Effects of Cell and Module Configuration on Battery System in Electric Vehicles

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Abstract- A battery system is one of the most important powertrain components in Electric Vehicles (xEV). The efficiency of a battery system directly affects the vehicle's range and performance. The configuration of cells and modules also play a key role in battery performance and safety. This study deals with a battery electric passenger vehicle with a battery energy content of 78 kWh. While the vehicle's battery is designed, the criteria to be focused on are evaluated for six different configurations of given cell quantity. The paper focuses on the differences between these configurations regarding the topics which are power losses, control structures, balancing strategies, electrical safety concerns, mechanical aspects, applicability and costs.

Keywords Battery electric vehicle, battery pack, battery module, battery cell

1. Introduction

Full electric and hybrid electric vehicles (HEV) stand out as a rising transportation solution with their energy saving and environmental benefits. In recent years, the number of battery electric vehicles (BEV) and HEVs are increasing day by day. However, there are some challenges to go beyond the limits for the market. One of the main challenge is that BEVs have a short-range capability compared to the conventional vehicles. On the other hand, high battery costs and long charging times are other points which need to be improved. In the near future, the electric vehicle market is expected to face with enhanced conditions which are longer range expectations, lower battery costs and shorter charging duration.

The high voltage (HV) battery is the key powertrain component in BEVs. Due to the lithium-ion batteries high energy and power density values, they are preferred in today's electric vehicles which fits both electrical, mechanical and thermal desired performance criteria [1]. The battery size directly affects the range, performance, weight and price of the vehicle. For this reason, vehicle manufacturers make the cell selection considering some basic boundaries for cell specifications such as kW/kg, kWh/kg, kWh/l, lifetime and kWh/$ values. During the design of a battery, vehicle structure, mechanical and thermal requirements are also essential such that in some cases the prominent structural, mechanical and thermal requirements even affect the cell selection.

The properties of selected cells are critical in achieving target voltage and capacity values within permissible volume and weight. Once the cell is identified, the configuration of the modules to be created with these cells needs to be determined. In this study, calculations are made to evaluate the effect of different module configurations on the battery system.

Battery capacity and battery weight optimization are important in terms of vehicle efficiency. Increased energy efficiency of up to 10% can be achieved with a suitable capacity for the vehicle and a choice of batteries at the right weight [2].

Another point to note when designing the battery and module is the thermal behavior of the battery. To avoid overheating of the cells, a functional cooling system must be integrated when the module structures are decided [3]. Non-effective cooling accelerates battery aging and may cause failures. Operating the battery in a suitable temperature range is an important parameter that increases the battery life. Lithium-ion batteries are also known to exhibit flammable and explosive behavior at high temperatures [4].

This study intends to summarize the cell and module configuration effects on battery performance for automotive applications. The main aspects presented here are to investigate the different power losses, control structures, electrical safety concerns, mechanical considerations regarding their applicability and costs between the various cell and module configurations. This paper presents all these approaches along with their respective performances. Finally, a discussion on the aspects advantages and drawbacks is proposed and optimum cases for each condition are presented.

2. System Definition

Development of a battery system requires fundamental requirements and specific parameters which should be considered. Thus, in this chapter, the state of the art situations are mentioned briefly which are evaluated during calculations and analyses such as power demand, module voltage limits with safety boundaries, the control structure of the system, weight limits and joining technologies.

In an average BEV application on the market, approximately quantity of 550-600 PHEV-2 VDA (German Association of the Automotive Industry) sized prismatic cells are fit to the battery volume [5]. Considering the BEVs on the market, approximately 80 kWh battery capacity is determined. These boundaries were considered in the design of this work.

Battery cycle life is directly related to state of charge (SOC) window which defines usable energy value in electric vehicles [6]. Batteries generally are not recommended to be operational above 90% SOC and below 10% SOC due to aging are accelerated on the edges of the SOC values. The SOC window is used to calculate the usable energy out of the installed energy. As an example, when 80% SOC window is used, the installed energy of 78 kWh can be calculated as 62,4 kWh usable energy.

Therefore, the usable energy value is 70 kWh for 90% SOC window and nominal current value is 142 A due to the nominal power value.

2.1. Power Demand

When a market survey is conducted for electrified passenger vehicles, it is observed that the nominal power levels are around 50 kW [5]. Therefore, the nominal power of 50 kW and the maximum power of 150 kW are selected as base power levels for the vehicle which is considered in this study. Moreover, the target voltage level is 350V ±20V due to availability of the components on the market.

2.2. Module Voltage Limit

DC and AC working voltage classes are classified in ISO 6469-3 standard [7]. Low voltage range is called Class A which is given in Table 1.

Maintaining the modules in low voltage class is important in terms of safety and practicality. Otherwise, exceeding the voltage level limit makes it necessary for trained personnel to work on the module. This causes problems throughout manual handling and repairing.

Table 1. Voltage classes [7]

Voltage class	Maximum working voltage	
	DC [V]	AC [V] (rms value)
Class A	$0 < U \leq 60$	$0 < U \leq 30$
Class B	$60 < U \leq 1500$	$30 < U \leq 1000$

2.3. Electrical Safety

During the design process of a battery, electrical safety parameters also affect design criteria. Isolation gaps are defined according to a voltage level in the standards as clearance and creepage distances. When a module or system voltage is increased by changing configurations, clearance and creepage distances also increase. This results in volume expansion.

