

Flexible High Voltage Architecture for Commercial Hybrid Vehicles

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09/13/2011Matthew Busdiecker, Benjamin Saltsman and Douglas Hughes
Eaton Corp

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ABSTRACT

Architecting and integrating commercial hybrid electric vehicles (HEV) is a long and labor intensive process which is unique every time. The challenge intensifies when one attempts to create an HEV capable of engine-off operation. In this case, electrical power needs to be supplied to devices which are normally powered by the engine accessory belt. These devices are referred to as e-accessories.

To address the issue of time to market and reduce vehicle integration burden, a plug-and-play architecture for connecting e-accessories has been developed. The Flexible High Voltage DC System is analogous to a USB hub on a PC and serves to provide power, control and communication to e-accessories such as electrified power steering, electrified brakes and electrified HVAC. The system performs several key functions: 1) it delivers power to devices according to their demand; 2) if demand exceeds supply, it limits power according to priority (safety critical = highest priority) and 3) it is capable of isolating device failures without affecting remaining devices. The system also provides pre-charge and contactor diagnostic capabilities.

This approach has been demonstrated on a number of experimental vehicles and has been put in limited production. The paper will cover design development approach starting with Voice of the Customer, stakeholder needs analysis, prototype development, approach to interface standardization and will conclude with prototype testing and results.

INTRODUCTION

Vehicle integration for the automotive environment is a challenging endeavor for any manufacturer. Two trends have worked in the opposite directions: on the one hand, over the

years companies have streamlined their processes to bring products to market faster, yet on the other hand vehicle complexity has grown substantially making such integration tasks even more time and resource consuming. Hybrid vehicles take the integration challenges to the next level. Not only does the OEM need to be concerned with the traditional powertrain integration, but now the added hybrid system needs to fit in and work seamlessly with the rest of the vehicle systems.

For example, adding a propulsion hybrid system to the Freightliner M2 vehicle resulted in over four years of development and 2 million miles of testing (1). Yet another level of complexity must be mastered for more advanced hybrids, which shut off the internal combustion engine (ICE) for a portion of the duty cycle. This may be desirable during such events as idling or regenerative braking or during extended electric operation, as is possible with PHEV. In these more advanced hybrids the accessories can no longer be powered by the engine accessory belt and must be converted to electric power, drawing from the same energy source as the hybrid propulsion system. Electric accessories need to be connected to the high voltage DC (HVDC) electric bus and their controls need to be managed together with the hybrid propulsion system.

Today most existing hybrid systems for commercial vehicles are purpose built to serve a specific vehicle class and drive cycle, and have components that are not easily interchangeable. This narrow area of application has limited hybridization in the commercial vehicle market because of the difficulty and cost of developing solutions for the needs of each specific vehicle class. For example, in some cases a hybrid system with energy storage may not be of benefit. However, electrification of certain accessories may still be desirable. At present there is no framework that facilitates

building electrified commercial vehicles with standard components.

For these reasons, Eaton Corporation developed the Flexible HVDC System for hybrid vehicles, and at the foundation of the system is the junction box. The junction box provides standard connection points for accessories and provides communication and control of the accessories. Additionally, the junction box houses software to enable plug-and-play connection of electric accessories, priority setting, battery power management, fault isolation and circuit pre-charge.

FLEXIBLE HVDC SYSTEM CONCEPT

The concept of the Flexible HVDC System evolved from the realization that the work required to integrate HVDC devices into an HEV could be minimized if a common interface to the HVDC bus was established. A common interface specification for HVDC devices obviates, or at least minimizes, the need to design custom hardware and/or software for integration of devices into the HEV. More specifically, flexibility is defined as the ability to connect HVDC devices to the system without the need to modify hardware or software in the hybrid system. The key features of the concept are as follows:

- Enable **connection** of electric devices to the hybrid system using a standardized HVDC bus.
- Provide a **communication** method for interfacing with electrical devices connected to the hybrid system.
- Provide a means to adapt the hybrid **control** strategy to accommodate the connected devices.

The Flexible HVDC System concept was created from the perspective that the hybrid system is the primary provider and manager of HVDC power. In this conception, devices request power from the FSC (Flexible System Controller), which then allocates available power to the devices depending on their device type and priority. The concept requires a communication mechanism between the devices and the FSC for the purpose of exchanging power management information. The FSC is also responsible for controlling the power up and shut down of the HVDC bus. It was assumed that energy storage in the hybrid system would serve to control the bus voltage and enable devices to sink and source current into the bus without significantly shifting the bus voltage.

