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Power Net Topologies for HEVs and EVs – Aspects on Vehicle Integration for Different Powertrain Configurations on System and Component Level

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Abstract

One of the main challenges in developing hybrid electric vehicles (HEV) and electric vehicles (EV) is to integrate HV system and novel high power EE components. In comparison to conventional vehicle systems, safety standards which are not internationally harmonised yet have to be considered and strict EMC regulations need to be met. The required vehicle performance and the resulting powertrain configuration determines the traction voltage levels, the definition of the corresponding power range of traction components (electric machines, power electronics, energy storage) and finally the topology of the power net architecture. This paper focuses on vehicle integration aspects of HV power nets with modular approaches for different architectures considering partitioning, clustering and selection of HV components. All results are based on the experience of HEVs and EVs developed by MAGNA STEYR which cover different degrees of electrification: hybrid powertrains with high-end full four wheel drive, pure electric powertrain configurations as well as concepts with range extender systems.

Keywords: BEV (battery electric vehicle), electric drive, EV (electric vehicle), DC/AC inverter, PHEV (plug in hybrid electric vehicle), net topologies

1 Power Net Topology– A Systems Overview

Fig. 1 shows a universal scheme of a power net topology which is the base for all investigations in this paper. This architecture represents the highest possible generic approach with plug-in functionality with restriction to two installed high power electric drives. The second drive can be either a traction application (second driven axle) or a generator dominated drive e.g. a range extender system or generator unit for a series hybrid. Most of the architectures can be covered by two electric drives, e.g. in hybrid transmissions on component level, such as the e-CVT described in [1] and [2]. Both electric machines are situated in one module. That is why both inverters (DC/AC) are located next to each other or are even merged together. More power electronics are required if bidirectional or unidirectional DC/DC converters are connected to 12V or to other different HV levels. Furthermore the system consists of at least one energy storage system and the HV A/C component. Different HV loads and charger devices can be optional parts of the system.

In case of a modular approach, e.g. for separately located drives, the optimal solution according to efficiency, package, volume, weight, serviceability and costs has to be found. For interconnection of the HV components a sophisticated distribution system is necessary. The number of required connections and hence the complexity of the distribution depends on the number of module-integrated components.

The topology for pure electric vehicles and fuel cell vehicles is a subset of this overall schematic. Electric storage systems like batteries can be connected to the system directly or via a DC/DC stage. In case of a capacitor storage device a DC/DC converter is essential.

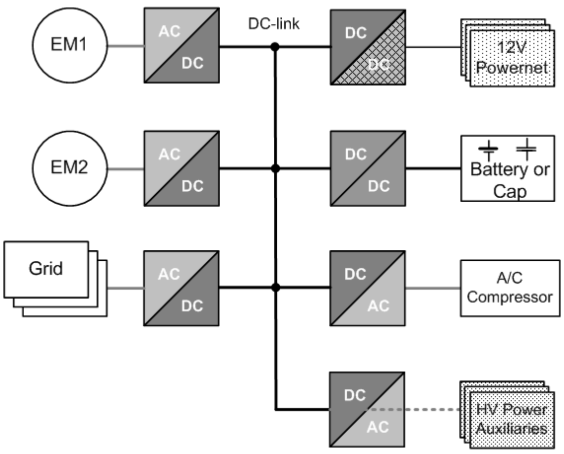

Figure 1: Basic schematic of a HV power net topology with two drives

2 Powertrain Configurations of MAGNA STEYR HEVs and EVs

Base for further considerations are power train configurations of vehicles that have been realized at MAGNA STEYR. All configurations have two electric drives with completely different characteristics and fields of application.

The modular design of the HySUV™ power train [3] represents a parallel hybrid drive combined with an electric front axle (see Fig.2a). This system has also the option to install only the parallel drive. Both electric machines are located within one module.

The second hybrid vehicle developed in the project Hi-CEPS [4] has two drives, one located in the front and one in the rear (Fig 2b). This configuration requires more effort to install an efficient topology and cabling. A DC/DC stage converts the low battery voltage level to the higher DC link for inverters and 12V DC/DC. The reasons for the low voltage battery are restricted package space and the dimensioning according to the power optimised performance. Nevertheless the HV DC/DC converter has the advantage of decoupling the battery from the inverter stage, and hence adds a safety aspect when using permanent magnet machines, because overvoltage on the battery side can be avoided.

Optionally a charger can be included for a plug-in version, but in that case an increased amount of energy is necessary.

