

Electrical Safety of Heavy Duty Transit Buses

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Summary

The past few years have seen the emergence of fully electric heavy-duty transit vehicles. The performance and capability of these electric vehicles are leading the way to a new era free of dependence on fossil fuels. This rapid transition raises questions about electrical safety. In most cases, technologies are evolving faster than regulations and standardization, creating a gap in safety. This paper will explore potential dangers related to high-voltage electric buses and the technical solutions the Volvo Group is implementing to address these issues, in keeping with the Group's core values of quality, safety, and environmental care.

1 Introduction

Over the years, legislation and regulations on heavy-duty diesel buses have evolved and made the technology safe and reliable. Carrying more than 100 passengers along with 500 liters of flammable fuel is not questioned. On the other hand, we now have autonomous electric vehicles carrying the same number of passengers with hundreds of kWh of electric energy on board. To obtain higher efficiency with lower currents, we have increased voltages up to 700 volts or more. This amount of energy and voltage must be treated with respect and care.

Safety standards such as SAE J2910 and ISO 6469 provide a solid framework for safe electric vehicle design. On the other hand, standards alone cannot guarantee a complete safety approach. This article highlights some of the major concerns and proposes a method to mitigate and quantify safety risks.

2 Electrical Risks

2.1 Live Potential of Batteries

- 2.1.1 Every ESS (Energy Storage System) constitutes a risk, as it is impossible to fully shut down its potential. Contactors can only secure the output poles, and thus represent a medium level of safety.

2.2 Multiple Sources

- 2.2.1 In most designs, large energy ESS are built by plugging a combination of multiple battery pack sources in parallel (see Figure 1). Such configurations multiply the need for HV (high voltage) cabling throughout the vehicle. For example, buses can have batteries in the engine compartment,

on the roof, in the passenger compartment, and embedded in the floor. This configuration entails the need for the right fusing design, since multiple sources joined together can supply enough current to feed a short circuit.

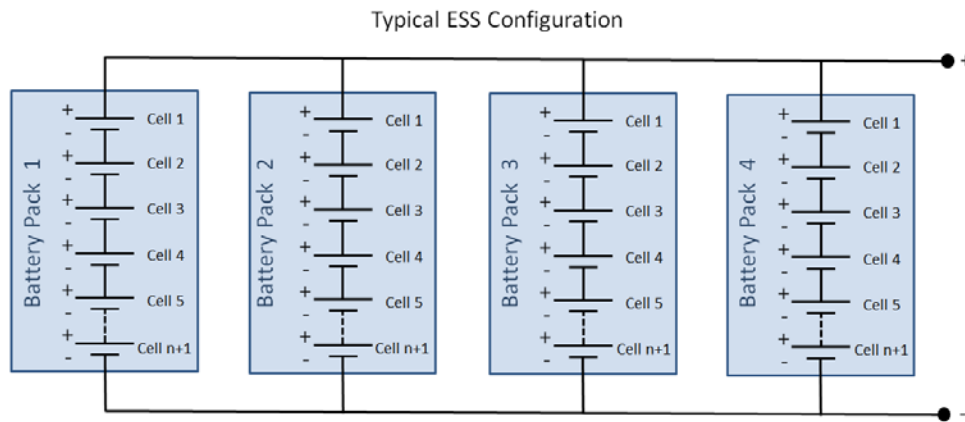


Figure 1: ESS

- 2.2.2 Vehicle maintenance and repairs require the vehicle to be electrically secured before any critical work can be done. A parallel source design increases the risk of electrocution when decommissioning the vehicle. Failure to follow procedure or taking shortcuts can lead to a dangerous situation. A single battery pack presents the same risk of electrocution as exposure to the full potential of the ESS. Therefore, decommissioning is not complete until **all** sources are disconnected.

2.3 Level of Energy

Fully electric vehicles are characterized by the use of ESS (Energy Storage Systems). The amount of energy they carry varies from one vehicle to the other but often reaches inordinate levels of kWh.

The high level of energy allows for very high currents to be extracted from the ESS. Two main risks derive from this available current.