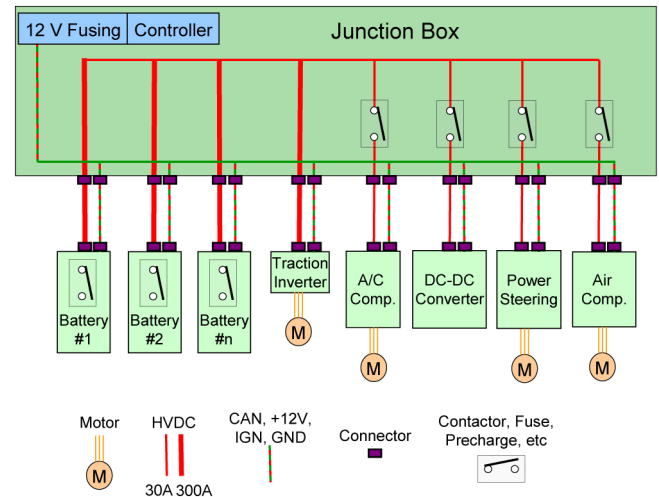


Figure 1. Schematic of Flexible HVDC System Concept

A high level illustration of the Flexible HVDC System is shown in Figure 1. For simplicity the HVDC bus is shown as a single line, although both positive and negative busses would be present in any real system. (A more detailed view of an individual channel is shown in Figure 2). In this view the junction box is the connection point of the HVDC, communication network, and low voltage wiring. A contactor, fuse, and precharge circuit are shown on the electric accessory connections inside the junction box. This illustration is one of many possible architectures of the Flexible HVDC concept, and does not prescribe that the system follows this structure (2). To elaborate further on the Flexible HVDC concept, some features of the HVDC interface that might be standardized are described in more detail below.

COMMUNICATION FOR POWER MANAGEMENT

As mentioned previously, a communication link between the HVDC devices and the FSC is needed to facilitate the exchange of power management information. On the communication link, a series of messages is transmitted between the hybrid system and the accessories. The messages are transmitted periodically, and each HVDC device has a unique address so it can be targeted as the destination of a message. The FSC transmits a specific message to each individual HVDC device and a broadcast message to all HVDC devices to communicate the global status of the HVDC bus. Similarly, each accessory transmits a message back to the FSC advising it of the device status and power request. Examples of data that might be contained in the messages follow.

1). FSC to device specific message (FSCtoDev)

a. Power limit - For each device, a power limit is communicated from the FSC to the device. The power limit has both an upper and lower bound to be compatible with devices that source power back into the bus (such as APU - auxiliary power unit).

b. Device priority - FSC provides the device with feedback indicating its priority in the hierarchy of the power management algorithm.

2). Device to FSC message (DevtoFSC)

a. Power Request - The device transmits this value to the FSC to request power allocation from the power management algorithm. If the device is supplying power to the bus, this value will be negative; effectively the device is asking permission to put power back onto the bus.

b. Actual Average Power - Devices report the average power consumed by the device to the HCM using this value.

c. Device Type - An example of device type is given in [Table 1](#).

Table 1. Type of devices possible on HVDC bus and their functions

Device type	Accessory Function
0 to 7	Steering, braking, or other critical chassis function
8 to 15	Power generation (120 VAC Hotel Loads)
16 to 31	Climate (for example, A/C compressor)
32 to 127	Other device

d. Load Dump Permission - The power management algorithm needs to know which devices are able to limit their power consumption to stay within the available power from the hybrid system. An example is an A/C system with a variable speed compressor. The compressor power can be reduced during times when the power could more advantageously be used by another HVDC device. Devices that are incapable of varying their power levels on demand, such as power steering, request an allocation of power that must be made available by the hybrid system, even at the expense of traction system performance.

Table 2. Categories of devices and their power requirements

Load Dump Permission Type	Description
Normal	Devices that can tolerate some reduction in power limit during periods when the total of power requests can not be met by the system, e.g. air conditioning compressor.
Excess power use only	Devices can request that the hybrid system supply any excess energy available to them. Excess energy is energy that would be stored in the traction battery if the device were not present. Useful for devices such as air compressors that have flexibility to operate over a large range of time.
Demand generation if needed	Devices can request that the hybrid system supply power under all conditions, even in situations that may require the hybrid system to generate power specifically for that accessory, e.g. electric power steering.

3). HVDC Bus Status Message (HBS)

a. Bus Status - The FSC reports the current operational state of the HVDC bus in the HBSBusStatus field. Devices use this information to sequence their internal operations. The value table below is an example of Bus Status values that might be useful.

Table 3. Examples of Bus Status values

Bus Status	Meaning
Initializing	The FSC is initializing.
Pre-charging HVDC Bus	The HCM is pre-charging the HVDC bus in preparation for closing the main contactors.
HVDC Bus Connected	The HVDC bus is connected, the device may begin to draw current.
Disconnecting HVDC Bus	The HVDC bus is in the process of being disconnected from the hybrid traction system.
HVDC Bus is Disconnected	The HVDC bus is disconnected from the hybrid traction system.
Fault	The HVDC bus has experienced a fault.

b. Bus Voltage - Where it is necessary to convert between power and bus current, this parameter should be used as the official conversion factor between current and power.

