltage range	C_1 Correction Coefficient
< 500VDC	0.8
≥ 500VDC	0.85

3. Cycling and overload factors to consider

a. Effects of "cyclic" variable currents: coefficient A'_2 In an E-mobility application, the current will vary with changes to the power output, such as acceleration, regenerative braking, charging, air conditioning etc. The ever-changing currents create a repetitive "cycle," which is typically given by the customer in "driving profile(s)" and is key to proper fuse selection process. Cycling can cause element temperature fluctuations. Repeated heating and cooling of the element causes it to expand and contract which can lead to mechanical fatigue. A'_2 is used to make sure the temperature gradient on the fuse element is small enough to mitigate element fatigue, resulting in adequate fuse life for the application.

A'_2 varies from 0.6 to 0.8 depending on the load profile and the fuse construction. Using $A'_2 = 0.7$ is a good starting point for many EV load profiles. It is recommended that the entire application be reviewed by Mersen Technical Services Engineers to make sure the correct factor is chosen.

b. Repetitive overloads: coefficient B'_2 Naturally, it is also necessary to review the different power cycles as they will vary in magnitude, speed, and duration. We must make sure that the fuse is able to withstand overload currents that occur under normal vehicle operation. The fuse time current curve (TCC) gives the melting point (I_{MELT}) at a given time. A simple method of ensuring that the fuse is large enough to withstand the cyclic overload is to require that the ON current I_1 does not exceed a certain fraction B'_2 of the current which would cause the fuse to melt in the time T_1. The equation for this is $I_1 \leq B'_2 * I_{melt}$



Graph 3: Overload Current vs. Fuse Melting point

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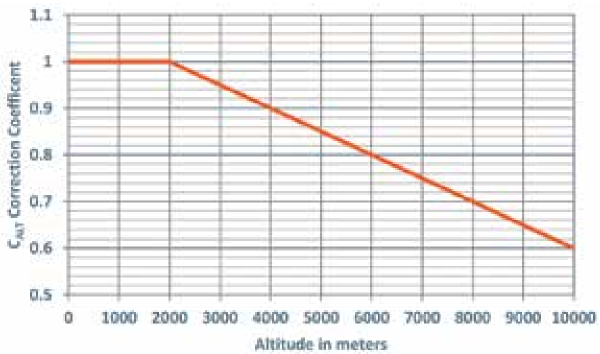
The coefficient B'_2 is directly related to the number of cycles. These factors vary depending on the fuse design. The table below are examples:

B'_2 Correction Coefficient	Number of cycles
0.31	10^6
0.35	10^5
0.45	10^4
0.5	4000
0.55	2000

4. Other factors to consider

a. Altitude: coefficient C_{ALT} At altitudes above sea level, the atmosphere density is reduced, decreasing fuse cooling which decreases the current carrying capability of the fuse. To account for this, a correction factor for altitude must be included in current rating calculation.

If the EV application requires continued use at elevations above 2000m, an additional derating factor must be used: it will decrease by 0.5 % for every 100m above 2000m.



Graph 4: Altitude derating

b. Fuse Interrupting Rating and Minimum Breaking Capacity The primary function of a fuse is to interrupt the over-currents safely, to protect the components and cables of the system from being damaged. However, every fuse has a range of currents it can interrupt safely, and the fuse should not be relied upon to interrupt currents outside of this range.

The Interrupting Rating (IR) and Minimum Breaking Capacity (MBC) are critical parameters defined by international fuse standards that outline the range of currents fuses open safely.

- IR is the maximum current a fuse is tested to safely open at a specific DC voltage and time constant (L/R)
- MBC is the minimum current a fuse is tested to safely open at a specific DC voltage and time constant (L/R).
- Therefore "MBC – IR" is the range of currents a fuse can safely open

The fuse MBC is published at a given voltage and time constant. MBC is a function of system voltage and time constant of the circuit where it is used. Mersen publishes the test conditions used to establish MBC values along with the maximum clearing time at MBC.

MBC can vary widely across fuse types. For fuses used in EV applications, MBC can vary from 2 to 10 times the current rating of the fuse. That means for a 350A fuse, MBC could be as high as 3500A.

The maximum time it takes for the fuse to open MBC is also published because the fuse must open quickly enough at low fault current to protect components.

While the IR is well-known to users, the MBC is commonly overlooked. In EV applications, the MBC must be taken into consideration, due to limited short-circuit current generating capabilities of Li-Ion batteries. Depending on the configuration of the battery cells and cell technologies, it is typical that the available short circuit current the battery packs provide in a range between 2 to 8kA.

