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DESIGN CONSIDERATIONS OF HIGH VOLTAGE BATTERY PACKS FOR ELECTRIC BUSES

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ABSTRACT
The use of electric vehicles (EV) is gradually increasing worldwide. The battery system, which is the heart of the EVs, consists of cells, battery modules and battery packs that are realised by combining battery modules. A battery management system is employed to control and protect the cells in these battery packs. However, battery systems become the most important bottleneck of electric vehicles during vehicle development phase because of high amount of the battery system costs. This increases the total vehicle cost and inhibits to compete with internal combustion engine vehicles.

In this paper, the design parameters and design production processes of battery packs were explained clearly. Especially, the commercial type of battery pack design is underlined. Also, the academic side of researches about electric buses battery design are given. The major contribution of the paper is the detailed explanation of commercial vehicle battery pack design.

INTRODUCTION
There are a few number of papers in literature about battery packaging. However, there is no particular explanation about design parameters of battery packs in these articles. Some of the mentioned battery pack design processes are belong to railway applications. The paper reports about lithium batteries in a cable railway plant, by presenting the design phase and the starting field tests [4].

Also, there are too much paper about design of electric cars battery in literature. The modular battery design for electric cars was mentioned in some articles [2]. Not only the electric car, but also the battery pack design of motors were reviewed in literature. The design and construction of a 9 kWh battery pack f a motorsports application is reviewed as an example [6]. The electric buses requires more power than motors and passenger cars because of their size, so battery pack design for electric buses is quietly different from other vehicles. In this paper, the focus point is battery pack design of electric buses as commercially. In every article, the importance of selecting the cell type and battery chemistry is emphasized. In this paper, the focal point is battery pack design of electric buses as commercial. As a summary, the commercial side of design is not mentioned in literature up to now.

DESIGN, PROTOTYPE PRODUCTION AND TESTS OF BATTERY PACK
There are three types of battery that used in electric vehicles. These are called as **prismatic**, **cylindrical** and **pouch** according to their shapes. Example of these three different type cells are seen in Figure 1.

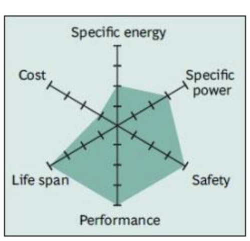
a) Prismatic b) Cylindrical c) Pouch

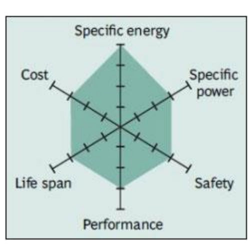
Figure 1: Cell Types

Generally, prismatic cells are being manufactured with $LiFePO_4$ chemistry but in cylindrical cells LiNMC is preferred. For pouch type cells, $LiFePO_4$, LiNMC and LiTitanate chemistry can be used. Prismatic cells are constituted by packing of pouch type cells in factory. Essential part of prismatic cells which sold in the market are manufactured with $LiFePO_4$ chemistry.

Battery chemistry is separated from each other in a point of specific energy, specific power, safety, performance, lifespan and cost features. In Figure 2, these features of LiTitanate, LiNMC and LiFePO4 battery chemistry are compared. While LiNMC chemistry have highest specific energy, LiTitanate have lowest specific energy. This means, maximum battery capacity for constant weight is obtained with LiNMC chemistry. When the specific powers are compared, it seen obviously there is no important difference between battery chemistries. In terms of safety, LiTitanate and $LiFePO_4$ get higher marks and LiNMC take lower place of them. It’s known that the security features of LiNMC are improved with latest researches. In performance comparison, while the LiTitanate is in the forefront but LiNMC and $LiFePO_4$ take place in lower position. Actually, the lifespan comparison graphic isn’t enough for making any comment. While LiTitanate cells can supply 20.000 life cycle, $LiFePO_4$ supplies 3000 – 4000 cycle and LiNMC supplies 1000 – 2000 cycle. Hence, LiTitanate cells appear as most expensive cells. LiNMC and $LiFePO_4$ have approximately same cost.

a) Lithium Titanate (LTO) **b)** Lithium Nickel Manganese Cobalt Oxide (LiNMC)





c) Lithium Iron Phosphate ($LiFePO_4$)