On the other hand, isolation resistances are also defined in standards with respect to voltage. Therefore, using a high voltage system leads to the necessity of using better insulator materials. Additionally, isolation resistance is depended on the number of modules.

EMC issues result from noise sources which generate electromagnetic disturbance. These electromagnetic disturbances affect victims that are susceptible to electromagnetic disturbance. This relationship creates a design concern which is called Electro Magnetic Compatibility (EMC). When EMC is considered in a battery, both inductive and capacitive coupling must be avoided.

2.4. Control Structure

Battery Control Unit (BCU) and Module Control Unit (MCU) usage is the most common approach of the control structure inside a battery system. Generally, BCU carries out basic battery system functions such as thermal management, switch on/off control, balancing request, power up/down, calculation of state of charge and state of health and etc. while MCU is responsible for measuring and sending cell voltage and temperature data to the BCU. Cell balancing function is also performed via MCU.

The control system topology inside a battery may vary. One of the topologies has multiple modules with integrated single MCU. In another topology, single MCU is utilized per module. When single MCU is used for multiple modules, the cost-related problems may be eliminated. This; however, also brings the complexities of wiring harness and assembly.

Moreover, as the number of series in the module increases, the number of modules that an MCU can manage decreases.

2.5. Cell Balancing

Cell balancing allows each cell to be aged equally. Cell imbalance is caused by specific internal reasons such as manufacturing tolerance, different self-discharge rates and cell impedance. In addition to these, external reasons such as cell configuration, electrical routing and temperature distribution in the system may have also effects on cell balancing.

Cell imbalance is a critical issue to be addressed during the design phase of the system. Otherwise, this may limit the battery system performance and various cell voltages may occur which lead to decreased battery capacity. Therefore, cell balancing plays a critical role in the battery lifetime [8,9].

Balancing method consists of two main categories as 'Passive' and 'Active'. The passive balancing method may be defined as depleting cell(s) charge which has too much charge over a resistor until every cell reaches to the same level of charge. This might be done via switching on a resistor in parallel to the relevant cell on MCU hardware. The active balancing method is simply transferring the energy between cells which are in different energy levels. The active balancing circuitry is based on using a capacitor and/or inductive component to store or transfer the energy.

2.6. Module Mass Limitations

On the automotive market, there is no regulation or standard about maximum weight to lift at work. Instead, there are guidelines or recommendations from different occupational health safety units.

Safe lifting limits are differentiated between men and women. The limit may also be different about how the load is being lifted, how close to the body and how high or low. The recommendation for maximum weight to lift at work is shown in Fig. 1.

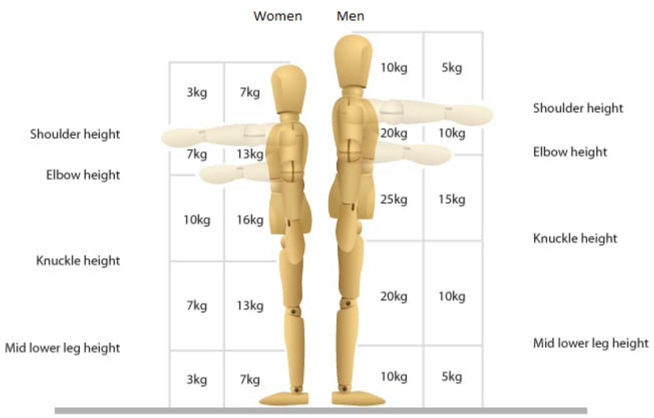

Figure 1. Maximum weight limits to lift at work [10]

2.7. Joining Technology

Different cell assembly methods may be used considering mass production. When assembling cells; resistance welding, ultrasonic welding or laser welding may be used depending on the terminal materials and type of the cells. The material types of the busbar or cables must also be considered when the cells are assembled. For instance, during joining dissimilar materials by using resistance welding (such as nickel and copper) the higher resistive material may be damaged. In another technique, laser welding may be difficult when the thermal conductivity or light absorption is different. On the other hand, in ultrasonic welding, cell terminals may be damaged because of the extreme micro-vibration conditions. Thus, joining technology must be selected regarding project requirements [11].

2.8. Cost Reduction

Cost reduction is an inevitable process for series production. Especially in the automotive market, companies always focus on to decrease costs. Firstly, the increase in voltage level in a module brings some additional cost because of required high-quality isolation materials, training of employees, special equipment for assembly and complexity of the design. Otherwise, smaller modules bring a high quantity of MCUs which causes increase in cost if identical modules are considered. Secondly, module mass also affects the production and maintenance costs. Increasing weight of modules requires special equipment to lift them. If the production is done by robots, this may be more expensive considering the first investment and complexity of production. Finally, joining technology affects the production as well as the maintenance costs. While resistance welding is a low-cost process considering investment and application costs, laser welding and ultrasonic welding have high investment costs.

