Battery-Pack Capacity Optimization Layout for Electric Motorbike Competition

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Abstract— This paper presents an experimental procedure to optimize the battery pack capacity of an electric motorbike designed to run on the MotoStudent International Competition of 2016. The optimization process has been realized by means of experimental tests, which have been carried out in a load bank testbench. This automated testing station was designed specifically to test the battery cells of the motorbike battery-pack. As a result of the optimization process the maximum difference between the highest module and the lowest module of the motorbike battery pack has been substantially reduced compared to a randomly located configuration.)

Keywords— *Electric motorbike, battery pack design, battery capacity optimization, MotoStudent International Competition*

I. INTRODUCTION

In an increasingly technological world, the number of science, technology, engineering and math (STEM) students has been decreased in the last decades in Europe and USA [1-2]. According to the statistics published by the Ministerio de Educación Cultura y Deporte of Spain, the number of STEM students have fallen by more than 57,000 (17.2% less) in only three consecutive courses [3]. In addition, corporate recruiters have problems to hire STEM graduates [4].

For this reason, many governments, institutions (like IEEE with the Teacher In-Service Program) and universities are promoting STEM studies in primary and secondary education to motivate future students in the area. Universities are also modifying study programs to keep engaged the current engineering students.

An effective way to motivate these engineering students is to work on real multi-disciplinary problems and to participate in different challenges and competitions [5]. In 1981, the Society of Automotive Engineers, SAE, introduced the Formula Student Program, an international competition in which engineering students had to design a performance vehicle [6]. This type of competition allows students to face a real working environment, controlling the budget, working on strict deadlines and time schedules and promoting teamwork.

Based in this idea, Moto Engineering Foundation & TechnoPark MotorLand promote the MotoStudent International Competition, a challenge between University student teams to apply their expertise acquired during their university studies in a real industrial project, by designing, developing and manufacturing a real racing motorbike prototype. There are two categories named MotoStudent Petrol (with internal combustion engine) and MotoStudent electric (with 100% electric propulsion system). In 2016 a team from Universidad Politécnica de Madrid (Spain), UPM-MotoStudent participated in the competition, designing an electric bike (called EME 16-E) from scratch, reaching a second position in the race (Fig. 1).

During the design of the modular battery pack it was observed by means of experimental tests that there was an optimal layout of the different battery modules. In this paper, this battery pack capacity optimization layout is presented.

II. MOTOSTUDENT COMPETITION

The teams enrolled in this competition are asked to play the role of a motorbike manufacturer. The students have to work together designing, manufacturing and evaluating the viability of a racing motorbike prototype not only from the engineering point of view but also as business model.

All teams are provided with the same kit including several components of the motorbike that are compulsory to be installed.

Fig. 1. UPM MotoStudent EM16-E

This kit includes the following components: an air cooled electric motor, an isometer insulation monitoring device, a set of front and rear rims and slick tires and a set of front and rear brake calipers and pumps (article A.4.4.2) [7].

There are two different phases during the competition:

MS1 Phase, where all projects are judged from the industrial and business point of view, evaluating the design, industrialization process, costs, etc.

Motorbikes are tested through different static and dynamic tests before MS2 phase, in order to ensure their functionality and safety.

MS2 phase will include a final race in the MotorLand Aragon Circuit (Spain).

III. BATTERY MODULE DESCRIPTION

The battery technology selection was based on the following technical and economic factors: specific energy (Wh/kg), which determines the total weight of the battery pack, energy density (Wh/L) which determines the total volume, the maximum discharge capacity (C-rate), which determines the maximum power that can be extracted from the battery pack by the electric motor and finally, the cost (€). The selected technology was LiPo (Lithium Polymer), which have higher discharge capacity rate and better temperature efficiency over a wide temperature interval compared to conventional Li-ion batteries [8].

Building a battery pack with this type of cells will imply to join them by means of welding, which is not allowed by the competition rules (article D.3.3.5) [7].

In order to comply the competition rules and keep the completed battery pack cost as low as possible, standard battery module from RC cars (130x46x22 mm) was selected. This module contains four cells in 2s2p configuration (2 cells in series and 2 cells in parallel). The technical specifications of this module are presented in Table I.