Therefore, it is imperative that the user takes notice of this MBC value. This information is important for system designers to evaluate whether a secondary protective measure is needed to address low fault currents:

$$I_{faultmin} > MBC_{fuse}$$

c. Coordination with other components (contactor, relay, circuit breakers and other fuses) The ultimate goal in EV battery protection is having a solution that safely disconnects the power and can cover the full spectrum of current loads:

- 0 (no load)
- Nominal current (I_n)
- Maximum overload current (I_{1max})
- Maximum prospective short-circuit current ($I_{faultmax}$)

However, no OCPD can cover this wide range by itself.

As a result, the protection strategy involves 2 devices in series: a resettable DC relay (or contactor) that operates (make/break), protected upstream by an OCPD, covering faults greater than the make/break capacity of the DC relay.

Matching a DC relay with an OCPD is not trivial. The need for coordination between both device operations is critical.

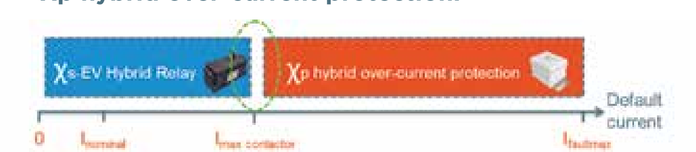
Typical coordination scheme looks like:

450VDC platform with DC mechanical contactor and DC fuse:

Requirements include:

- $MBC_{fuse} \leq I_{max\ Contactor}$
- The fuse must open fast enough to protect the contactor
- The contactor must be capable of opening all possible overcurrents less than fuse MBC

850VDC platform with Xs-EV hybrid relay and Xp hybrid over-current protection:

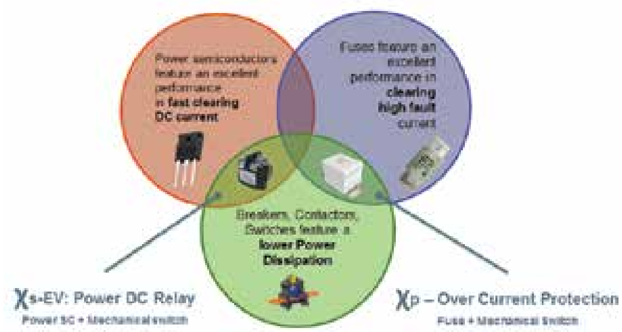


5. Hybrid solutions for the ultimate protection

Recent evolutions ranging from an increase in battery capacity and voltage, to more demanding mission profiles; as well as new regulations, and a better understanding of safety and performance requirements, have pushed traditional OCPDs to their limits.

For instance, while a high-speed fuse can perform well under large DC fault currents, it does not perform as well under low fault currents and is prone to ageing due to the challenging cycling and overload conditions.

Mersen has recently developed hybrid solutions: the Xp and Xs series; two innovative OCPDs that address the shortcomings and overloads of traditional fuse technology and fulfil customers' safety and performance requirements over all current ranges up to 1000 VDC.



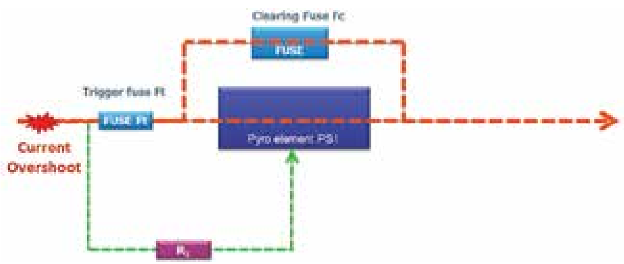
Mersen Hybrid Solutions

The Xp series has been engineered specifically to be a high cycling performance DC protection device with a very fast operating time and a very high overload current withstand rating.

It is comprised of a combination of a clearing element and a pyroswitch in parallel. This architecture prevents the ageing of the elements due to the mission profile or fast charging requirement while ensuring a fast disconnection in case of short circuit.