3. System Evaluation

In chapter 2, the basic concept points which need to be considered during a battery design for automotive market was mentioned shortly. In this chapter, the specific system configurations which are selected to make a comparison with these concept points are evaluated. All the cases are compared regarding their power losses, control structures, weights, applicability and their cost.

3.1. System Configuration

Three different cases are considered in the scope of this work. Moreover, each case is separated into two subcases. As mentioned above in Chapter 2.1, all the cases have the same number of cells, only the module-system configurations and the connection patterns are different. Case configurations are given in Table 2 and detailed drawings are shown in Fig. 2.

In order to use the flexibility of 12 cells, all module configurations are selected with 12 cells except Case 3.1 as in Table 2. When a module consists of 12 cells, the configuration has the capability to be organized as 12s1p, 6s2p, 4s3p and vice versa.

In Cases 1.1 and 1.2, modules are connected in series, then series modules are connected in parallel as called string connection pattern. Unlike, in Cases 2.1 and 2.2, modules are connected in parallel first, then parallel modules are connected in series which can be seen in Fig. 2.

In Cases 3.1 and 3.2, modules are directly connected as series. To exhibit the effects of huge module configuration and a high number of parallel cells in a module, the module configurations are selected as 12s6p and 2s6p.

Considering the inter-module busbar drawings of Case 2 as shown in Fig. 3, the parallelization of the module connections would lead to complexity and unnecessary busbar amount. It is clear that this situation is not feasible; therefore, Case 2 is excluded from the calculations and analyses.

The module configurations are intended to be lower than 60 V as a voltage level. Consequently, safety limit about voltage level is applied according to ISO 6469-3 standard.

Table 2. Case configurations

Case Numbers	Modules in Series	Modules in Parallel	Cell quantity of Series in Modules	Cell quantity of Parallel in Modules	Number of Cells
1.1	8	6	12	1	576
1.2	24	2	4	3	576
2.1	8	6	12	1	576
2.2	24	2	4	3	576
3.1	8	1	12	6	576
3.2	48	1	2	6	576

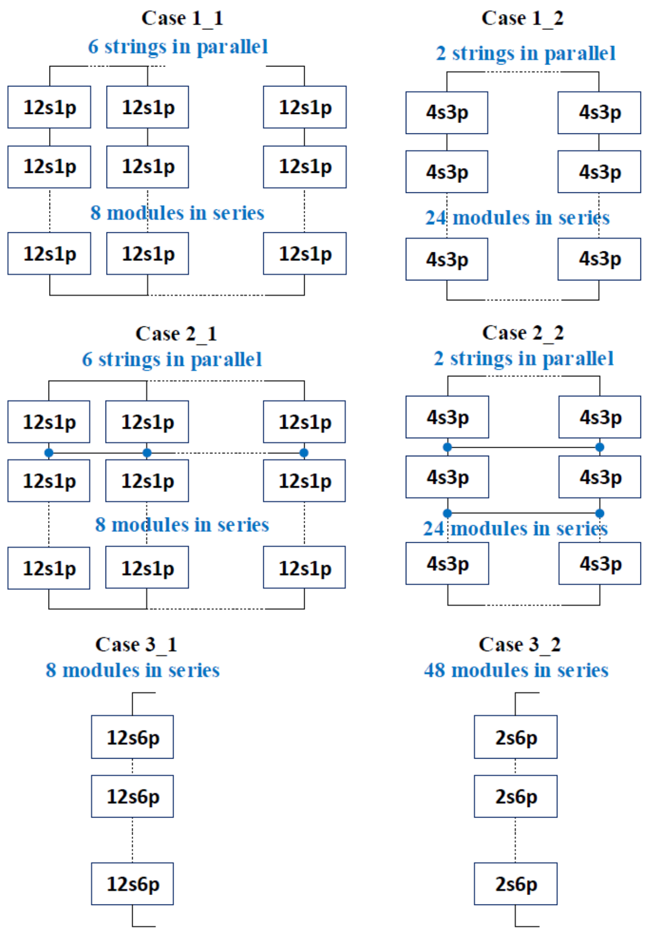

Figure 2. Representative drawings of the cases

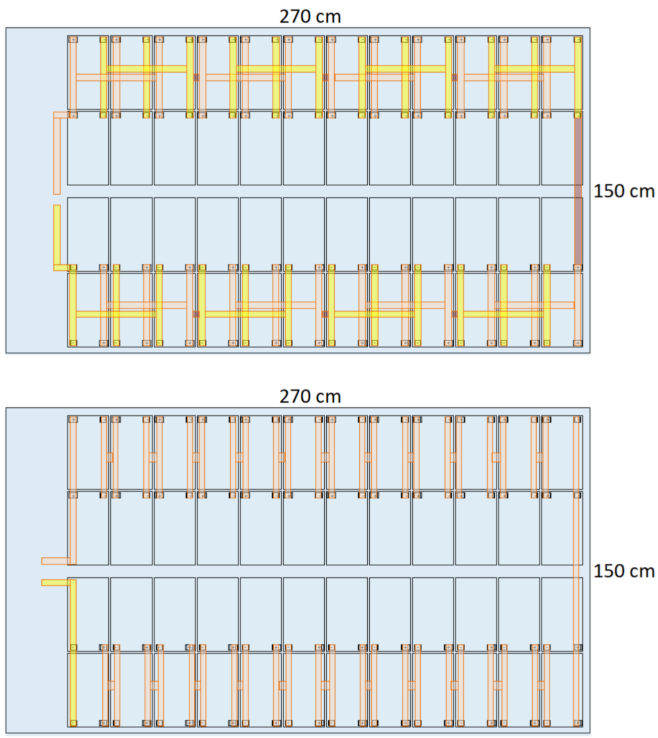

Figure 3. Representative drawing for Case 2

3.2. Power Loss

In order to calculate the power losses of the systems for various configuration of cases, resistances of modules and systems are determined according to equations (1), (2) and (3).