TABLE I. BATTERY MODULE SPECIFICATIONS

Battery Module Specifications	
Technical specifications	Value
Configuration	2s2p
Nominal Voltage	7.4 V
Maximum Voltage	8.4 V
Discharge Cut-off Voltage	6 V
Weight	0.296 kg
Nominal Capacity	5.8 Ah
Discharge Current Limit	20C

According to the competition rules (article D.1.1.1) [7], the maximum permitted voltage of the HV system shall be 110 VDC with fully charged batteries (worst case). In this situation, the maximum number of battery modules connected in series shall be:

$$110V/8.4V=13 \quad (1)$$

It is critical to perform a good estimation of the electric consumption. If more modules than necessary are included in the battery pack, the total weight of the motorbike will be increased (worsening its dynamic characteristics), but on the contrary, including fewer modules than necessary can compromise the final race, reducing the total range and preventing the bike to reach the end. The estimated battery consumption per track session is 4.14 kWh, from this value the capacity pack is calculated as:

$$\frac{4140 \text{ Wh}}{3.75 \text{ V} \cdot 26} = 42.43 \text{ Ah} \quad (2)$$

According to Table I, the nominal capacity of each battery module is 5.8 Ah, therefore the number of battery modules connected in parallel shall be:

$$42.42 \text{ Ah}/5.8 \text{ Ah}=7.3 \quad (3)$$

This number is rounded to the nearest integer towards infinity; in this case, 8 layers (with 13 battery module per layer connected in series). The proposed battery pack is presented in Fig. 2.

The state of this battery pack is continuously monitored by a self-made battery management system (BMS) which control the charging/discharging processes, avoiding unsafe operating conditions and balancing the cell voltages during the charging periods. In this manner, the negative effects of deep charging-discharge cycles in cells lifetime are diminished [9]-[10].

Fig. 2. Battery module with 104 standard RC car battery pack (13 modules per layer, 8 layers)

IV. LOAD BANK TESTBENCH FOR BATTERY MODULE VALIDATION

In order to avoid installing a defective battery module in the final battery pack, an automated testing station has been designed to conduct discharge tests over the commercial battery modules as soon as they arrive to our team.

This station is composed by 40 incandescent lamps (12V-50W) located in 10 independent rows with four lamps connected in parallel in each row. 10-relay coils perform the connection/disconnection of each row, which in turn is controlled by an Arduino device. This testing facility allows discharging batteries modules up to 2000 W-170A, selecting constant current values by the users. A picture of this test bench is shown in Fig. 3

V. TESTING RESULTS

All new battery modules were tested as soon as they arrive to the University, identifying the current real capacity of each module. Battery cells in each battery module were initially charged at its maximum voltage (4.2 V per cell) and then they were discharged at 3.5 C until reach the minimum voltage.

In Fig. 4 the discharge voltage of two battery modules are presented. The first two cells from battery pack 1 have a cut off time of 1044 seconds (17.4 minutes) but cell #2 from battery pack 2 is in poor conditions and the cut off time is significantly reduced to 617 seconds (10.28 minutes), which represents a 40.9% efficiency reduction. If this faulty module were installed, the efficiency of the whole battery pack would have been compromised.

VI. BATTERY MODULE DISTRIBUTION OPTIMIZATION

The correct placement of each battery module within the pack is critical, in order to minimize the total capacity variation of each layer.

To identify the position of each module within the pack, the following coding was used: a number 1-8 identifies the current layer and a letter from A to M identifies the position of the module within the specific layer, according to the scheme shown in Fig. 2.

Fig. 3. Load Bank Testbench

Battery cells exhibit substantial capacity variability among them due to the manufacturing process. Eight different orders to the manufacturer were placed to ensure that all modules of the same level in the battery pack have been manufactured on the same date.