2.3.1 Thermal Runoff

Without sufficient protection, a short circuit could exist and lead to a fire in the cabling and/or vehicle. The main means of mitigating this risk involves implementing proper fusing, not only within system components but also for cabling. Having multiple sources connected in parallel may bring high current to the smaller gauge wires of low power auxiliary systems. Figure 2 shows enhanced cabling protection through the addition of 25A, 250A, and 500A fuses. High current detection should also be implemented in the ESS BMS (Battery Monitoring System). Among its primary functions, the BMS monitors cell temperature and cuts off out-of-control current flow.

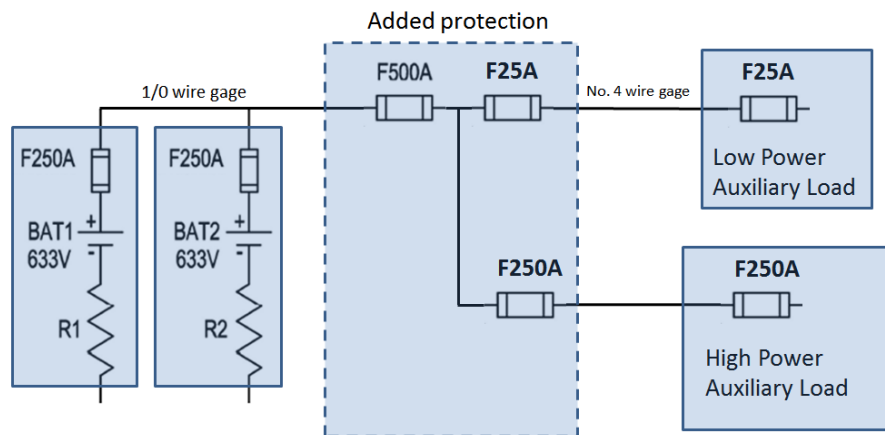


Figure 2: Added Protection

2.3.2 Arc Flash

In combination with a large amount of current and high voltage levels, the risk of arc flash events can exist in electric vehicles – generally category Type II and III for ESS-equipped vehicles. Proper arc rated personal protection equipment should be worn during operations where live potential may exist. Until the high voltage is completely decommissioned, high risk must be assumed whenever workers can access live potential. This is especially true when working directly on propulsion batteries.

2.4 High Voltage

2.4.1 Electric shock

The 700-volt level falls within the category of high voltage. Conventional signs of danger, such as noise or moving parts, are no longer present to caution workers of risk

2.4.2 Human factor

Overconfidence and lack of training can sometimes be the cause of incidents/accidents. Training programs and certification are crucial to maintaining a safety level.

2.4.3 Arc Flash (see 2.3.2)

3 Design for Safety

- 3.1 The previous chapter presented some of the dangers and risks related to purely electric vehicles. Through the development of the Nova LFSe vehicle, we have addressed these risks and developed solutions to minimize them and provide a safe environment for drivers, passengers, maintenance personnel, etc. Our approach to safety revolves around two basic principles.
 - 3.1.1 Passive safety. Safety starts with proper design that uses protective measures such as double insulation, mid-pack disconnects, the right fusing strategy and wire gauges, touch-proof connectors, mechanical designs that limit access to certain components, detection of unplugged cables, keyed connectors, minimized cable lengths, poka-yoke lug sizes to prevent swapping, etc.
 - 3.1.2 Active safety. In addition to passive safety considerations, systems such as HVIL (High Voltage Interlock Loops), current leak detection and intervention, ECU fault monitoring, multi-pole battery contactors, and so on, complement the overall strategy.