When the calculations are made according to equation (1), (2) and (3) the nominal current value is taken as 142 A since the nominal power value is 50 kW and the nominal voltage value is 352 V.

It is also assumed in this study that laser welding is applied to the prismatic cells with aluminum terminals and that the busbars inside the modules are also aluminum. Due to the high electrical conductivity for the connections between modules, the copper busbars are used with steel bolt nuts. The busbar thickness inside the module is chosen to be 2 mm so that the welding depth value for laser welding is acceptable. However, the thickness of the copper busbars between modules is chosen to be 3 mm to increase the mechanical strength.

Afterward, busbar shapes are classified and values are added to inner cell resistance and laser welding resistance. Thereafter, categorization is determined in terms of busbar shapes and calculated values are added to screw and module resistances. Calculated module-system resistances and power losses regarding the resistances and nominal current value for cases are given in Table 3.

3.3. Control Structure

Selected battery management system (BMS) uses a BCU-MCU structure which is a reference control structure for this study. MCUs are flexible to control a single module or multiple module. The main target is here to create a common MCU-BCU structure to compare the results from the cases.

The MCUs of the selected BMS have 18 measurement points. 2 temperature measurement points for each module are preferred to be used in this work. According to the results of the simulations made, the temperature sensors are placed at the hottest and coldest points of the module. Considering the number of temperature and voltage measurement points, the required number of MCUs are shown in Table 4.

$$R_{Module} = (2.R_{Contact} + R_{Cell\_inner}).\frac{N_{cell\_series}}{N_{cell\_parallels}} + R_{ModuleBusbars}.\left(N_{cell_{series}} - 1\right) + 2.R_{PoleBusbars} \quad (1)$$

$$R_{Pack} = (2.R_{Contact} + R_{Module}).\frac{N_{module\_series}}{N_{module\_parallels}} + R_{PackBusbars}.\left(N_{Module_{series}} - 1\right) + 2.R_{PoleBusbars} \quad (2)$$

$$P_{loss} = I^2 R_{pack} \quad (3)$$

Table 1. Power losses of the cases

Comparison of Cases			
Case Numbers	Module Resistance	System Resistance	Power Loss. @ 142A 25^{o}C %50 SOC
1.1	28.82 mΩ	38.57 mΩ	781.00 W
1.2	3.20 mΩ	39.63 mΩ	802.61 W
3.1	4.80 mΩ	39.24 mΩ	794.59 W
3.2	0.80 mΩ	43.24 mΩ	875.55 W

Referenced cell resistance: 2.4 mΩ

Table 4. Quantity of MCU of cases

Case Numbers	Approach	Voltage measurement points in each module	Temperature measurement points in MCU	No. of MCUs
1.1	1 MCU per module	13	2	48
1.2	1 MCU per 2 modules	5	2	24
3.1	1 MCU per module	13	2	8
3.2	1 MCU per 3 modules	3	2	16

The number of voltage measurement points are determined by using the equation (4).

$$n_{v\_measurement} = n_{series} + 1 \quad (4)$$

n_{series}: $Cell\ number\ of\ series\ in\ module$

$n_{v\_measurement}$: $Number\ of\ voltage\ measurement\ point\ on\ module$

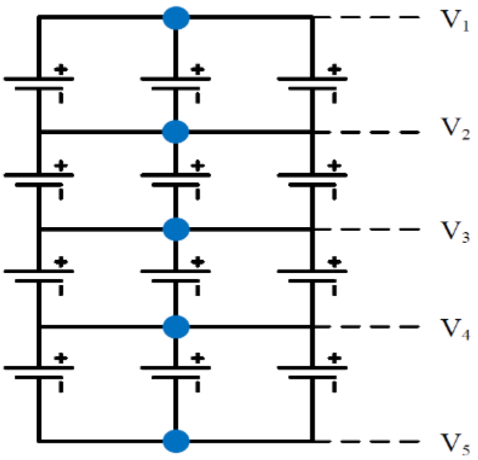

Figure 4. Representation of voltage measurement point on 4s3p module configuration

3.4. Balancing Strategy

In this study, passive balancing method is selected since active balancing requires a more complicated circuit with higher cost, extra software function and algorithm. Using single MCU for multiple modules is another low-cost consideration. In addition to this, the more parallel cell number causes more balancing duration due to a certain balancing current of MCU which is split to parallel branches in the circuit. That's why Cases 1.1 and 2.1 have the shortest duration of balancing which is beneficial in the charging process.