This solution is categorized into 4 main families that can be tailored to each and every customer's application:

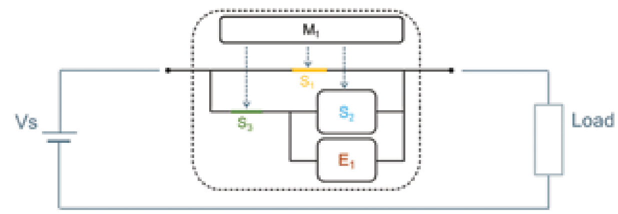
- Xp-S: External trigger signal (airbag, current sensor...) to clear the fault
- Xp-ST: Self-Trigger feature that enables the device to clear the fault by itself
- Xp-STT: Identical to ST with an optional external triggering feature
- Xp-e: Self triggered by electronics



Xp-ST Principle

Xs is a combination of relay and a semiconductor. It has been developed to provide high DC switching performances, at both high voltage and high current, versus conventional mechanical power relays along with the possibility of customizing its characteristics.

Xs' basic principle is to have a semiconductor switch, a secondary relay and a varistor in parallel with the main relay. During normal operation, the semiconductor switch is turned off, making the main relay handle all the current with very low resistance. When an overload occurs, the semiconductor is switched on; the main relay will be switched off at zero voltage while the semiconductor handles the breaking procedure. With this unique feature, Xs can handle at 1200V up to 2kA clearing capability and be resettable.

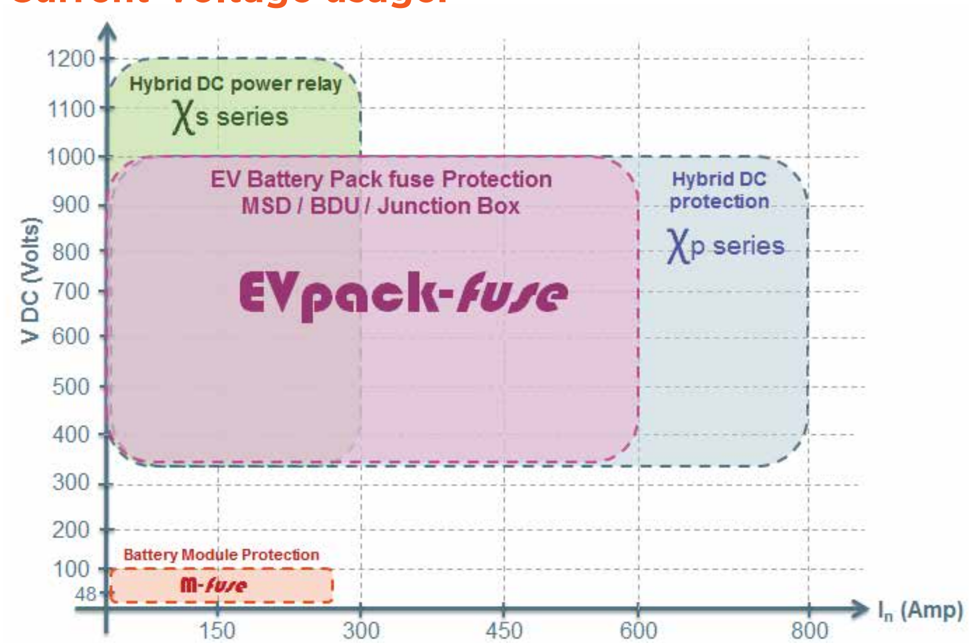


Xs Principle

- Fast mechanical switch (S_1)
- Semiconductor switch (S_2)
- Energy absorption module (E_1) : e.g. Varistor
- Mechanical isolation switch (S_3)
- Monitoring and signal processing (M_1)

Both Xp and Xs have been designed to offer the enhanced protection for E-mobility applications with arc-less protection and full compliance with automotive safety requirements; fast-acting operation, close-to-zero conduction losses and a small footprint; and a same time remain fully customizable.

Typical Current-Voltage usage:



Application Information:

A new commercial vehicle, with a life expectancy of 10 years, is being designed that requires overcurrent protection for the EV battery system.

The electric characteristics are:

- V_{nom} = 540VDC
- V_{max} = 620VDC
- V_{min} – 426VDC
- Time Constant < 0.9ms
- Operating Ambient Temperature inside enclosure: up to 80° C
- Altitude < 2000M

Fault Current Range :

- $I_{fault\ max}$ = 5400A (V_{max} Charge located just downstream of fuse)
- $I_{fault\ min}$ = 2200A (V_{min} at furthest location before next OCPD)

- $I_{Charging}$ = 156A for 1 hour

Multiple operating profiles were provided. Analysis yielded the following required parameters:

- I_{rms} = 148A

Worst case overloads and requirement to achieve 10 year vehicle life:

- 670A_{rms} for 1s, 4000 times during life of vehicle
- 520A_{rms} for 8s, less than 2000 times during life of vehicle
- 296A_{rms} for 60s, 10,000 times during life of vehicle

1. Fuse Current Rating Calculations:

The maximum voltage is 620VDC with a time constant of <0.9ms. The fuse must have a voltage rating equal to or greater than 620VDC at a time constant of 0.9ms. The maximum IR of the fuse is 20kA which is greater than the max available fault current of 5400A. The minimum breaking capacity will be checked after the fuse ampere rating is chosen.