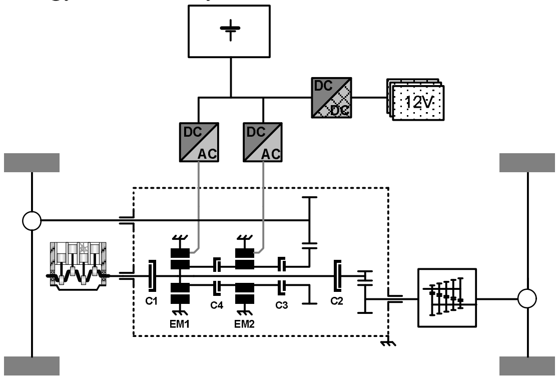

Figure 2a: Vehicle 1: HySUV™

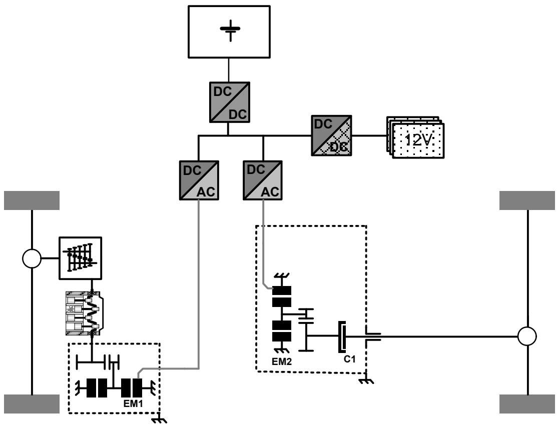

Figure 2b: Vehicle 2: Hi-CEPS (SP4000)

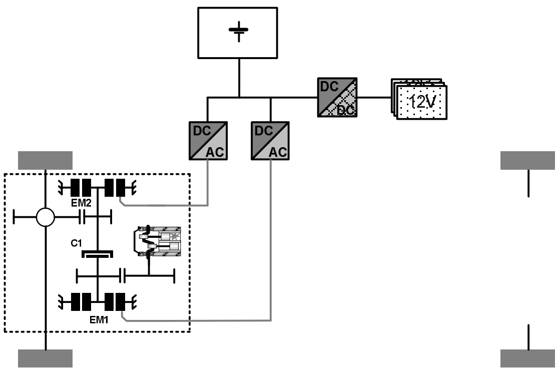

Figure 2c: Vehicle 3: MILA EV

Figure 2: Configurations of MAGNA STEYR prototype vehicles

The third configuration shown in Fig. 2c is an electric vehicle with range extender option called MILA EV [5]. The internal combustion engine can directly drive the front axle via a gearbox at higher speeds. Both drives are located in the front. The configuration also offers the option of an electric driven rear axle. This would be basically the same situation as in the Hi-CEPS vehicle (see Fig. 2b) but the electric machine would be used as primary drive.
All electric drives are powered by lithium-ion batteries developed at MAGNA STEYR [6]. Table 1 shows the main data for comparison. Vehicle 1 and vehicle 3 have a battery voltage range of approximately 200-400 V, which is a common voltage level using 600 V IGBTs. Vehicle 2 has a battery voltage range of 120-205 V. The DC/DC converter steps up the voltage by a factor of two for optimal utilization of the 600 V inverter semiconductors.

Table 1: Technical data of HV components

	Vehicle 1 HySUV™	Vehicle 2 Hi-CEPS	Vehicle 3 MILA EV
Battery Voltage Range [V]	250 – 430	120 - 205	250 - 400
Inverter DC – Input Voltage range [V]	250 – 430	240 -410	250 - 400
No. Inverter [kW peak]	2 50, 50	2 *) (double) 12, 24	1+(1) 70, 45
E-machine type	IM,IM	IPM,IPM	IPM
No. Charger 3.3 kW peak	-	(1)	1+1+(1)
LV – HV DC/DC 3.5 kW peak	1	1 *)	1
HV –HV DC/DC 40 kW peak	-	1 *)	-
Cell type	Graphite/ $LiNiAlO_2$	Graphite/ $LiFePO_4$	HC/ NMC
Battery peak power [kW peak]	67	40	70
Battery energy installed [kWh]	2.6	1.2	21
HVDU type	battery integrated	battery integrated	Stand-alone/ battery integrated

*) integrated in one power electronics box
( ) options

2.1 Generic approach of topologies

Based upon Fig. 1 and the different EV and HEV topologies presented in Fig. 2 a generic power net topology can be derived. Fig. 3 shows the results for all topologies. The three- phase cabling between e-machine and inverter depends on the distance of these components. Attached inverters have short bus bars to the terminals of the e-machine windings, long distances are covered by three shielded single pole cables.