3.5. Electrical Safety

Regarding electrical safety concerns, according to IEC 60664-1 standard [12], clearance distance remains the same for different modules, as it is determined by the structure of the installation. If the number of series exceeds critical voltage levels string fuses may be necessary.

The clearance and creepage distances are valid between conductive HV and low voltage (LV) parts, conductive HV parts and chassis, and between conductive parts of HV+ and HV-. The minimum clearance and creepage distances must be ensured within the module and within the whole battery system considering end of life (EOL). Clearance distance is simply defined in IEC 60664-1 as "minimum air distance between two conductive parts" and the creepage distance is also defined in the same standard as "minimum distance between two conductive parts along the surface of an insulator". According to SAE Application of Insulation Standards to High Voltage Automotive Applications [13], pollution degree can be selected as Pollution Degree 2 or 3 considering the explanation as 'It is proposed that packages with dust protection ratings of IP5KX or better and water protection ratings of IPX4 or better be considered pollution degree 2'.

Comparative Tracking Index (CTI) is used for measuring the electrical breakdown properties of an insulating material along its surface. The higher CTI value indicates to have the better insulation material and the values are shown in Table 5.

Overvoltage is defined in IEC 60664-1 as "any voltage having a peak value exceeding the corresponding peak value of the maximum steady-state voltage at normal operating conditions". Overvoltage category II is also defined as "Equipment of overvoltage category II is energy-consuming equipment to be supplied from the fixed installation".

Table 5. Material group

Material group I	Material group II	Material group III
CTI ≥ 600	600> CTI ≥ 400	400> CTI ≥ 175

Considering the installation technology, overvoltage category level is proposed as overvoltage category II with rated impulse voltage of 2500 V for equipment. Therefore, the clearance distance is selected as 1.5mm without altitude correction. Considering altitude correction factor for 5000 m, 2.3mm is calculated as clearance distance from the standard IEC 60664-1.

As stated above, the creepage distance is given in the relevant standard to specify the insulation capability of an insulator material. According to module voltage levels, the creepage distances are calculated by interpolating from standard table values which are shown in Table 6.

Clearance and creepage distances are affected by installation technology, the quality of the insulator materials used in the module and packages, the altitude levels, the IP class of the module or packages and the amount of humidity and moisture in the environment. It can be clearly seen that increasing voltage levels increases the module as well as the system dimensions with the effect of clearance and creepage distances while the pollution degree and the material group levels are also affecting on the dimensions.

On the other hand, HV busbar layout in the cases may be evaluated regarding EMC issues. In Case 1.1, there is a long busbar couple which carries both HV and high currents. Therefore, this can cause EMC issues if measurement and signal cables are routed close to HV busbars. However, because there is one MCU per module, measurement cables will be inside of the modules.

In Case 1.2, the middle region of the pack is not occupied. Thus, measurement or signal cables can be routed via this area. As long as, HV busbars are perpendicular to the measurement cables, the inductive coupling is avoided.

Table 6. Creepage distances

Configuration	Voltage Levels (V)	Pollution Degree 2 (mm)			Pollution Degree 3 (mm)		
		MG1	MG2	MG3	MG1	MG2	MG3
2s	8.4	0.4	0.4	0.4	1	1	1
4s	16.8	0.47	0.47	0.47	1.18	1.18	1.18
12s	50.4	0.61	0.87	1.22	1.54	1.74	1.94

In Case 3.1, high current carrying busbars are routed on the side of the pack. Therefore, the middle region is available for LV and signal routing.

In Case 3.2, because single MCU controls more than one module, voltage and temperature measurement wires are routed outside of modules. This case requires the most sensitive wiring harness design considering EMC. To avoid inductive coupling, measurement cables must be perpendicular to the HV busbars. Besides, to prevent capacitive coupling, measurement cables must be placed as far as possible from HV busbars.

3.6. Mechanical Aspects

In addition to the electrical calculations, the cases are also evaluated mechanically. The weight limitation is also tried to be not exceeded for all module configurations. But to have reliable comparison results with the huge module configurations, the module for Case 3.1 consists of a high number of cells which lead to exceeding the weight limitations. This causes to have limitations about manual handling and needs to have operating machines for handling and maintenance. Considering the production plants, series productions are made with robotic technology; therefore, Case 3.1 is also presented.

In order to calculate the gravimetric ratios based on the module, two conceptual modules designed by AVL are investigated. One of the modules examined has 12-cell (6s2p) with 10.75 kg total cell weight and the other one has 24 cells (6s4p) with 21.12 kg total cell weight. The aim here is to observe how the weight ratios change based on the module even though the number of cells is doubled. The cells in approximately same dimensions are used in the examined modules. As a result of the investigations, the ratio of the total cell weight with respect to the module weight may be understood more clearly and the ratios are shown in Table 7. This emphasizes that as the total number of cells in a module are doubled, the percentage of useless weight in a module decreases as 3%. Busbar weights and volumes are calculated according to the busbar cross sections that can carry nominal currents and the results are given in Table 8. Module weights are calculated considering busbar weights, cell weights and housing weights which are represented as useless weight in Table 7 and the result are given in Table 9.