Fig. 4. Constant-current discharge test for the best and worst battery module

Fig. 5. Battery pack capacity with optimal distribution of the battery modules

Fig. 6. Battery pack capacity with random distribution of the battery modules

TABLE II. CAPACITY MEASUREMENTS (MAH) OPTIMIZED CONFIGURATION

Module	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Total/module
A	5619	5353	5872	5502	6020	5505	6031	5275	45177
B	5586	5358	5856	5617	6012	5554	5969	5321	45273
C	5582	5358	5794	5632	5659	5583	5954	5524	45086
D	5581	5364	5750	5641	5626	5605	5913	5624	45104
E	5574	5370	5731	5658	5608	5617	5895	5631	45084
F	5541	5390	5728	5684	5601	5649	5884	5689	45166
G	5484	5391	5698	5708	5579	5655	5868	5698	45081
H	5465	5393	5686	5731	5574	5692	5867	5714	45122
I	5462	5399	5673	5737	5562	5720	5866	5721	45140
J	5462	5420	5661	5765	5530	5749	5838	5724	45149
K	5457	5428	5637	5769	5512	5889	5837	5741	45270
L	5447	5428	5636	5828	5327	5901	5821	5748	45136
M	5390	5461	5630	5835	5228	6049	5737	5776	45106

TABLE III. CAPACITY MEASUREMENTS (MAH) RANDOM CONFIGURATION

Module	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8	Total/module
A	5457	5353	5637	5731	5601	6049	5838	5776	45442
B	5574	5390	5661	5769	6012	5605	5954	5624	45589
C	5447	5428	5856	5658	5626	5505	5837	5721	45078
D	5586	5399	5794	5835	6020	5692	5969	5698	45993
E	5541	5391	5731	5765	5579	5649	5895	5524	45075
F	5465	5461	5630	5641	5574	5901	5821	5741	45234
G	5582	5364	5636	5708	5659	5617	5913	5714	45193
H	5484	5428	5673	5632	5530	5720	6031	5321	44819
I	5619	5370	5728	5737	5327	5889	5884	5689	45243
J	5390	5420	5872	5617	5608	5749	5867	5631	45154
K	5462	5358	5698	5828	5512	5655	5868	5724	45105
L	5581	5358	5750	5502	5228	5583	5866	5275	44143
M	5462	5393	5686	5684	5562	5554	5737	5748	44826

After performing the previous described tests in all the received modules and known the amount of energy that these battery modules can store, they were ordered from the position A to M in descending order of capacity in the odd layers (and in ascending order in the even layers).

Tables II and III show capacity measurements (mAh) in each layer for optimized configuration and random configuration. Fig. 5 shows the battery capacity of each layer with the proposed optimal layout. Fig. 6 shows the battery capacity of each layer, where the battery packs of each layer have been randomly located, simulating that the battery packs have been placed in each layer without any preset order. Table IV presents the summation of the capacity of each module extended to all layers. It is observed that, in the proposed layout configuration, the maximum difference between the highest module and the lowest one is 192 mAh (0.42%) while in the randomly located configuration the maximum difference is 1850 mAh (4.04%). This optimization process improves EME 16-E battery pack performance as it was verified during the MotoStudent competition.

TABLE IV. BATTERY CAPACITY OPTIMIZATION

Battery Capacity per Module (mAh)		
<i>Optimal proposed configuration</i>	<i>Random configuration</i>	<i>Module</i>
45177	45442	A
Max. Value: 45273	45589	B
45086	45078	C
45104	Max. Value: 45993	D
45084	45075	E
45166	45234	F
Min. Value: 45081	45193	G
45122	44819	H
45140	45243	I
45149	45154	J
45270	45105	K
45136	Min. Value: 44143	L
45106	44826	M

VII. CONCLUSIONS

In this paper the experimental procedure developed to optimize the capacity of the EME 16-E motorbike battery-pack is presented. This motorbike was designed by the UPM student team to run on the MotoStudent International Competition of 2016.

The battery-pack performance is a key factor in the motorbike operation, however the battery module tests revealed significant capacity variability among them. To correct this situation a battery-pack optimization layout has been designed. This load bank test bench allows carry out discharge tests automatically. As a result of the tests the motorbike battery-pack distribution has been optimized. In this manner, the maximum difference between the highest module and the lowest one of the optimized configuration (0.42%) was lower than the maximum difference of the randomly configuration (4.04%). During the competition the optimized motorbike battery pack presented good results. The EME 16-E motorbike designed by UPM student team finished the race at a promising second position.

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