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Battery Sizing for Hybrid and Electric Rail Vehicles

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Summary

There is currently significant pressure on the transport sector to reduce CO2 emissions. Rail vehicles are currently one of the most efficient forms of transport, particularly when electrically propelled. However, the requisite infrastructure enabling this limits flexibility, with electrification of the whole network prohibitively expensive. One alternative is the use of on-board energy storage systems, such as batteries, which enable vehicles to operate on discontinuously electrified, or even completely non-electrified, lines. There is, however, a multitude of possible battery configurations. Thus, a high-level battery configuration tool for batterification of rail vehicles is presented.

This tool allows a comparison of different chemistries, cell formats and cell sizes for known energy, power and voltage requirements. The tool can be used to prioritise solutions based on combinations of number of cells, mass, and volume. The benefit of the tool is that it allows a quick and early investigation into the feasibility of hybridisation and/or batterification of rail vehicles. Herein, this is used to compare the performance of four potential lithium-ion batteries, developed using currently available automotive technologies: lithium iron phosphate (LFP), nickel cobalt manganese oxide (NCM), nickel cobalt aluminium (NCA) and lithium titanate (LTO).

Whilst NCM and NCA offer potential in the automotive sector due to their higher discharge rates, this is less important in the rail sector due to symmetry in the acceleration and deceleration rates. Meanwhile LFP offers lower volume and mass

than other chemistries. LTO offers up to 10 times cycle life, with the total cost of the battery over the life of the pack an important consideration for vehicle manufacturers. It should be noted that detailed modelling of the energy and power requirements, considering the exact vehicle and route parameters, is required to specify the battery system further.

The battery pack configuration tool presented in this paper provides a methodology for comparing the technical parameters of different cells, whilst also offering manufacturers considerable learning opportunities. However, the specific choice of cell/configuration can ultimately be guided by other factors, including battery lifetime and economic viability.

Keywords: hybrid, battery, sizing, discontinuous electrification, zero emissions

1 Introduction

All forms of transportation, including rail, are facing pressure to reduce CO2 emitted during operation [1] whilst also reducing harmful local air emissions (NOx, PM, CO) in cities [2]. Rail systems have a long history of using electrical energy to reduce emissions at the point of use [3], typically via overhead catenary and 3rd rail systems [4]. However, whilst they offer superior emissions performance compared to diesel-powered vehicles, such fixed infrastructures lack flexibility, with electrically propelled trains only able to travel where the infrastructure exists. Recent developments to overcome this issue include bi-mode trains, which take power from a catenary system where it exists, and use an on-board diesel generator or on-board energy storage systems [5] elsewhere.

Another alternative to reduce emissions, whilst offering flexibility, is a hybrid diesel-electric train [6], where battery power supplements a diesel generator. This enables the engine to operate more efficiently when it is on, by facilitating operation close to its optimum operating point (OOP) for minimum fuel consumption and hence CO2 emissions. The battery handles the power when the demand exceeds this level; conversely the engine charges the battery when demand is lower than the power available at the engine OOP.

Batteries also offer the possibility of improving the flexibility of catenary or 3rd rail powered vehicles. Here, the batteries allow short periods of electrically powered vehicle operation away from the electric supply; this is the principle of discontinuous electrification [7]. For example, a battery could be used to bridge a gap of 10 km between existing electrified sections, rather than requiring the costly installation of catenary systems. Additionally batteries could be used to provide short term emissions free running of otherwise diesel-powered vehicles, by, for example, sizing the battery to allow the rail vehicle to travel within a zero emission zone if mandated in the future.

The final application of batteries on rail vehicles enables complete catenary free operation, usually for urban areas where catenary systems are considered unsightly. In this case, the sole energy supply for the vehicle is the battery [8].

There is therefore likely to be a large future demand for batteries in rail transportation, requiring a high-level battery pack configuration tool. In this paper, we propose such a tool, derived from automotive applications [9], aimed at simplifying the battery selection process.

2 Methods

The constrained operating parameters of a rail vehicle offers considerable advantages for hybridisation over automotive vehicles. The well-known, physically constrained route is broadly repeatable and follows a defined timetable. In addition, any discontinuities in electrification are known so that the energy and power demands of a vehicle can be accurately calculated [10].

One important distinction compared to automotive battery sizing concerns regenerative braking. In automotive applications, the regenerative braking capability is considerably smaller than the conventional friction brake system as the motors are sized based on acceleration rates and the friction brakes are sized to perform emergency braking manoeuvres. For a rail vehicle, the regenerative braking demands can be the dominant factor in the battery sizing calculations since typically rail vehicles accelerate and brake at similar rates [11]. This means that a rail battery typically has a higher charging requirement during use than an automotive application.

Therefore, to perform a battery configuration exercise for a rail vehicle, the following parameters are required as a minimum:

- System voltage;
- Energy required;
- Maximum discharge power (and duration); and
- Maximum charge power (and duration).

However, this information alone does not offer any realistic constraints on mass or packaging size. Therefore, to narrow a selection down, these additional factors should be considered, along with lifetime requirements and costs.

The current battery chemistry of choice for transport applications is lithium ion, since it has the highest energy and power density of the available electrochemical energy storage options [12]. However, this broad chemistry description contains numerous sub-chemistries, such as nickel-cobalt-manganese-oxide (NCM), nickel-cobalt-aluminium (NCA) and lithium-iron-phosphate (LFP). These chemistries relate to the cathode, with the anode being a form of carbon [13]. There are also cells with anodes from lithium-titanate (LTO), combined with cathodes of a material such as those described above, with NCM the most commonly used [13]. The different properties these cell types have complicates the decision as to which chemistry to use. However, this choice can become considerably more apparent if a consistent sizing methodology is followed, as described herein.