POWER MANAGEMENT ALGORITHM

A strategy has been developed for delegating HVDC power management to the Flexible System Controller. This strategy abstracts the HVDC devices so that the main hybrid controller is insulated from the details of individual devices, and instead sees all of the accessory loads as a single entity.

Using the messages described earlier, the power management algorithm uses the Device Type and Load Dump Permission Type parameters to prioritize the device. The FSC allocates power to devices in the following manner:

1). The Power Request of all devices with the Load Dump Permission Type set to “Demand generation if needed” will be summed. This sum will be used as an input to the hybrid control strategy. The hybrid system will attempt to maintain the requested power to these devices regardless of driving conditions or fuel economy considerations.

2). The FSC will create a list of all devices appearing on the network and sort this list according to the following rule:

- Devices with Load Dump Permission Type set to “Demand generation if needed” will appear first in the list. Within each sub category where Load Dump Permission Type is equal, the lowest value Device Type will appear first.

3). The FSC will allocate available power to the devices starting from the top of the list and work down to the lowest priority device at the bottom of the list.

HVDC ELECTRICAL INTERFACE

Regardless of the devices to be integrated, connecting devices into the HVDC bus requires a junction point for the HVDC cables. Due to the type of connectors used, fusing requirements, and safety implications, it is usually not practical to create a multi-branch wiring harness for HVDC distribution as is commonly done for LV wiring. This necessitates creating one or more junction boxes where HVDC connections are made. Once a junction point for HVDC cables is created it is then natural to include any necessary interface hardware inside the junction box. The internals of the junction box can be as simple as a ring terminal connection point, or as complex as an ECU with power electronics. From this perspective the junction box is the gateway into the hybrid system HVDC bus.

Standardization of the HVDC electrical interface is based on the idea that, for devices operating within a similar power range, it is possible to create a standard set of connectors that simplify wiring harness design in the vehicle. As shown in [Figure 1](#), the standard device connector set could include the HVDC connections and the low voltage and communication wiring as well. Since nearly all HVDC devices utilize the 12 volt vehicle electrical system for wakeup detection and controller power, the ability to route the entire device wiring to the junction box seems beneficial.

For discussion, one channel of the junction box concept is shown in [Figure 2](#). Note that in subsequent illustrations of the junction box this single channel architecture is repeated for each channel. This implementation of the concept has the following features:

1. Fusing to protect wires of different sizes.
2. Precharge circuit and voltage measurement to detect completion of precharge.
3. Main contactors for each channel allow sequenced connection of devices to the HVDC bus, and the capability to disconnect or prevent connection of faulted devices.
4. Contactor diagnostics - Provides diagnosis of stuck or welded contactors.
5. HVIL loop for accessory circuits.
6. Capability for current measurement.

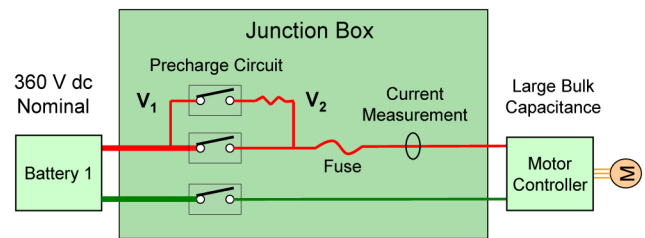


Figure 2. Single Channel of the Junction Box

STARTUP AND SHUTDOWN SEQUENCING

A standardized power up / enable sequence prevents devices from drawing current before the hybrid system is ready. Using the HBS message, the FSC informs the accessories of the status of the HVDC bus. By making use of the bus status information, the devices can coordinate power up with the hybrid system, and execute a graceful shutdown by reducing current draw to zero before the HVDC bus contactors are disconnected.

FAULT DETECTION AND ISOLATION OF FAULTED DEVICES

Including main contactors for each junction box channel enables the FSC to disconnect, or never connect, a faulted accessory. This feature has value for ensuring a reliable HVDC supply for critically important devices. For example, if an A/C compressor develops a chassis isolation fault, it is desirable to disconnect it from the bus, and preserve HVDC supply to more critical devices such as power steering/braking.

To prevent connection of known faulted devices, prior to HVDC bus power up, some mechanism for identifying faulted devices with a de-energized HVDC bus is envisioned. Diagnostics could be included in the devices to verify that each device is functioning properly before connection to the main HVDC bus. If a device knows that it is faulted, it could communicate this condition to the FSC, which would then not connect the device to the main HVDC bus. Another