Selecting fuse ampere rating – Charging and running profiles must be evaluated:

$I_{charging}$ = 156A

$$I_{nfuse} \geq \frac{I_{RMS}}{A_1 B_v C_1 A'_2 C_{ALT}} = \frac{156}{(0.75)(1)(0.85)(0.7)(1)} = 349.6A$$

I_{rms} = 148A

$$I_{nfuse} \geq \frac{I_{RMS}}{A_1 B_v C_1 A'_2 C_{ALT}} = \frac{148}{(0.75)(1)(0.85)(0.7)(1)} = 331.65A$$

Correction factors:

Ambient Temp 80C:	A_1 = 0.75
Air Flow – none:	B_v = 1
Connections - V_{nfuse} > 300V:	C_1 = 0.85
Cyclic Loading:	A'_2 = 0.7
Altitude < 2000M:	C_{ALT} = 1

Rounding the results of both calculations up to 350A gives us the fuse current rating. If these two calculations had given different fuse ampere ratings, use the higher of the two ratings.

2. Voltage Rating – Time Constant Verification:

For this application, we need a 350A fuse rated at least 620VDC with a time constant of 0.9mS or more. The MEV70A series is rated 700VDC with a circuit L/R < 1ms, which meets the voltage-time constant requirements of this application.

3. MBC and IR Verification:

Maximum IR of the fuse is 20kA which is greater than the max available fault current of 5400A. MBC requirements are: Fuse MBC $\leq I_{fault\ min}$

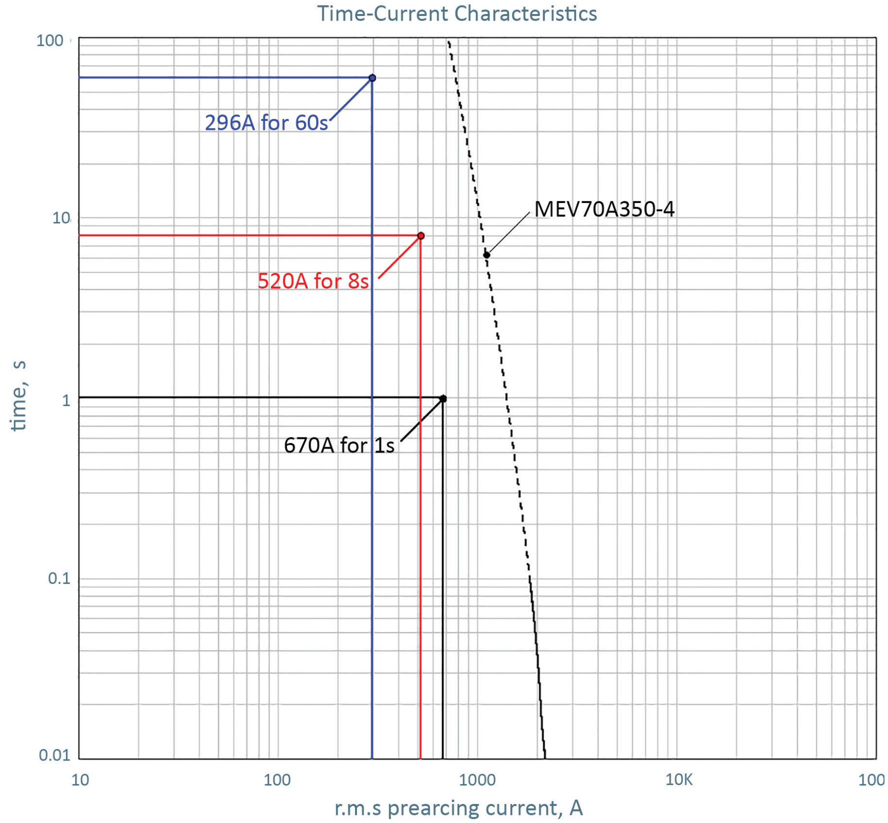
From the MEV70A350-5 datasheet we find MBC = 1840A with a max clearing time of 140ms.