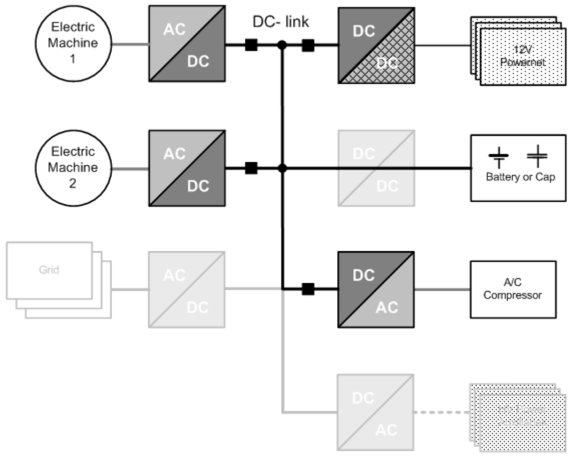

Figure 3a: HySUV™

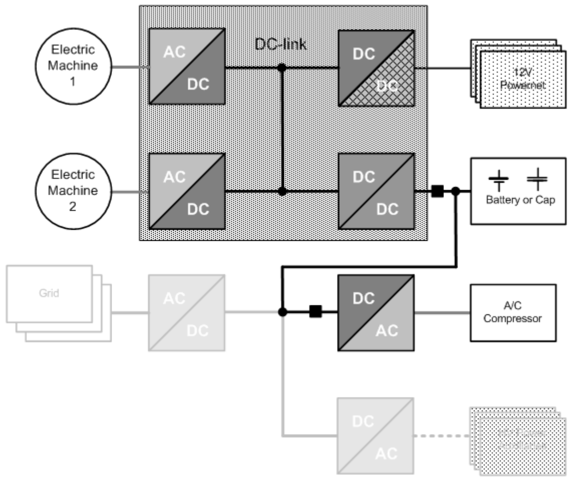

Figure 3b: Hi-CEPS

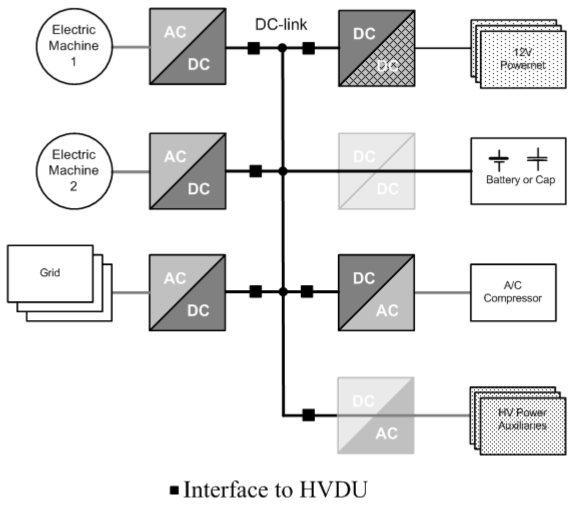

Figure 3c: MILA EV

Figure 3: Generic overview of MAGNA STEYR power net topologies

More importance is allocated to the cabling of the DC link. Considering different topologies it is obvious that several components can be integrated into one module. This makes the power net less complex but shifts the complexity towards component design and integration.

2.2 Packaging of the HV Power Net

The main challenge for the package of the HV wiring harness is passenger safety. The following aspects have to be considered:

- Crash area free of HV wiring
- Crash detection and immediate shutdown
- Measures against accidental contact
- Ground fault monitoring
- Prevention of disconnect under power (arc suppression)
- Orange marking of HV wiring harness and double insulation according SAE J1673
- Safety concepts, e.g. interlock