Table 7. Weight ratios

$Useless\ weight = module\ weight - total\ cell\ weight$	Useless weight / total cell weight
Referenced Module 1 (6s2p)	%28
Referenced Module 2 (6s4p)	%25

Table 8. Busbar weights and volumes

Case Number	Total module busbar weight	Inter-Module busbar weight	Total module busbar volume	Inter-Module busbar volume
1.1	3.45 kg	12.09 kg	1.27 L	1.35 L
1.2	4.29 kg	2.30 kg	1.58 L	0.26 L
3.1	14.07 kg	2.59 kg	1.57 L	0.35 L
3.2	4.80 kg	12.46 kg	1.77 L	1.39 L

Table 9. Module Weights

Case Numbers	Module weights
1.1	12.36 kg
1.2	12.38 kg
3.1	70.30 kg
3.2	12.39 kg

3.7. Applicability

Safe operation of the battery system requires specific components such as contactors, fuses and current sensors as well as connectors. In certain applications, power electronics components like onboard charger and/or dc-dc converter may also be placed as a part of a battery system. During the design process, a detailed analysis of these components must be done in harmony with each other.

The safety components which are also called as battery distribution unit (BDU) need a certain space inside the battery system. Thus, available space for these elements is crucial during design.

Escalated voltage and power level may cause expansion of the volume for these components. As an analysis bullet point, this is considered to compare different cases.

Applicability of the cases is evaluated in terms of the utilization space for BDU and ease of installation. When the drawings are interpreted, it is clear that Case 3.1 has the most utilization space for BDU. The assembly of Case 3.1 is simpler than the other cases, since, it has the minimum number of busbars. Additionally, cross-over busbar type which is used in

Case 1.1 and Case 3.2 is harder to produce than the straight busbars according to installation. Therefore, those cases are considered more complex than the others.

In Fig. 5, module layout, busbar shapes and busbar geometries are given for Case 1.1. Modules are divided into two parts and pole busbar lines are placed between these parts. Moreover, 6 different busbar types are used; therefore, this makes the production and the assembly phase more complicated.

In Fig. 6, the general system layout is given for Case 1.2. Modules are also divided into two parts and 3 busbar types are considered in this case. Two of them are used as main pole connections while the other one is used for the connections between the modules. This case is more efficient for the assembly stage because of less type of busbar.

Fig. 7 represents the system schematic of Case 3.1. In this configuration, the pack includes larger modules than the other cases; thus, less quantity of busbar is needed for current flow. It decreases the assembly time and increases the production efficiency.

In Fig. 8 which represents Case 3.2, most of the modules are connected using cross busbars. Although 6 busbar types are used, most of them have the same shapes which reduce the assembly time. Additionally, selecting cross busbars provide less complexity and low EMC interference due to its geometrical structure and layout.

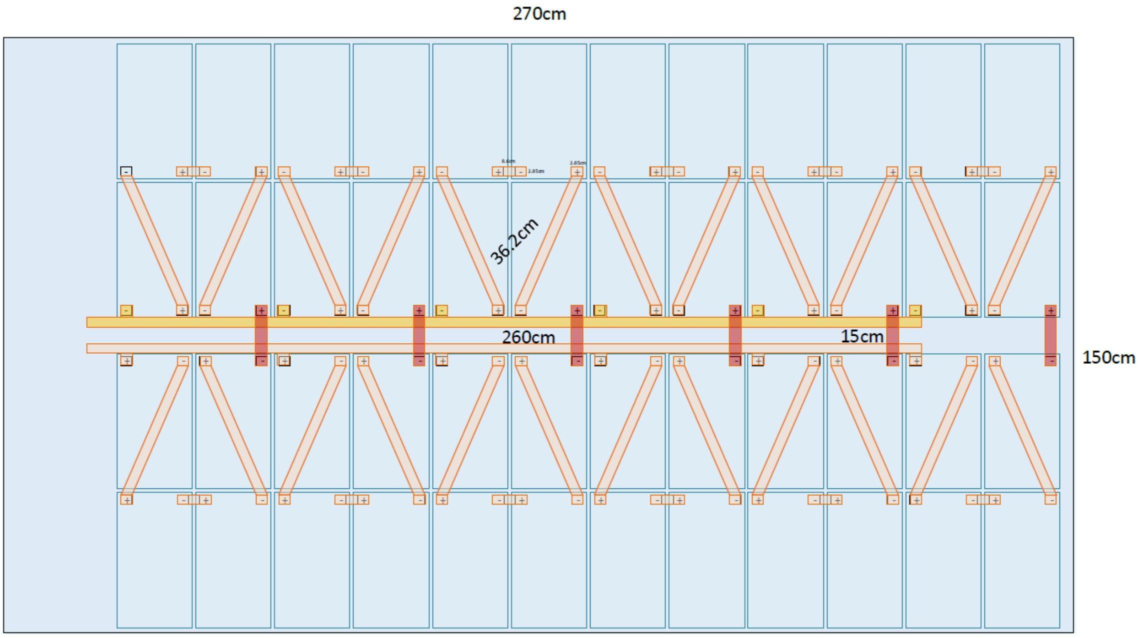

Figure 5. Case 1.1 with detailed representation of the module busbars and dimensions