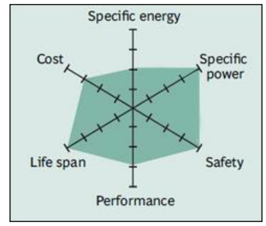


Figure 2: Comparison of battery chemistry
(http://batteryuniversity.com/learn/article/types_of_lithium_ion)

The important technical specifications of battery chemistries are listed in Table 1. The nominal voltages of batteries determine the number of required series cells used in battery packs. As an example, if it assumed that equal capacity cells are used for making a 300 V battery pack, approximately 130 Li-Titanate cells are required. However if Li-NMC chemistry is preferred, this number drops to 81. Also, if the $LiFePO_4$ chemistry is chosen, 94 cells are required for the pack.

Table 1: Comparison of battery chemistry

	Li-Titanate	**Li-NMC**	**$LiFePO_4$**
Nominal Voltage	2.3 V	3.70 V	3.20 V
Maximum Voltage	3.0 V	4.15 V	3.65 V
Minimum Voltage	1.5 V	2.70 V	2.50V
Nominal Discharge Current	1 C	2C	0.5 C
Maximum Discharge Current	4 C	3C	2 C
Nominal Charge Current	1 C	2C	0.3 C
Maximum Charge Current	4 C	3C	1 C
Life Cycle	15000-20000	3000-4000	1500-2000
Operating Temperature (Charge)	Between -30 and 45 C	Between 0 and 40 C	Between 0 and 40 C

In table 2, the information about batteries which is in sale on the market and the possible procurable are summarized.

Manufacturer	Capacity	Chemistry	Type	Weight	Life Cycle	Operating Temperature
A123	14 Ah	LiFePO4	Pouch	0.51 kg	> 1000	Between -30 and 55 C
	20 Ah	LiFePO4	Pouch	0.5 kg	> 1000	Between -30 and 55 C
	2.5 Ah	LiFePO4	Cylindrical	0.076 kg	> 1000	Between -30 and 55 C
CALB	20 Ah	LiFePO4	Prismatic	0.66 kg	> 2000	Between -20 and 55 C
	22 Ah	LiNMC	Pouch	0.51 kg	> 3000	Between -20 and 55 C
	40 Ah	LiFePO4	Prismatic	1.5 kg	> 2000	Between -20 and 55 C
	60 Ah	LiFePO4	Prismatic	2 kg	> 2000	Between -20 and 55 C
	72 Ah	LiFePO4	Prismatic	1.9 kg	> 2000	Between -20 and 55 C
	100 Ah	LiFePO4	Prismatic	3.4 kg	> 2000	Between -20 and 55 C
	180 Ah	LiFePO4	Prismatic	5.7 kg	> 2000	Between -20 and 55 C
	400 Ah	LiFePO4	Prismatic	13.6 kg	> 2000	Between -20 and 55 C
BestGo	10 Ah	LiFePO4	Pouch	0.255 kg	> 3000	Between -20 and 55 C
	15 Ah	LiFePO4	Pouch	0.38 kg	> 3000	Between -20 and 55 C
	8 Ah	LiNMC	Pouch	0.17 kg	> 3000	Between -20 and 55 C
	10 Ah	LiNMC	Pouch	0.235 kg	> 3000	Between -20 and 55 C
	14 Ah	LiNMC	Pouch	0.275 kg	> 3000	Between -20 and 55 C
Sinopoly	40 Ah	LiFePO4	Prismatic	1.5 kg	> 2000	Between -20 and 55 C
	60 Ah	LiFePO4	Prismatic	2 kg	> 2000	Between -20 and 55 C
	66 Ah	LiFePO4	Prismatic	2.1 kg	> 2000	Between -20 and 55 C
	100 Ah	LiFePO4	Prismatic	3.15 kg	> 2000	Between -20 and 55 C
	200 Ah	LiFePO4	Prismatic	5.9 kg	> 2000	Between -20 and 55 C
	300 Ah	LiFePO4	Prismatic	9.6 kg	> 2000	Between -20 and 55 C
	400 Ah	LiFePO4	Prismatic	14.4 kg	> 2000	Between -20 and 55 C

Samsung	60 Ah	LiNMC	Prismatic	-	-	Between -20 and 55 C
	94 Ah	LiNMC	Prismatic	-	-	Between -20 and 55 C
	2.6 Ah	LiNMC	Cylindrical	0.048 kg	> 1000	Between -20 and 60 C
Lec	30 Ah	LiTi	Pouch	1.1 kg	> 15000	Between -20 and 60 C

Table 2: Procurable battery cells in the market

When designing a battery pack, the most suitable cells will be determined by evaluating the alternatives in Table 2 and the other alternatives which may occur during design. After that, the charge and discharge tests will be done per cell basis. This tests will let to validate the data given in the specs of the battery cells.