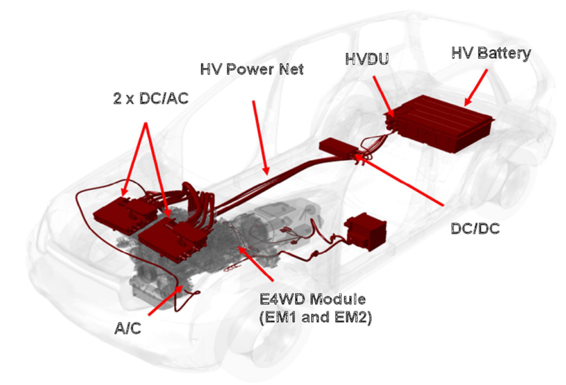

Figure 4a: HySUV™

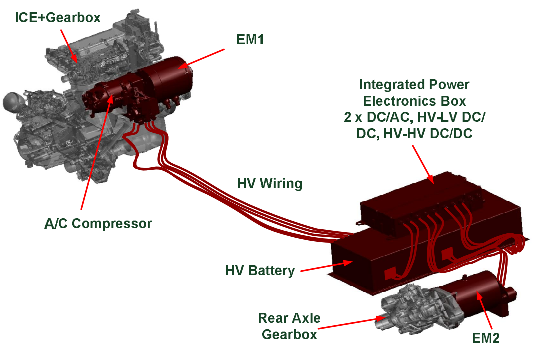

Figure 4b: Hi-CEPS

Fig. 4a-c show the DMU of the HV systems for the vehicles 1-3.
Although the HV wiring harness is usually shielded, it has to be packaged appropriately to avoid any EMC problems.

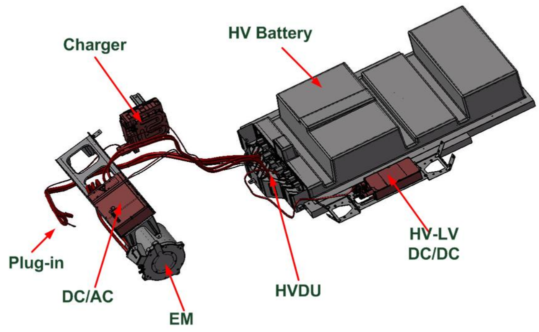

Figure 4c: MILA EV without REX module

Also environmental conditions like temperature, humidity and vibration have to be taken into account for the package.
Common issues concerning the assembly of the HV cables are

- Optimization regarding minimal cable length
- Optimization regarding diameter and losses
- Innovative conductor and insulation materials
- Mechanical boundaries like bending radius (r = 4d)
- Cable terminals (bolted or mated connector types)

2.3 Power Net Distribution

The dimensioning of the HV system is determined by the current load profile of the components. The resistance of a typical cable, e.g. 25 mm^2, is 0.75 mΩ/m. For a moderate continuous power of 25 kW "only" a few W/m occur. More important criteria is the reduction of cable lengths because of high copper weight (for single pole 25 mm^2 approx. 0.3 kg/m!) and moreover the resulting costs (e.g. copper price at stock exchange 3.72 €/kg [11]).
Components connections can be realized as bolted or mated (plug) design. The superior solution is a mated connection but this is very cost intensive and needs space for plugging. Special flexible interface adapters can be foreseen to allow the use of different mated connector types.
Due to interlock reasons usually connector systems are also used for the central distribution box or connector board so-called High Voltage Distribution Unit (HVDU). Fig. 5 shows a general scheme of a full version with an external charger connection for off-board charging the battery. Modular HVDUs make sense, primarily to add fused HV ports for low power auxiliaries (< 5kW).

The numbers of such HV loads can vary in a wide range especially for EVs and FCVs. The HVDU can be realized as a simple component without any complex electronic circuits. The HV electric energy storage system takes over the monitoring of the complete HV power net. The battery system can be disconnected via the two-pole power switches for regular operation and shut down in failure conditions. Basically the functions are preload, over-current, over-voltage, ground fault detection and charging management on battery relevant level.

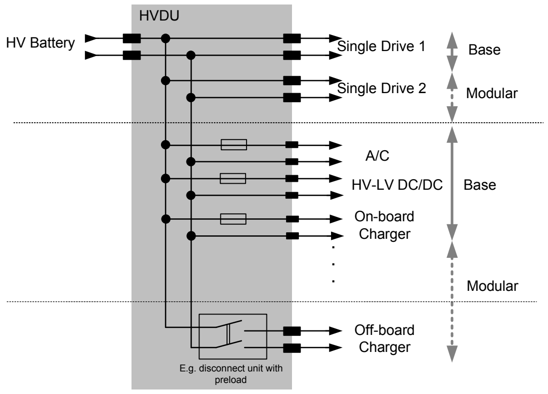

Figure 5: General scheme of a HVDU

Disconnect devices and additional preload circuits for external charging have to be provided off-board.
Battery integrated HVDUs with plug connectors are used for vehicle 1 and vehicle 2 (see Fig. 6a).

Figure 6a: Version / HySUV™ and a similar concept for Hi-CEPS

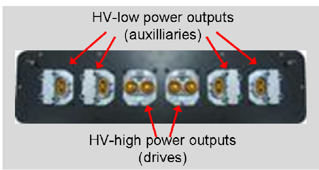

Figure 6b: Design examples for the HVDU

These are production orientated versions. Two HVDU versions are available for vehicle 3. Fig. 6b (on the left) shows the "quick and dirty" stand-alone solution which is used for MULE vehicle installations. Variant 2 (Fig. 6b on the right) is a prototype for battery integration with modular design and plug connectors.