4 Risk Calculation and Mitigation

- 4.1 The safety risks described previously may become actual dangers during the overall life cycle of the vehicle. From the time of its construction to the end of its service life, incidents or accidents may occur. Quality issues, deficient workmanship, and maintenance should be factored into the equation.
- 4.2 The nonexistence of zero risk is admitted in theory. However, in practical terms, no one wants to be exposed to risks. The challenge resides in finding ways of having infinitesimal probability of defect occurrence.
- 4.3 Our findings reveal that cascading and adding layers of protection provide a better means of increasing safety than working solely on improving a single safety feature.
- 4.4 The overall key safety approach can then be determined through mathematical probability. Considering every passive and active safety feature and combining their probability factors can lead to a near null probability of defect occurrence. Without safety feature combination, a high risk still exists. For example, based on supplier MTBF (Mean Time Between Failures), relying solely on contactors for high voltage protection yields a defect probability of $P = 1.E-05$ (1/100,000).
- 4.5 The state of the vehicle also dictates the applicability of safety features. Safety features may or may not be operational or efficient depending on whether the vehicle is in operation or under construction or maintenance. For example, a vehicle involved in an accident may present the lowest safety level condition. This is particularly true when high power batteries are deformed as a result of an impact. This condition may render the voltage insulation insufficient or the ESS contactors inoperative. A complete FMEA (Failure Mode and Effect Analysis) study can reveal failure conditions and mechanisms, and determine the probability of feature/system failure.
- 4.6 The following simplified example describes the probability calculation of human exposure to high voltage. The example is provided for methodology purposes only. Numbers and features **should not be used or copied, in whole or in part**. Exhaustive calculations should be performed using precise defect rates for each specific safety feature or system used by the vehicle manufacturer.
 - 4.6.1 A list of vehicle states (use cases) is established (see Table 1).

Vehicle States
In operation
Maintenance or repair
Troubleshooting (live HV)
Under construction / assembly
Battery transportation
Emergency intervention / accident

Table 1: Vehicle States (Use Cases)

4.6.2 A list of safety features and systems is established (see Table 2).

Active and Passive Safety Features and Systems
HVIL
Internal battery contactors (both poles)
Voltage leak detector (hot coach)
Contactor state measurement
No use of chassis ground for current return (HV)
No easy accessibility to live potential
Galvanic isolation between HV and low voltage circuit
Shielded power cables
Common chassis ground for all components
Manual service disconnect
Unplugged battery connector(s)
Use of HV protective gloves
Isolated pole caps
Finger proof connectors
Work and safety instructions
Training and certification

Table 2: Safety Features and Systems

- 4.6.3 The reliability or defect rate of each feature or system is established and categorized. A defect rate of 1.E-06 (1/1,000,000) is assigned to a HIGH level of safety, one of 1.E-05 (1/100,000) to a MEDIUM level of safety, and one of 1.E-04 (1/10,000) to a LOW level of safety.
- 4.6.4 The reliability or defect rate of each feature or system should be evaluated in relation to the state of the vehicle. For example, internal battery contactors present a MEDIUM safety level during normal vehicle operation. When severe deterioration of mechanical ESS integrity occurs, however, their safety may drop to a LOW level.
- 4.6.5 The relationship between vehicle state and safety features is established (see Tables 3 and 4).

Vehicle State	Active Safety	Level of Safety	Passive Safety	Level of Safety
In operation	HVIL	Medium	No use of chassis ground for current return (HV)	High
	Internal battery contactors (both poles)	Medium	No easy accessibility to live potential	High
	Voltage leak detector (hot coach)	Medium	Galvanic isolation between HV and low voltage circuit	High
	Contactors state measurement	Low	Shielded power cables	High
			Common chassis for all components	High
			Manual service disconnect	n/a
			Unplugged battery connector(s)	n/a
			Use of HV protective gloves	n/a
			Isolated pole caps	n/a
			Finger proof connectors	n/a
			Work and safety instructions	Medium
			Training and certification	Medium
Vehicle State	Active Safety	Level of Safety	Passive Safety	Level of Safety
Maintenance or repair	HVIL	Medium	No use of chassis ground for current return (HV)	High
	Internal battery contactors (both poles)	Medium	No easy accessibility to live potential	n/a
	Voltage leak detector (hot coach)	Medium	Galvanic isolation between HV and low voltage circuit	Medium
	Contactors state measurement	Low	Shielded power cables	Low
			Common chassis for all components	Medium
			Manual service disconnect	High
			Unplugged battery connector(s)	High
			Use of HV protective gloves	Medium
			Isolated pole caps	n/a
			Finger proof connectors	Medium
			Work and safety instructions	Low
			Training and certification	Low
Vehicle State	Active Safety	Level of Safety	Passive Safety	Level of Safety
Troubleshooting (live HV)	HVIL	Low	No use of chassis ground for current return (HV)	High
	Internal battery contactors (both poles)	Low	No easy accessibility to live potential	Low
	Voltage leak detector (hot coach)	Low	Galvanic isolation between HV and low voltage circuit	Low
	Contactors state measurement	Low	Shielded power cables	Low
			Common chassis for all components	Low
			Manual service disconnect	n/a
			Unplugged battery connector(s)	n/a
			Use of HV protective gloves	Low
			Isolated pole caps	n/a
			Finger proof connectors	Low
			Work and safety instructions	Low
			Training and certification	Low