Battery pack configuration and cell selection methodology has been undertaken considering the hypothetical requirements for an existing DMU (e.g. Class 170 Turbostar 2 car set [14]) to be configured for discontinuous electrification and/or emissions-free running in a zero emissions zone:

- System voltage = 800 V;
- Energy required = 50 kWh;
- Discharge power required = 300 kW; and
- Charge power required = 300 kW.

3 Results

Four specific cells have been considered from the aforementioned chemistries. The cells are a mix of pouch format (LFP), prismatic (LTO) and cylindrical format (NCM and NCA) as these represent the 3 type of cells available on the market.

The configuration of the battery pack for these four chemistries is shown in Table 1. A pack designer must first consider if any of the cells offer a pack that is ‘well balanced’. That means that the number of cells required to meet the energy demands is similar to those required to meet the power demands, in this case the LTO and LFP cells are close to this. Additionally, are the number of cells required for charging and discharging similar? There are two chemistries that are broadly symmetric in charge and discharge capabilities, i.e. they are able to be charged and discharged at similar rates – these are LFP and LTO cells, and this can be validated through Table 1. It can be seen, therefore, that for the NCA and NCM chemistries the sizing limitation is dominated by the charging rate of these cells, since the charge rate of these chemistries is typically more than 3 times lower than the discharge rate [13].

The space available on vehicles for battery packs is limited particularly in the case of hybridisation. Additionally, increasing the mass of rail vehicles impacts the current performance and limits the capacity. Hence, thought must also be given to the mass and volume of the cells. Of the chemistries assessed herein LFP offers the lowest mass and volume.

Finally, consideration must be given to the lifetime of the cells for a production vehicle. Here, LTO cells offer a considerable advantage since the cycle life is generally up to 10 times higher than all other chemistries (for the same usage case) [13]. However, ageing performance of cells has a significant dependence on the specific applications, and therefore practical testing is recommended to give an estimate of performance for the specific application [15]. The lifetime in turn impacts the life cycle cost; whilst LTO cells typically require more initial investment than other lithium-ion chemistries [16], the reduced maintenance requirements may offset this over the total pack life. Clearly, considerable detailed design must be performed after this initial study to achieve a suitable battery pack from a performance, lifetime and cost perspective.

Table 1 – Resulting Battery Configuration for the Four Chemistries Considered

		Toshiba 20Ah (LTO)	A123 20Ah (LFP)	Panasonic NCRBD (NCA)	LG HG2 (NCM)
Cells in Series	Ns	348	243	223	223
Strings in Parallel (E)	Np(E)	4	4	21	21
Strings in Parallel (P) (Chrg)	Np(P) (C)	5	4	125	94
Strings in Parallel (P) (DisC)	Np(P) (D)	3	2	38	19
Strings in Parallel	Np	5	4	125	94
Reviewed Strings Parallel	*Np*	***5***	***4***	***125***	***94***
Total # Cells	N	1740	972	27875	20962
Volume of cells	m³	0.471	0.256	0.587	0.441
Mass of cells	kg	896	482	1366	985
Actual Pack Voltage	V	800.4	801.9	802.8	802.8
Actual Pack Energy	kWh	80.0	64.2	301.1	226.4
Compared to Target (E)	%	***160***	***128***	***602***	***453***
Actual Pack Power (Chrg)	kW	320.2	320.8	301.1	301.9
Actual Pack Power (DisC)	kW	640.3	641.5	1003.5	1509.3
Compared to Target (P) (Chrg)	%	***107***	***107***	***100***	***101***
Compared to Target (P) (DisC)	%	***213***	***214***	***335***	***503***

4 Conclusions and Contributions

A battery pack configuration tool has been presented in the context of a rail vehicle. The brief description has highlighted that the choice of chemistry and cell is not straightforward. A case could be made for any chemistry choice depending on the priorities of the manufacturers. Considering rail application requirements, it was shown that the selection is dominated by LTO chemistry, particularly if battery lifetime is also considered.

Therefore, for a production vehicle, it is likely that LTO will be the chemistry of choice, although the final decision depends on the total battery pack cost over the vehicle life, including the cost and frequency of replacement/maintenance. If non-LTO cells can be sourced such that the total battery pack costs over the vehicle life are lower than the LTO solution then this approach could be taken.

Work has been presented that compares the performance of LFP, LTO, NCA and NCM cells for a hybrid rail application. Whilst greater energy and power densities could be achieved using LFP or NCM cells, it has been previously shown that the lifetimes of these chemistries could be prohibitively short [17]. This is a particular concern considering the high availability requirements of rail vehicles and the significantly greater annual distances typically covered than by other transport modes.

However, if the vehicle is expected to see light usage with reduced regenerative braking, more like that seen in the automotive industry where the battery pack might be used for only 1-2 hours per day, NCM or NCA chemistries could be preferred, which could then catalyse developments in the automotive industry.

The battery pack configuration tool presented in this paper allows a good technical cell selection overview and offers considerable learning opportunities. However it is worth noting that other factors, such as battery lifetime and economic viability, could ultimately drive the specific choice of cells for a given application.

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