3 Aspects on System Partitioning

3.1 Voltage Level

The voltage level is determined mainly by the power rating of the installed drives, by availability of semiconductor devices and by the modularity of the battery system.
The use of a traction DC/DC converter like in the Hi-CEPS vehicle allows different voltage levels on the battery side and on the DC-link side. A higher voltage level in the DC-link reduces the ohmic losses in the e-machine at the cost of an additional element in the efficiency chain. It has to be verified by means of calculation/simulation whether the overall efficiency is increased by the use of the DC/DC converter. Investigation results in [7] based upon one drive topology show that the installation of a traction DC/DC has small cost disadvantages on components level (stand-alone). The difference can be reduced if the battery voltage deviation is higher (in particular system related at super capacitors) or higher degree of integration (e.g. common use of filter circuits). Aspects on vehicle system level are cost reduction due to constant voltage for other HV loads and optimal positioning of the traction DC/DC (cabling efforts). Applied to the two drives topology it depends strongly on the cycles of both drives. For hybrid application were the battery is not involved permanently e.g. in e-CVTs or systems with series hybrid capabilities it is an advantage to step up the already low battery voltage to higher levels – in case of the Hi-CEPS configuration only with a factor of two due to relatively low installed power and selection of commonly used 600V IGBTs.

3.2 Cooling Circuits

Most of the involved HV components have completely different cooling requirements (see Table 2). The power electronics components require water/glycol coolant with low inlet temperatures at moderate flow rates. Regarding the harmonization of the different cooling circuits, the HV components can be housed within one mounting case hence reduction of piping and numbers of interfaces. This integrated box consisting of such stand-alone components is the advanced solution for EVs. This concept gives you the potential of an integrated system without losing

the modularity on components level. From the electric point of view the HV distribution is shifted towards to an internal wiring. EMC efforts can be reduced dramatically due to shared filter circuits.
Because the battery has to be low temperature-conditioned, a clustering with other power electronics components is not useful. A battery module integrated charger can be an option due to functional reasons.
Basically the e-machine can be operated at higher temperature. E-machines can be cooled combined with the ICE at HEVs. For energy density dominated applications like EVs the e-machine is cooled together with the power electronics cooling system because of the lower temperature level.

Table 2: Typical technical data for cooling the HV components for the three vehicles

	Type Cooling	Coolant inlet temp. level [°C]	Flow Rate [l/min]
Battery	climate control liquid/air	25 - 35°C	4-16 *)
Inverter	liquid	65-70°C	8-12
E-machine	liquid	65-70°C	8-12
HV – HV DC/DC	liquid	65-70°C	8-12
LV – HV DC/DC	liquid	60°C	4-6
Charger 3.3 kW peak	liquid /air	60°C / 40°C	4-6

*) wide range depending on battery system

3.3 Example for Integration on System/Components Level – On/Off-board Charger for EVs

The integration of a charger in an EV topology depends on the grid, the battery system, charging capabilities of the battery, available power from the grid and cooling concept for charger and batteries. There are concepts for onboard charger for charging from the standard grid outlets and concepts for quick charging units with enhanced external chargers. Basically both concepts can be mixed in an EV vehicle, whereas for an EV an on-board charger is the minimum equipment.
Fig. 7 shows the architecture of an EV that is available on the market based on the generic scheme. The charger unit rated at 3.3 kW is one sub-module of a combined unit which also includes the HV-LV DCDC converter and the traction inverter. This concept simplifies the cooling system and the HV wiring harness and hence decreases the costs for the HV system. A user interface device between vehicle's plug-in socket and grid, handles safety issues (GFI) and gives possibilities for setting modes and indicating charging power.