Table 3: Relationship between Vehicle State and Safety Features

Vehicle State	Active safety	Level of Safety	Passive safety	Level of Safety
Under construction / assembly	HVIL	Low	No use of chassis ground for current return (HV)	High
	Internal battery contactors (both poles)	Low	No easy accessibility to live potential	n/a
	Voltage leak detector (hot coach)	Low	Galvanic isolation between HV and low voltage circuit	Medium
	Contactor state measurement	Low	Shielded power cables	Medium
			Common chassis for all components	High
			Manual service disconnect	High
			Unplugged battery connector(s)	High
			Use of HV protective gloves	n/a
			Isolated pole caps	Low
			Finger proof connectors	Medium
Battery transportation			Work and safety instructions	Low
			Training and certification	Low
	HVIL	n/a	No use of chassis ground for current return (HV)	High
	Internal battery contactors (both poles)	Medium	No easy accessibility to live potential	Low
	Voltage leak detector (hot coach)	n/a	Galvanic isolation between HV and low voltage circuit	Medium
	Contactor state measurement	n/a	Shielded power cables	n/a
			Common chassis for all components	n/a
			Manual service disconnect	High
			Unplugged battery connector(s)	High
			Use of HV protective gloves	n/a
Emergency intervention/accident			Isolated pole caps	Low
			Finger proof connectors	Medium
			Work and safety instructions	Low
			Training and certification	Low
	HVIL	Low	No use of chassis ground for current return (HV)	High
	Internal battery contactors (both poles)	Low	No easy accessibility to live potential	Medium
	Voltage leak detector (hot coach)	Low	Galvanic isolation between HV and low voltage circuit	Low
	Contactor state measurement	Low	Shielded power cables	Low
			Common chassis for all components	High
			Manual service disconnect	High
			Unplugged battery connector(s)	n/a
			Use of HV protective gloves	n/a
			Isolated pole caps	n/a
			Finger proof connectors	n/a
			Finger proof connectors	Low
			Training and certification	Low

Table 4: Relationship between Vehicle State and Safety Features

4.6.6 The total composite probability of exposure to HV is then calculated as follows:

$$P(A \cap B \cap C \cap \dots n) = P(A) \times P(B) \times P(C) \times \dots P(n)$$

4.6.7 The calculation yields the following results (see Table 5).

Vehicle State: In operation	Probability of HV Exposure	Vehicle State: Maintenance or repair	Probability of HV Exposure
HVIL	1E-05	HVIL	1E-05
Internal battery contactors (both poles)	1E-05	Internal battery contactors (both poles)	1E-05
Voltage leak detector (hot coach)	1E-05	Voltage leak detector (hot coach)	1E-05
Contactor state measurement	1E-04	Contactor state measurement	1E-04
No use of chassis ground for current return (HV)	1E-06	No use of chassis ground for current return (HV)	1E-06
No easy accessibility to live potential	1E-06	No easy accessibility to live potential	1E+00
Galvanic isolation between HV and low voltage circuit	1E-06	Galvanic isolation between HV and low voltage circuit	1E-05
Shielded power cables	1E-06	Shielded power cables	1E-04
Common chassis for all components	1E-06	Common chassis for all components	1E-05
Manual service disconnect	1E+00	Manual service disconnect	1E-06
Unplugged battery connector(s)	1E+00	Unplugged battery connector(s)	1E-06
Use of HV protective gloves	1E+00	Use of HV protective gloves	1E-05
Isolated pole caps	1E+00	Isolated pole caps	1E+00
Finger proof connectors	1E+00	Finger proof connectors	1E-05
Work and safety instructions	1E-05	Work and safety instructions	1E-04
Training and certification	1E-05	Training and certification	1E-04
Total Probability	1E-59	Total Probability	1E-69