There are many parameters that must be taken into account in design of battery packs. The determination of optimum combinations of these parameters constitute the main subject of the battery pack design. Regardless of the cell types, the basic parameters must be considered in pack design are listed below:

- **Cell Capacity:** The cells are provided in different capacities according to their type and chemistry. Therefore, the determination of most suitable cell capacity is very important for obtaining required battery capacity.
- **Cell Chemistry:** The cell chemistry determines the number of cells in series and directly effect the pack size.
- **Placement of cells (horizontal or vertical):** Cells can be positioned in a pack horizontally or vertically and manufacturer's directives must be considered while determining the orientation of cell. This placement directly affect the volumetric design of battery packs.
- **Climatization Requirements (ventilation with air or liquid):** The vehicle can be operated in +40 °C temperature. It is obvious that if the ventilation doesn't enough for cells, the temperature of cells can rise up to +40 °C temperature. For this reason, to prevent the damage of cells and loss of performance, cells need to be climatized. The air or liquid cooling methods can be used in cooling of battery packs.
- **Pre-heating requirements (air, liquid or electrical preheat):** It is expected that vehicles can be operated in -20 °C temperature. However, there is no battery chemistry that can operate under this environment conditions. Therefore, preheating methods must be examined and suitable techniques must be selected.
- **Support elements for stabilisation of batteries (plastic or metal, paracellular pieces):** Support elements are needed for stabilisation of cells in modules.
- **Cables, busbars:** It must be analyzed that how it is made the connections between cells and modules with most suitable shape and method.
- **Safety Requirements**: The position of fuse, contactor and other auxiliary protection equipments which are required for protection of packs and modules must be examined in detail.
- **Pack Weight:** The weight of packs must be limited at certain value in order to increase mechanical strength and servability of packs.
- **Welding methods:** The welding methods that are used for packing of cells directly affect the lifespan of cells and modules. Therefore, the welding methods must be researched broadly.

The main operations that used for design and development of battery packs with different type cell are given below.

DESIGN AND DEVELOPMENT OF BATTERY PACKS WITH PRISMATIC CELLS

It is easier to develop the battery pack mechanically from prismatic cells however it causes some problems while assembling on the vehicle. In Figure 3, an example battery pack made by prismatic cells is given.

There are series and parallel cells in this pack, the voltages of series cells are measured by Battery Management Unit (BMU) and the temperature information is given from three different points of pack. Also, there is a fuse for protection and fans for ventilation of the pack. BMU controls the ventilation fans.

Figure 3: Example battery pack made with prismatic cells

DESIGN AND DEVELOPMENT OF BATTERY PACKS WITH CYLINDRICAL CELLS

Although it is difficult to develop the battery pack with cylindrical cells, most efficient volume and minimum cost can be achieved with this type. The success of Tesla depends on using of these cells and it is a very good example about cylindrical cells. In Figure 4, 85 kWh, 400 V (max) Tesla Model S battery pack is shown. Tesla put the all batteries into one battery pack that is located under the vehicle but battery pack is deployed as battery modules. Tesla is currently using the Li-NMC chemistry and battery pack consists of 96 series cells and 74 parallel. Hence, totally there are 7.104 cylindrical cells in the battery pack that seen in picture.

Figure 4: Tesla Model S battery pack

Tesla Model S Battery pack is realised by connecting 16 battery modules in series. It is seen obviously from Figure 4, there are 2 overlapping modules at the frontmost. There are 6 series and 74 parallel cells in each module. The top view of module is given in Figure 5. The own BMS card is available on each module.

Figure 5: Model S battery module

Cooling of module is achieved by a method developed by Tesla. A cross-section of this system is shown in Figure 6. The cells are climatized by a flexible duct that passes around cells. The cooling liquid flows through this duct.