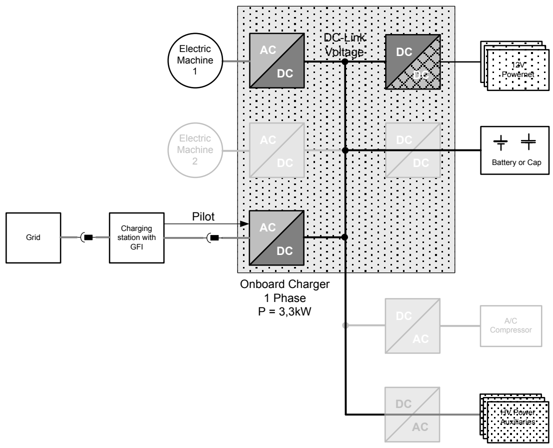

Figure 7: Topology of a series EV, embedded on-board charging system

Fig. 8 shows the more detailed topology for the MULE vehicle MILA EV. To halve charging periods the installed charging power is now 6.6 kW. Two chargers with each 3.3 kW are connected to two phases of the three phase 400V AC grid. The combined chargers are connected via the HVDU to the HV battery system. There is the possibility to charge from 230V AC system with one phase and from 400VAC with two phases by using different cables.
Development target is a standardised coupler (consisting of a connector and vehicle inlet) complying with the supply systems. The coupler can be used for common supply outlets from home and public stations

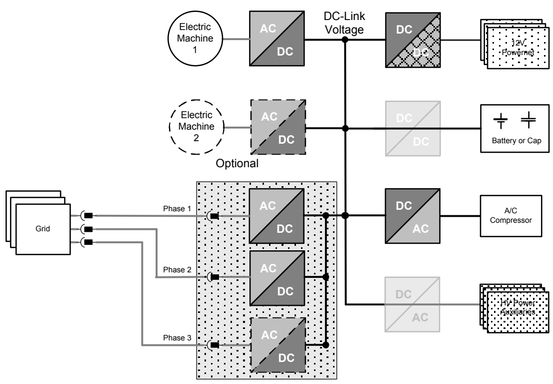

Figure 8: MILA EV charging concept

Finally this concept can be enhanced to three charger units on three different phases. All three chargers can be combined to one module to save in packaging and cooling efforts. Consequently optimisation leads to a well-designed highly

integrated three- phase on-board charger with input rectifier. This charger can be operated at the three phase 400V grid fused by 16 A. This complies with vehicles requirements standard AC Level 2 [8, 9].
Fig. 9 represents a concept using the traction inverter as an on-board charger. During charging procedure windings of the e-machine are separated from the HV system. This is an advantage for safety issues, but requires an additional multi pole switch on-board.
Due to the high three phase grid voltage 1200V IGBTs are necessary for the power electronics. The concept without DC/DC converter is based on a battery voltage level from at least 540V. A nominal battery voltage of e.g. 700V increases the effort for the lithium ion battery system because the double number of cell supervising circuits is needed. The inverter topology implies bidirectional energy flow (V2G functionality). All HV loads have to be connected to this enhanced voltage level or these components have to be fed via a separated DC/DC converter. Optional an additional HV DC/DC converter transforms the power rating of the battery to a conventional voltage level for the battery and the remaining HV components. Preferred application is the small EV with the peak power of approx. 50 kW.

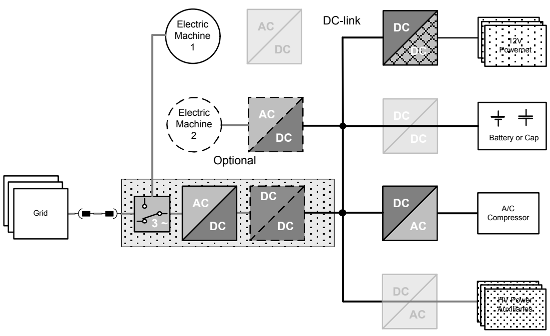

Figure 9: Example: on-board charger integration using the inverter

In general the off-board charger is connected to the vehicle via a DC link. This charger has full functionality to ensure the requested charging currents and voltages. Optional the charger can be separated in two functional units (see Fig. 10). All infrastructural parts are off-board. On-board there is only a DC/DC converter which operates supplies the battery according to the required current/voltage characteristics. The corresponding DC link between grid and vehicle can be operated at a constant, standardised voltage level.

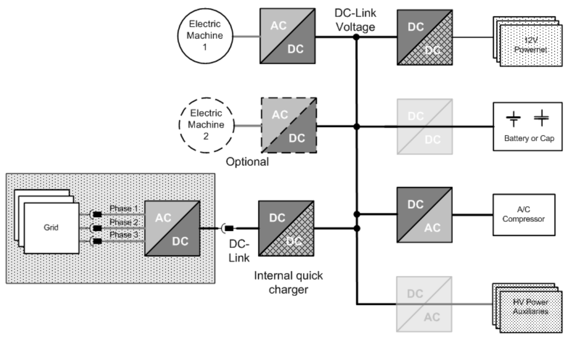

Figure 10: Concept for external charging (combination of on-off board)

3.4 Example for Integration on System// Components Level – Exchangeable Energy Modules for EVs

3.4.1 Exchangeable Range Extender Systems

The MILA EV optionally includes a REX system which is installed permanently in the vehicle. A smaller power version (APU variant) can also be an exchangeable system. From the HV wiring system point of view the REX system is an autonomous black box docked to vehicle's DC link. The partition on components and system level is clearly defined in Fig. 11.