Vehicle State: Troubleshooting (live HV)	Probability of HV Exposure	Vehicle State: Under construction / assembly	Probability of HV Exposure
HVIL	1E-04	HVIL	1E-04
Internal battery contactors (both poles)	1E-04	Internal battery contactors (both poles)	1E-04
Voltage leak detector (hot coach)	1E-04	Voltage leak detector (hot coach)	1E-04
Contactor state measurement	1E-04	Contactor state measurement	1E-04
No use of chassis ground for current return (HV)	1E-06	No use of chassis ground for current return (HV)	1E-06
No easy accessibility to live potential	1E-04	No easy accessibility to live potential	1E+00
Galvanic isolation between HV and low voltage circuit	1E-04	Galvanic isolation between HV and low voltage circuit	1E-05
Shielded power cables	1E-04	Shielded power cables	1E-05
Common chassis for all components	1E-04	Common chassis for all components	1E-06
Manual service disconnect	1E+00	Manual service disconnect	1E-06
Unplugged battery connector(s)	1E+00	Unplugged battery connector(s)	1E-06
Use of HV protective gloves	1E-04	Use of HV protective gloves	1E+00
Isolated pole caps	1E+00	Isolated pole caps	1E-04
Finger proof connectors	1E-04	Finger proof connectors	1E-05
Work and safety instructions	1E-04	Work and safety instructions	1E-04
Training and certification	1E-04	Training and certification	1E-04
Total Probability	1E-54	Total Probability	1E-67

Vehicle State: Battery transportation	Probability of HV Exposure	Vehicle State: Emergency intervention/accident	Probability of HV Exposure
HVIL	1E+00	HVIL	1E-04
Internal battery contactors (both poles)	1E-05	Internal battery contactors (both poles)	1E-04
Voltage leak detector (hot coach)	1E+00	Voltage leak detector (hot coach)	1E-04
Contactor state measurement	1E+00	Contactor state measurement	1E-04
No use of chassis ground for current return (HV)	1E-06	No use of chassis ground for current return (HV)	1E-06
No easy accessibility to live potential	1E-04	No easy accessibility to live potential	1E-05
Galvanic isolation between HV and low voltage circuit	1E-05	Galvanic isolation between HV and low voltage circuit	1E-04
Shielded power cables	1E+00	Shielded power cables	1E-04
Common chassis for all components	1E+00	Common chassis for all components	1E-06
Manual service disconnect	1E-06	Manual service disconnect	1E-06
Unplugged battery connector(s)	1E-06	Unplugged battery connector(s)	1E+00
Use of HV protective gloves	1E+00	Use of HV protective gloves	1E+00
Isolated pole caps	1E-04	Isolated pole caps	1E+00
Finger proof connectors	1E-05	Finger proof connectors	1E+00
Work and safety instructions	1E-04	Finger proof connectors	1E-04
Training and certification	1E-04	Training and certification	1E-04
Total Probability	1E-49	Total Probability	1E-55

Table 5: Total Probability of HV Exposure

5 Conclusions

- 5.1 The example in chapter 4 demonstrates that a very high safety level is achieved for various use cases of the vehicle. It is observed that safety risk levels vary with feature activation and are influenced by usage context.
- 5.2 The methodology used in chapter 4 can also be applied to measure safety relative to high currents and thermal runoff.
- 5.3 Our findings demonstrate the efficiency of building safety by adding and cascading layers of protection rather than working solely on a single system.
- 5.4 Unlike what is sometimes seen in standards, the safety approach cannot be solely based on single failure mode.
- 5.5 We recommend adopting a complete safety approach in design that integrates and combines standards such as SAE J2910, FMEA analysis and risk calculations based on the safety features and systems inherent in the manufacturer's vehicle.

Author

Over the course of his career as an engineer, Jocelyn Lefebvre has cumulated several years of experience in transit bus design and engineering. He participated in the first bus electrification concepts and prototypes. As a member of the Volvo Group, he works as a technical leader and support engineer in the roll-out of the City Mobility program.