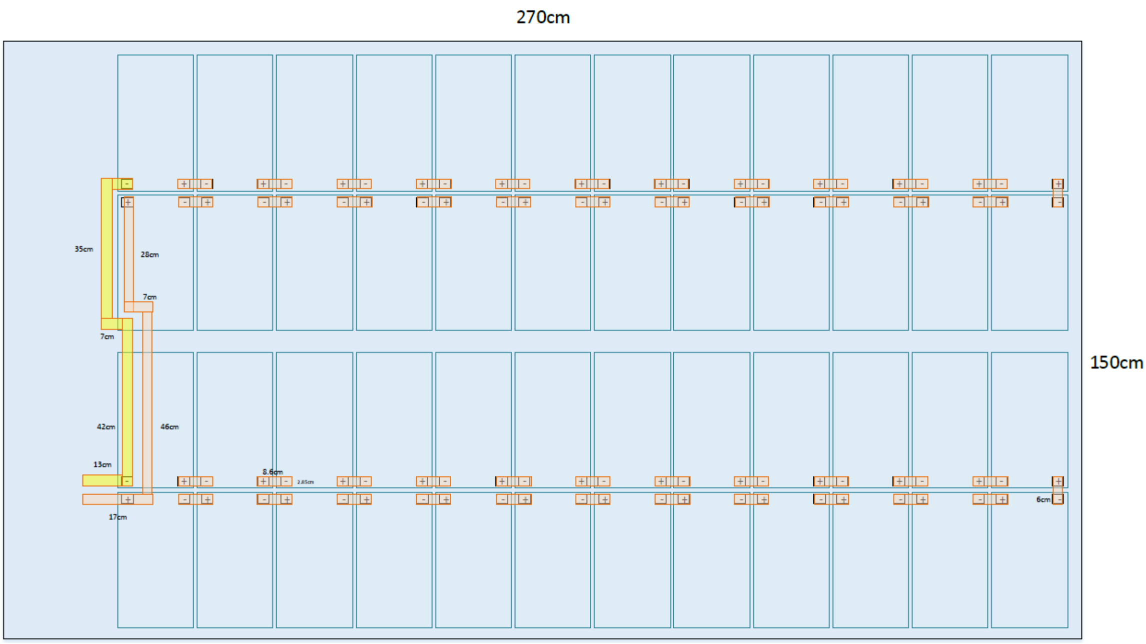

Figure 6. Case 1.2 with detailed representation of the module busbars and dimensions

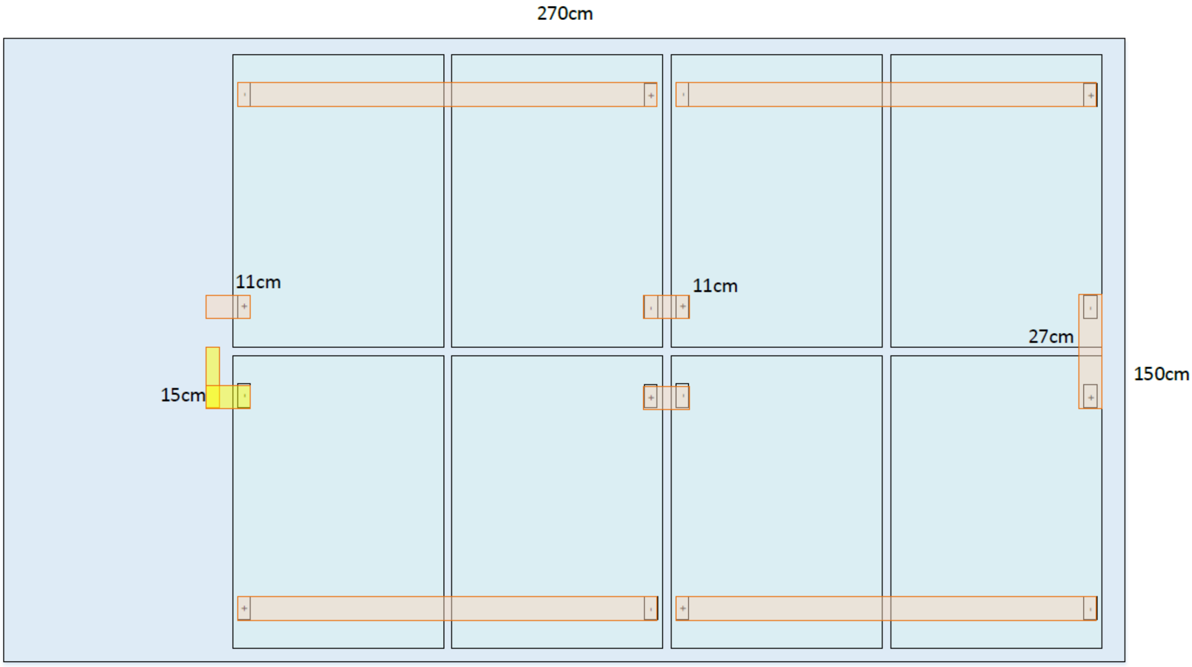

Figure 7. Case 3.1 with detailed representation of the module busbars and dimensions