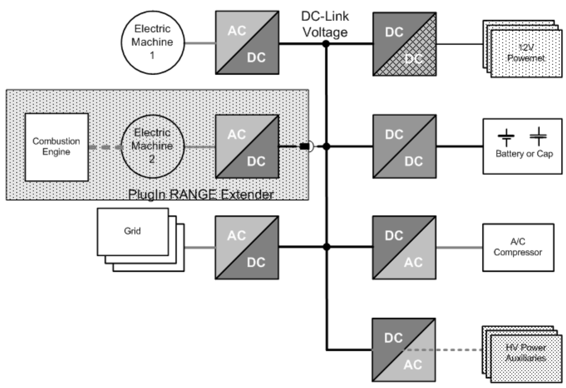

Figure 11: Example Exchangeable Range Extender Systems

3.4.2 Exchangeable Electric Energy Systems

Following the idea of an exchangeable system, the installed electric energy storage can be configured. In this case each exchangeable module has to be compatible to vehicles DC-link via a bidirectional DC/DC converter (see Fig. 12).

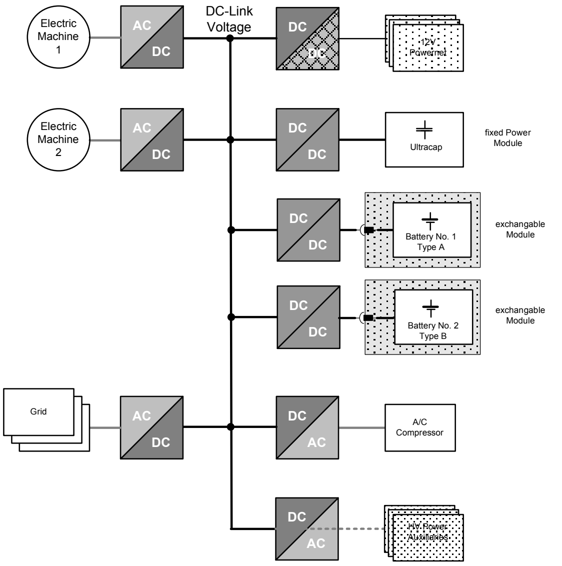

Figure 12: Example: Exchangeable battery modules

If the modularity is increased by using exchangeable systems, a highly sophisticated power distribution is required to provide the necessary ports for different powertrain architectures.

4 Considerations for EVs – Coming from the upper level

4.1 IMC

Following the idea of exchangeable modules, and scalability of EVs the maximum degree of freedom for packaging from the complete vehicle point of view is to develop a completely new flexible platform. Fig. 13 shows this concept called IMC. The target is compatibility for different carry-over bodies. It has a changeable, flexible powertrain, either pure electric or with REX. The IMC concept consists of the space frame, powertrain, chassis, heating/cooling system, the energy storage system and an intelligent vehicle controller.

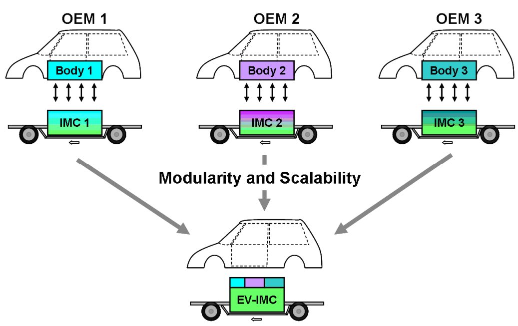

Figure 13: Innovative Module Concept for EVs

The compatibility between the rolling chassis and carry over body requires a new definition for either modules or mechanical and electrical interfaces. It is desirable to minimize the number of interfaces and to optimize functional partitioning. Thereby the IMC has standardized interfaces to assemble other modules and different vehicle bodies. The target is to get more autonomous modules.

5 Summary

The paper describes some aspects of different power net topologies and problems encountered on system and component level regarding the aspects of vehicle packaging. Based on vehicles developed by MAGNA STEYR a generic approach is introduced to identify optimised geometric integration. The package strongly depends on the powertrain configuration and vehicle class and affects the complete EE architecture of the vehicle. The key issue is to find the trade-off between the development of the HV system and the components or modules. An extreme clustering of components tends to restrict the flexibility and scalability for other topologies.