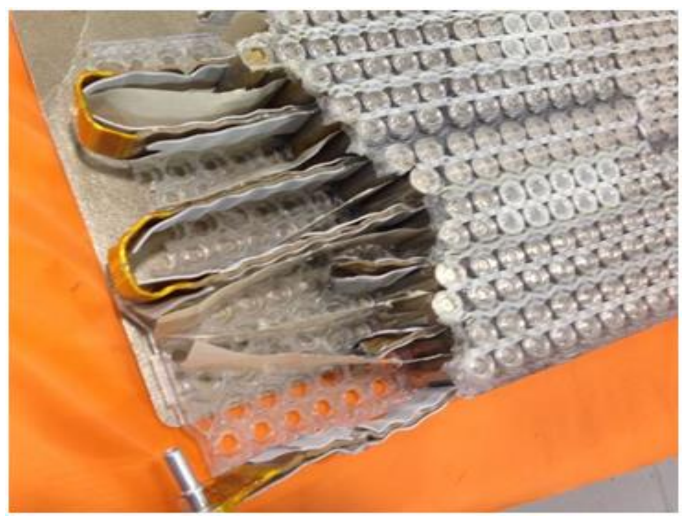


Figure 6: Tesla battery module ventilation method

Tesla's success depends on utilization of batteries in the most efficient way. The use of same structure in commercial vehicle will provide significant decrease on vehicle cost. Also, the easiness of packing will be the other advantage of this case. The biggest disadvantage of using cylindrical cells is low cycle life. The battery packs that consists of cylindrical cells can be implemented by gathering up modules in a similar approach. The battery capacity is very bigger than Tesla, so more than one pack should be developed instead of single pack.

The laser welding technology could be used for assembling of cylindrical cells. This technology allows quick welding without heating the batteries. The resistive welding is another alternative for battery module assembly.

DESIGN AND DEVELOPMENT OF BATTERY PACKS WITH POUCH CELLS

Prismatic cells are made by gathering and packing of pouch cells by battery manufacturer and these cells are covered with plastic or aluminum enclosure. However, the use of factory assembled prismatic cells decrease the design flexibility during placement of battery packs. The use of pouch cells directly in battery assembly allows production of lighter and thinner packs or modules. The battery modules that is realised with pouch cells by several manufacturers are in sale in the market. In Figure 7, Enerdel battery module is cited as an example.

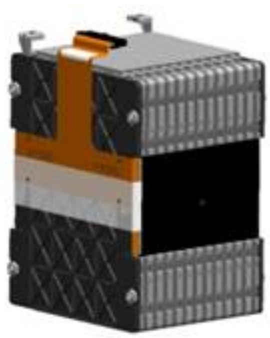


Figure 7: Enerdel's battery module

Enerdel battery module has 35 Ah and 44,2 V nominal voltage capacity. There are 12 series and 2 parallel branch that consists of 17,5 Ah and 3.7 V pouch cells. The battery packs can be manufactured by gathering of these modules.

The similar battery modules could be designed with most suitable combination of pouch cells. The developed modules could be used to make battery packs. In this point, special welding techniques must be considered.

RESULTS AND DISCUSSION

The most suitable battery packs that consists of prismatic cells and can be put in the spare parts on vehicle will be designed with this project. The many parameters taking into account during design phase such as layout of batteries, capacity of batteries, cooling and heating requirements, the methods of cooling and heating, required parts for stabilisation of batteries, security requirements, ease of cabling and layout of battery management unit

CONCLUSION

The different battery cell types (prismatic, pouch and cylindrical cells) and battery chemistries (LTO, LiNMC, $LiFePO_4$) are reviewed interms of packaging convenience. After many researches and discussions, prismatic cells are selected as most suitable for packing batteries which will be used in electric vehicles. The battery packs are supplied from China now. Thanks to this workings, TEMSA will develop own prismatic cells instead of buying available battery pack from China. This situation will provide cost advantage and design flexibility to TEMSA.

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NOMENCLATURE

- EV : Electric Vehicle
- Cell : the smallest individual electrochemical unit of a battery
- Module : composed of a few cells either by physical attachment or by welding in between cells.
- Pack : composed of modules and placed in a single containing for thermal management
- $LiFePO_4$: Lithium Iron Phosphate
- LiNMC : Lithium Nickel Manganese Cobalt Oxide
- LTO : Lithium Titanate
- R&D : Research and Development

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