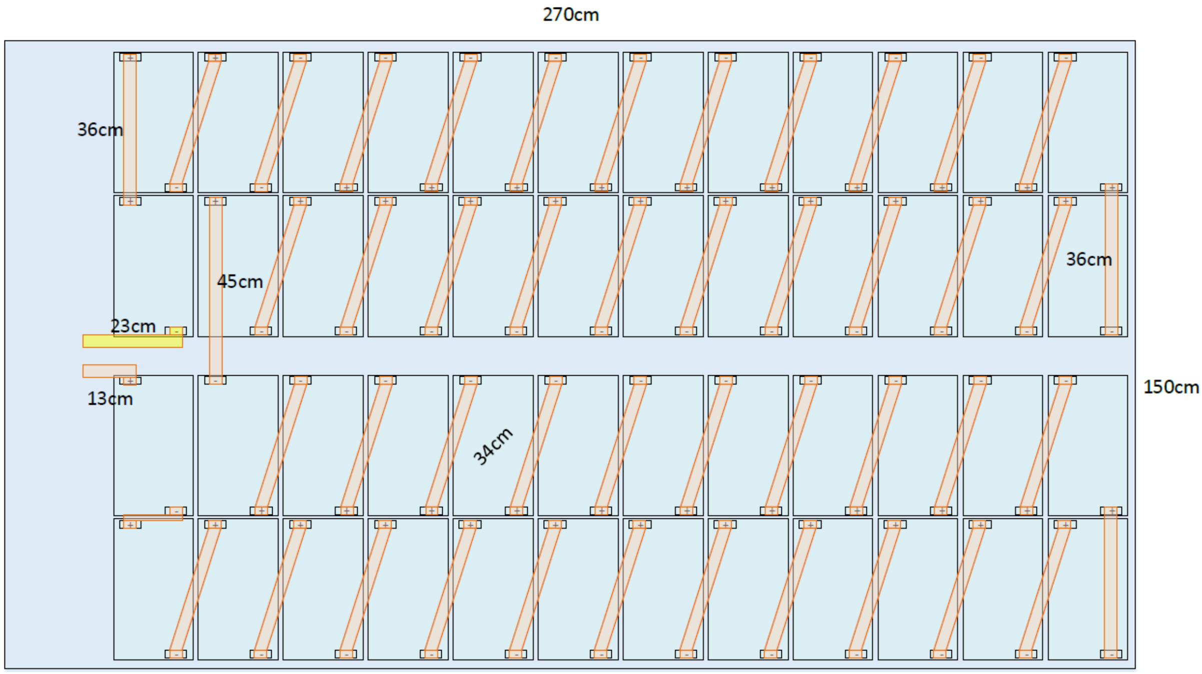

Figure 8. Case 3.2 with detailed representation of the module busbars and dimensions

3.8. Cost

In a battery system, the quantity of used materials and their complexity affect overall cost. In Case 1.1 which has the maximum number of MCUs, the total number of 48 MCUs are integrated while 8 MCUs are placed in Case 3.1 which has the minimum number of MCUs for the same quantity of cell. When this data is considered, Case 3.1 requires the lowest cost in terms of MCU quantity.

Considering cost reduction, the production process has also a crucial impact. When the busbar layout is examined, the assembly of multi-piece structures becomes difficult to handle during the manufacturing process. A high number of busbar pieces require a large number of bolts and nuts with their assembly process. Case 3.1 has an advantage regarding the manufacturing of module to module busbars and assembly process of the modules due to a less number of module connections. When the cases are compared in terms of busbar weights and volumes, Case 3.2 seems to have the highest cost because it contains the highest quantity of busbar.

4. Conclusion

In the EV market, battery system and module design are very crucial steps in terms of efficiency, ease of production and cost. In the study, 3 basic battery designs with their two sub configurations are investigated and compared.

Case 2.1 and 2.2 are not feasible given the ease of production and efficiency. In addition, since the busbar layout is too complex, it is not suitable for electrical safety and production costs.

In the case of the modules containing the same number of cell, it can be seen that the total power loss is reduced by about 11% if the parallelization is performed between the modules instead of cell strings inside the module. The minimum power loss is obtained in Case 1.1 while the maximum power loss is obtained in Case 3.2 where all modules are connected in series.

On the other hand, the quantity of MCU depends on the series connection of cells in the module. This may also effect on the overall cost of the system. Moreover, using more parallel branch in every series node increases the balancing time.

According to the drawings, the remaining volume for the BDU varies due to different configurations, although cases have the same number of cells. In this study, it can be seen that Case 3.1 has the most free space for BDU. Moreover, large and few modules occupy less space than small and plenty of modules.

The busbar volumes and weights used for inter-module connection vary due to different configurations. The heaviest busbar mass in the system is obtained in Case 3.2 due to the higher number of busbars. The positioning of the modules affects the busbar lengths which is important regarding the weight.

Taking everything into account, when the effect of module and cell configurations on system performance is investigated, it is not possible to talk about an optimum case due to different parameters. Depending on the application, the advantages and disadvantages of each case can be mentioned. The results are presented in terms of feasibility to a real battery system.

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