1. HEV Integration
When hybridising an existing vehicle package space for components is very restricted. A common solution is to use single components spread all over the vehicle. In that case the HV wiring harness is very complex. On component level clustering the LV-HV DC/DC converter and the AC/DC inverter can reduce complexity. (see Table 3).
In particular for the HySUV™ vehicle concept a possible optimisation is to attach the inverters directly to the windings of the e-machine [10]. As a result the HV wiring is reduced (one three phase cable less) but complexity is shifted to the component level.
For the Hi-CEPS vehicle a maximum optimisation has been achieved. The power electronics is a highly integrated electrically merged module. This is a common application derived from hybrid transmissions (see Table 3, VI). This entails a maximum degree of integration on component level. For the system only one additional connector has to be installed at the battery housing for A/C. The HV wiring is reduced to a minimum.
Generally the expensive stand-alone HVDU should be avoided. The optimum solution is a battery integrated distribution unit.

2. EV Integration

For a single e-machine topology the combined power electronic module with single components inside is the most efficient solution (see table 3, II). The module has to be located as near as possible to the e-machine. Two e-machine topologies for EVs are characterized by a modular approach.

Table 3: Summary of system partitioning including MAGNA STEYR vehicles

Level	Battery	Power electronics					HV-loads (Auxiliaries)		HVDU [1])
		DC/AC	HV-LV DC/DC	DC/AC	Onboard charger	HV-HV DC/DC	A/C	others	Connections
I	1	1	1	-	-	-	1	-	2
II	1	1	1	-	1	-	1	-	2
III	1	1	1	-	1	-	1	x	2+x
IV	1	1	1	1	-	-	1	-	3
V	1	1	1	1	1	-	1	x	4+x
VI	1	1	1	1	-	1	1	-	2
VII	1+x	1	1	1	1	1+x [2])	1	x	2+xxx

[1]) preferred battery integrated unit
[2]) optional integrated
(dotted box) Module with combined single modules
(solid box) Module highly integrated

- I Single drive
- II I + on board charging capability (e.g. MILA EV without REX)
- III II + other HV loads
- IV Two single drives (e.g. HySUV™)
- V IV + on-board charging capability + other loads (e.g. MILA EV)
- VI IV + controlled DC link voltage (Hi-CEPS)
- VII VI + exchangeable battery modules (IMC)

Single scalable components should be shared for different EV applications following the IMC idea. Especially the on-board charger dimensioning is under discussion. In particular the complete merger of two inverters to a double inverter is necessary, e.g. for tandem or hub drives due to safety reasons.

In the concept phase a systemic investigation can help to show all relevant aspects for power net topologies to get a cost optimized solution for series production.

Especially new approaches for battery driven electric vehicles have a lot of synergy potential. The innovative modular concept for power train platforms with defined interfaces to the body offers the OEM a cost-efficient alternative to an in-house development.

The generic approach is a method to design power net topologies according to optimised functionality, costs, efficiency, weight and volume. MAGNA STEYR is pushing HEV and EV development with innovative concepts. An intensive cooperation with component developers is necessary to realize these concepts. Together with MAGNA POWERTRAIN and MAGNA ELECTRONICS, MAGNA STEYR is a key player in vehicle integration of EE net structures with cost-optimized modular systems and components.

Abbreviations

A/C	Air Conditioning
AC	Alternating Current
APU	Auxiliary Power Unit
BMS	Battery Management Systems
BEV	Battery Electric Vehicle
C	Clutch
DC	Direct Current
DC/DC	Direct Current Converter
DC/AC	Inverter
DMU	Digital Mock Up
E-CVT	Electrical Continuous Variable Transmission
EE	Electric/Electronic
EM	Electric Machine
EMC	Electromagnetic Compatibility
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GFI	Ground Fault Interrupt
HEV	Hybrid Electric Vehicle
Hi-CEPS	Highly integrated Combustion Electric Propulsion System: EC funded integrated project; here: SP4000 vehicle
HV	High Voltage
HVDU	High Voltage Distribution Unit
HySUV™	Hybrid Sports Utility Vehicle (TM by MAGNA STEYR)
ICE	Internal Combustion Engine
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Machine
IMC	Innovative Module Concept
IPM	Internal Permanent Magnet Machine
LV	Low Voltage
MILA	Magna Innovative Light Automobile
REX	Range Extender
OEM	Original Equipment Manufacturer
V2G	Vehicle to Grid

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