Catalog number	Rated DC voltage	Rated current I_n	Power dissipation at 0.5 I_n	Min. Breaking Capacity (MBC)	Max. time to clear MBC	Weight
MEV70A350-4	700 V	350 A	10.2 W	1840 A	140 ms	0.26 kg

The smallest fault current the fuse is required to open for this application is 2200A, which is larger than the MEV70A350-4 MBC satisfying the requirement. The MEV70A350-4 can safely interrupt the required range of fault currents 2200 – 5400A

4. Life Requirements Review

Next, we need to make sure the MEV70A350-4 meets the life requirements of the application. The three overload requirements are shown below plotting on the fuse time current curve. The requirement is: $I_1 \leq B'_2 I_{melt}$



Overload Current – I_1 (A_{rms})	Duration of overload(s)	Times occurring over expected vehicle life	B_2'	I_{melt} at overload duration (A_{rms})	$B'_2 I_{melt}$	Is requirement $I_1 \leq B'_2 I_{melt}$ met
670	1	4000	0.5	1400	700	YES
520	8	<2000	0.55	1070	588.5	YES
296	60	10,000	0.45	780	351	YES

The overload requirements are met by the MEV70A350-4.

MEV70A350-4 meets the operating lifetime requirements and will provide suitable life for this application.

In-House Testing Capabilities

Fuse selection can often be complex, especially for E-mobility as developments are going faster than international electric standards. Mersen is able to offer customers an accurate, reliable and confidential process for testing and qualifying products, applications and design concepts, as well as testing to a wide variety of regulatory standards.

The test center actually houses five labs, for both AC and DC high power, electrical performance, PV solar, mechanical, and environmental and process tests through two laboratories — one in Newburyport, Massachusetts, USA and the other in Lyon, France.

Our labs also play a critical role in custom-fuse development, enabling us to test prototypes quickly and efficiently to keep pace with customer's development schedule. The labs are an essential part of our quality control program. The test labs have accreditation and approvals from all the main global agencies, including COFRAC, ASEFA, LCIE, VDE, UL, ISO/IEC 17025, etc.

Customized Fuses

Our customized fuses can address customers' unique application needs in a quick and reliable fashion. Mersen has implemented this service in order to provide solutions for our customers that are requesting rapid design, development, and manufacture of specific products.

About Us

Mersen Electrical Power designs innovative solutions to address its client's specific needs to enable them to optimize their manufacturing process in sectors such as energy, transportation, electronics, chemical, pharmaceutical and process industries. We bring our expertise in fuses, surge protection, high power switches, cooling solutions and bus bars designed to meet your application challenges and to make them safe, reliable and profitable.

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E-MOBILITY FUSE TECHNICAL QUESTIONNAIRE

MERSEN
Expertise, our source of energy

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State/Province-ZIP/Postal Code	Fax:	
Project Name:	Date:	
Project Schedule		
Project Lifetime:	Project Volume:	
Project Schedule	A-Sample	Date:
	B-Sample	Date:
	C-Sample	Date:
	D-Sample	Date:
Requirement	**Unit**	**Value**
1. Fuse location in charging circuit	Y/N	
2. Fuse location in main circuit	Y/N if Yes, does the main circuit includes charging?	
3. Fuse location in auxiliary circuit	Y/N	
4. Max battery voltage	VDC	
5. Continuous operation current RMS	A	
6. Max pulse discharge current and duration / how often	"A - duration in s / quantity in lifetime"	
7. Cont. charge current and duration	A - duration in min	
8. Max. breaking current (standard Mersen 20kA)	A	
9. Coordination requested	Y/N if yes which device and characteristics	
10. Min. breaking capacity (MBC) and response time	A - duration in ms	
11. Time constant L/R of clearing currents (standard Mersen 1ms)	ms	
12. Cable connection - cross section	mm²	
13. Fuse connection type	blade, bolted blade, bracket, flush ends, others (specify)	
14. Connection plating (standard Mersen tin plated)		
15. Fuse resistance	μΩ	
16. Dimensions L	mm	
17. Dimensions W or diameter	mm	
18. Dimensions H	mm	
19. Weight	g	
20. Operating temperature range (standard Mersen max 85°C)	°C	
21. Service life	years / km / h	
22. Vibration	Standard #	
23. Shock	Standard #	
24. Altitude range	m	
25. Other requirements (please specify or attach)		

Your contact:			
Name:			
Address:	T	M	Email: