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Design, Dimensioning and Analysis of a novel, locally emission-free Propulsion Concept for Regional Trains on non-electrified Railway Lines

Holger Dittus*, Marcus Hoffmann, Sebastian Streit, Stefan Kaimer

German Aerospace Center, Institute of Vehicle Concepts, Stuttgart, Germany

*Contact: holger.dittus@dlr.de

Abstract

This paper describes a novel, locally emission-free propulsion concept for regional trains on non-electrified railway lines. The propulsion concept is designed and dimensioned for the *Next Generation Train – LINK (NGT LINK)* train concept, a fast, double deck feeder train developed by German Aerospace Center (DLR). First, the NGT LINK is introduced and a novel propulsion concept based on on-board energy storage units (ESU) and inductive energy transfer system (IETS) is developed. For the dimensioning of the components a round-trip on the modified German relation Ulm - Oberstdorf - Ulm is considered as a non-electrified reference route. Furthermore an implementation strategy pictures out, how the transition from current status quo to complete implementation of the novel propulsion concept may be achieved.

Keywords: non-electrified lines, energy storage unit, inductive energy supply, novel propulsion concept

1. Introduction

Today, approximately 26 % of the worldwide railway network is electrified. In Europe, the degree of electrification is considerably higher with about 51 % [1]. Service on the non-electrified lines is typically provided by diesel multiple units and diesel-locomotive-hauled trains accepting the drawbacks of pollutant emissions and lower traction power compared to electric propulsion systems. However, trackside electrification with overhead catenary lines is often not economically viable, especially on less frequented routes and pure energy storage trains are limited in range [2]. To resolve these issues a novel propulsion concept for non-electrified lines based on on-board energy storage units and inductive power supply is developed and exemplarily dimensioned for the train concept Next Generation Train – LINK [3]. Figure 1 shows a rendering of NGT LINK's end car and the first of five identical intermediate cars.

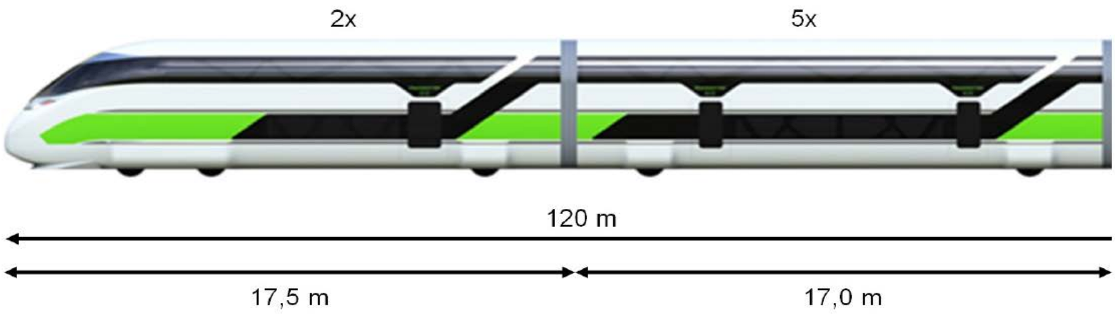


Figure 1: NGT LINK (end car and first intermediate car)

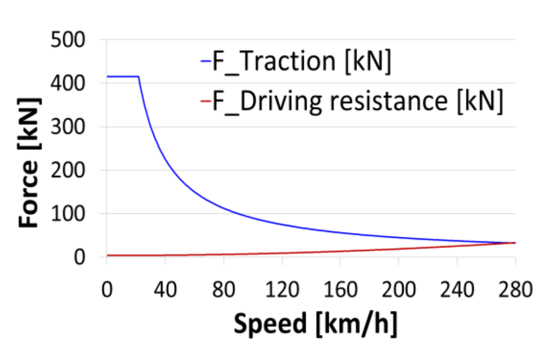
2 Requirement specifications

2.1 NGT LINK concept

Researchers in German Aerospace Centre (DLR) develop innovative concepts for future trains aiming on faster, more comfortable, more efficient and environmentally-friendly transport of passengers and goods, amongst others. One innovative train concept is NGT LINK, a double-decker regional and intercity train specified to travel with up to 230 km/h on electrified lines. This train concept combines a variety of novel technologies like single wheel single wheelsets and modular lightweight honeycomb structures [4].

Table 1: Relevant design parameters according to NGT LINK specification [5]

Starting tractive force at wheel	412 kN
Maximum tractive power at wheel	2500 kW
Maximum operational speed	230 km/h
Design mass (fully loaded)	272 t
Required acceleration from start	1.4 m/s²
Train length	120 m
Train configuration	2 end cars 5 intermediate cars
Constant auxiliary load	303 kW
Number of wheelsets and traction drives	32



The most important requirements for the propulsion concept are to provide locally emission-free train operation, to enable recuperation of brake energy and to guarantee a high degree of modularity, scalability and flexibility.

2.2 Power and energy demand on reference scenario

For the dimensioning of the components a round-trip on the modified German relation Ulm - Oberstdorf - Ulm is considered as a non-electrified reference route including the slopes and speed limitations of the original track (Figure 2). The overall distance of one roundtrip is 254 km. To ensure compatibility to the NGT LINK specification the original relation was modified in terms of served stations: on each trip between Ulm and Oberstdorf and back two intermediate stops are served at Memmingen and Kempten. The train stops two minutes at these stations and 20 minutes at the Oberstdorf turning station.

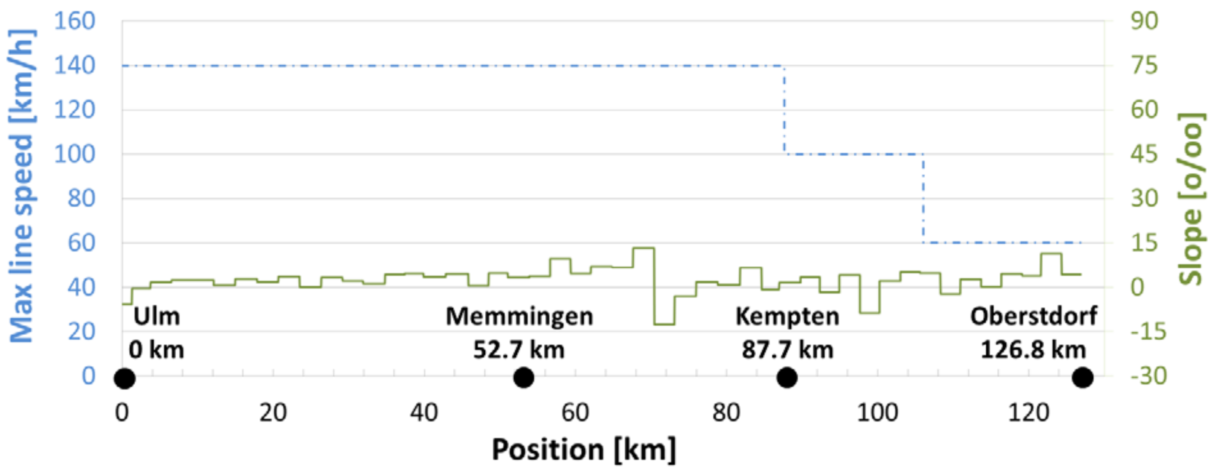


Figure 2: Maximum line speed, station positions and slopes of the reference route Ulm - Oberstdorf

The total journey time Ulm – Oberstdorf – Ulm of almost three hours (10776 s) was determined by simulations with All-Out-driving style and a time reserve of 5 %. The power profile at wheel level is plotted in Figure 3.

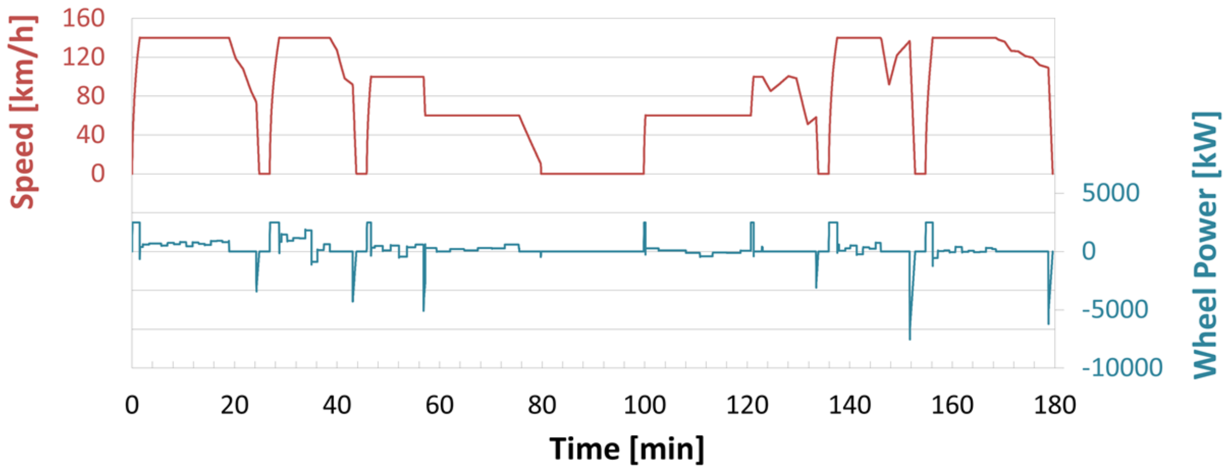


Figure 3: Speed and wheel power for timetable run on reference route Ulm - Oberstdorf - Ulm

The resulting journey times and wheel energies for All-Out and timetable run are shown Table 2. For the dimensioning of energy and power demand a constant auxiliary power of 303 kW at intermediate circuit is assumed (worst case, heating in winter).

Table 2: Journey times, energy and power demand for non-electrified route Ulm - Oberstdorf - Ulm

	All-Out run	Timetable run (5 % time reserve)
Journey time incl. stops [s]	10342	10776
Max. traction / brake power at wheel [kW]	2500 / 7812	2500 / 7534
Traction / brake energy at wheel [kWh]	1099 / 309	900 / 200
Constant auxiliary load at intermediate circuit [kW]	303	303
Auxiliary energy at intermediate circuit [kWh]	871	907

3. Propulsion concept design and analysis

For the NGT LINK three propulsion concepts are developed and discussed in this paper. All concepts are based on electrochemical energy storage systems in combination with external energy supply via inductive energy transfer system (IETS) to charge the energy storage units. Detailed information on the specifics of the suggested IETS can be taken from the paper "Inductive Power Supply for Main-line Railways" by Joachim Winter et al. appearing in the proceedings of this same conference.

The general approach lying behind these concepts is a modular propulsion system with a high degree of scalability and flexibility. The main motivation is to enable a smooth transformation from current state of the art diesel multiple units to the future propulsion systems in different realisation stages. This shall enable an optimised allocation of resources between vehicle (mainly energy storage units) and infrastructure (mainly inductive energy transfer system), where the share of infrastructure investments growths and investments per vehicle decay with increasing number of vehicles on the relation. Thus two of the described concepts allow charging only during standstill phases (static charging) while the third concept also allows charging during driving on defined track sections (dynamic charging). The dynamic charging concept described here takes into account IETS-equipment within a range of three kilometres prior and after each station. The layout of the main current circuit of the train (Figure 4) is intended to be common in all propulsion concepts to provide a high degree of flexibility, modularity and scalability; when additional IETS-modules are installed on a route it shall be possible to adapt the trains already being in use to the new track environment.

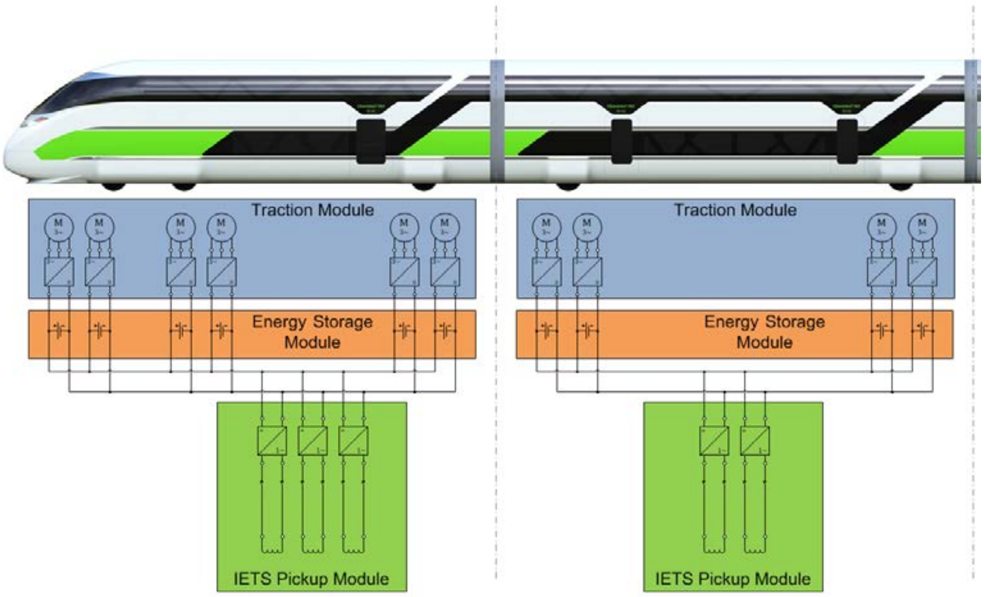


Figure 4: Layout of NGT LINK main current circuit in end car and first intermediate car

While the layout of the main current circuit and the traction drives are identical for the three propulsion concepts, the dimensioning of the on-board energy storage units varies according to the energy demand resulting from the different charging options. To evaluate the energy demand at energy storage unit average efficiencies for the propulsion components have been defined; with 90 % for the traction drive and 95 % for the traction inverter, the overall traction efficiency is 85.5 %. Furthermore it was taken into account, that the recuperation is limited to the maximum electric brake power of 2500 kW at wheel level. The efficiency of the ESU was set to 98 %. The energies, which have to be provided by the energy storage unit during the round trip are displayed in Figure 5, with the energy at start set to zero.

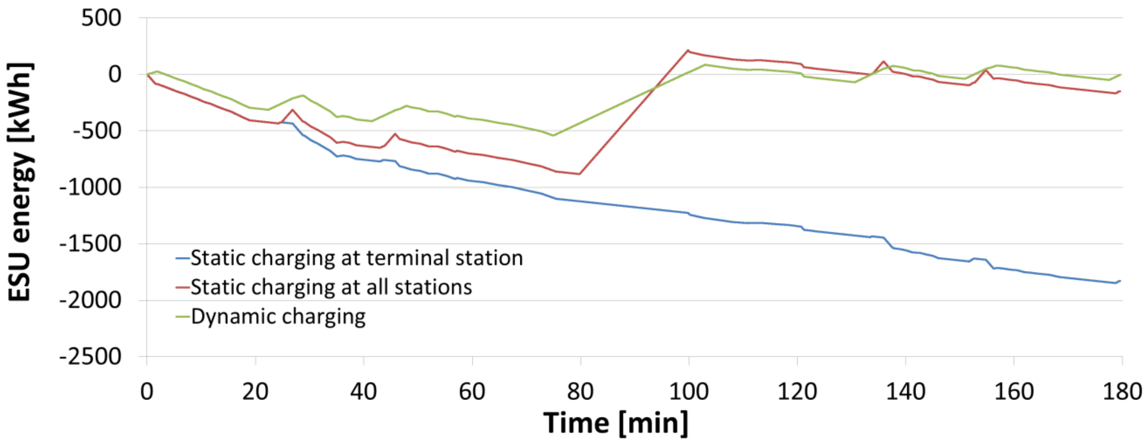


Figure 5: ESU energy for non-electrified track Ulm-Oberstdorf-Ulm

Table 3 summarises the results. Obviously, concept 3 (dynamic charging) requires the smallest useable capacity for the energy storage unit. In comparison to concept 1 (static charging at terminal station) the capacity of the energy storage unit is reduced by 66 %. Another benefit of this concept is the possibility to start a new round trip without waiting for the storage unit to be recharged.

Table 3: Comparison of resulting energy demand

	Concept 1: Static charging at terminal station	Concept 2: Static charging at all stations	Concept 3: Dynamic charging
Change of energy storage content (start to end) [kWh]	-1830	-150	-3
Maximum discharge [kWh]	1848	1097	627
Required recharging energy after round-trip [kWh]	2080	170	3
Required recharging time [min]	34	3	0
External total energy [kWh]	2080	2069	2045
Energy savings compared to concept 1	0	0,5%	1,7%

4 State of the art component characteristics

This section summarises characteristic properties of state of the art propulsion components in terms of energy and power density and specific energy and power. To derive the values a component database was build incorporating data sheets of commercially available components for railway traction system components. Regarding electrochemical energy storages the analysis of currently available storage units resulted in selecting the lithium nickel manganese cobalt oxide chemistry (NMC) as most suitable chemistry for the requirements of the propulsion concept of NGT LINK.

Table 4: Characteristic properties of components for NGT LINK propulsion concept

	Specific power [W/kg]	Power density [W/l]	Specific energy [Wh/kg]	Energy density [Wh/l]
Lithium based battery (NMC)	264	355	91	123
Traction inverter	770	620	-	-
IETS rectifier	1160	930	-	-
Auxiliary converter	370	170	-	-
IETS Pick-up-module	1647	-	-	-

As mentioned before each single wheel single wheelset uses the same traction drives. They have been developed and dimensioned within the Next Generation Train project. Each of the 650 kg traction drives is designed for a nominal mechanical power of 80 kW resulting in NGT LINK’s total wheel traction power of 2560 kW.

5. Propulsion concept dimensioning

The requirements specification for the NGT LINK train concept includes specifications of target mass and target volume of the propulsion system. The dimensioning of the components is based on the previously specified and calculated powers and energies in conjunction with the characteristic component properties specified in Table 4. As an additional constraint for the energy storage system it is assumed, that the admissible Depth of Discharge (DoD) is limited to 60 % in all cases. The results of the component dimensioning are displayed in Figure 6. It is obvious that realisation of concept 1 (static charging only at terminal station) is not viable due to neglecting mass and volume restrictions. The other concepts are in accordance with the conceptual design mass and volume.

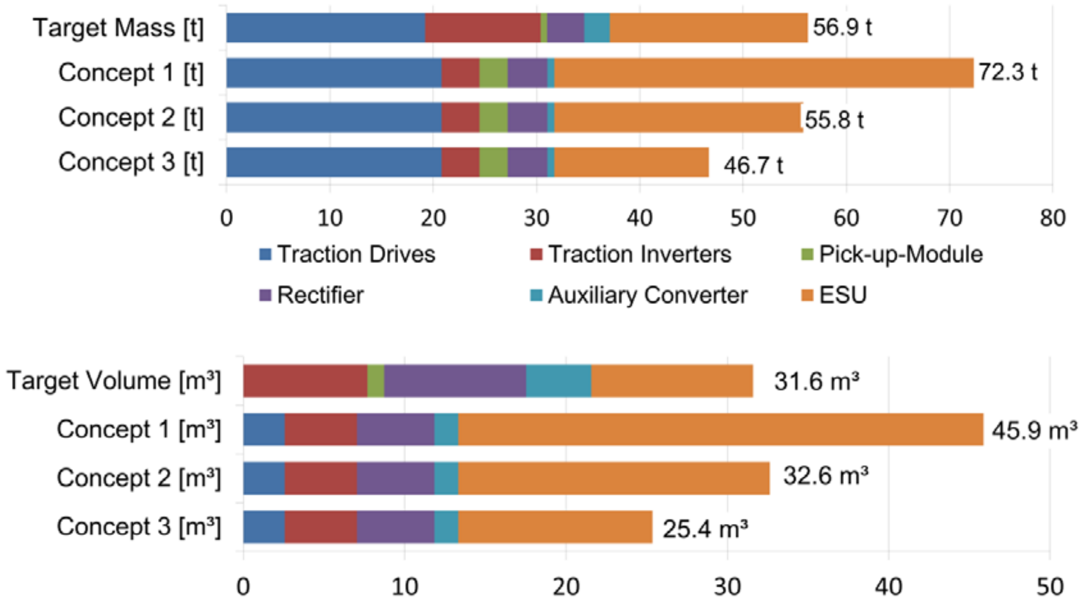


Figure 6: Mass and volume balances of the three propulsion concepts compared to specified targets

6 Implementation strategy and modularity of the NGT LINK propulsion concept

Currently service on non-electrified railway lines is provided with diesel-driven trains and multiple units. In future some of these lines may be operated by electric locomotives and electric multiple units, which are especially adapted by integration of a small diesel-generator. Nevertheless these so called "Last-Mile" propulsion concepts are neither able to completely avoid diesel emissions in the long term, nor do they provide the necessary performance to serve greater distances on non-electrified lines. The major novelty of the proposed NGT LINK propulsion concept is its focus on operation on these non-electrified lines in conjunction with avoiding diesel propulsion and related emissions in the long term. Furthermore the underlying implementation strategy (Figure 7) enables a smooth transition from current non-electrified lines to future infrastructure with demand-oriented partial IETS-electrification.

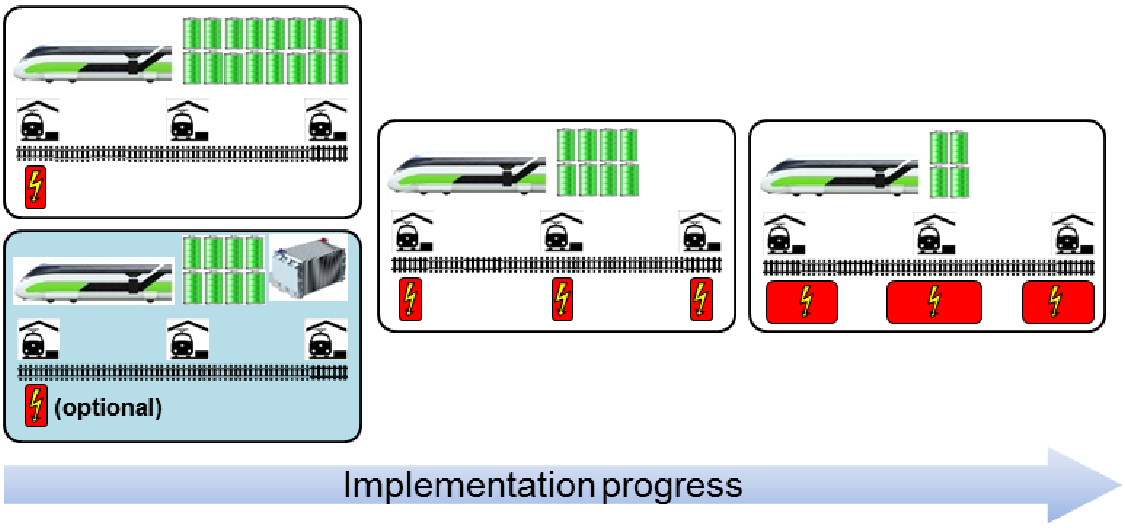


Figure 7: Shifting of traction equipment from vehicle to track during different implementation phases

At the beginning of implementation two propulsion variants are used to substitute current diesel-driven vehicles: either a propulsion system incorporating energy storages and independent power sources (fuel cells or internal combustion engine with generator) or a pure energy storage based propulsion system. If the electric energy provided by the independent power source during a round trip is sufficient to ensure charge sustaining operation of the energy storage system, the whole propulsion system is referred to as a hybrid system. If, in contrast, energy storage is operated in charge depleting manner the propulsion system is called a range extender system. Both, range extender and pure energy storage propulsion systems depend on external power supply via IETS, while the hybrid propulsion system is not bound to external energy supply. According to the implementation strategy the share between energy storage equipment installed in the vehicle(s) and trackside IETS equipment is shifted towards track with increasing demand, i.e. when the number of vehicles and / or traffic on the line increases. This allows efficient allocation of resources tailored to the specific requirements of each line.

To provide flexible choice of energy sources required for the implementation strategy the basic propulsion concept is designed to be extended with additional power modules (Figure 8). During the first implementation phase the independent power source (fuel cells or internal combustion engine with generator) and related subsystems such as fuel tanks or cooling equipment are installed in one or both end car(s), depending on dimensioning of the power to be delivered by the optional systems. If the train shall also be used on tracks electrified with a catenary, the mid-train intermediate car is intended to be substituted by a special car equipped with a pantograph and transformer. In this case all cars are connected by an electrical interface between the IETS Pickup Modules. Hence, the higher voltage level ensures low currents compared to a connection on battery voltage level, thus limiting losses during energy transfer.

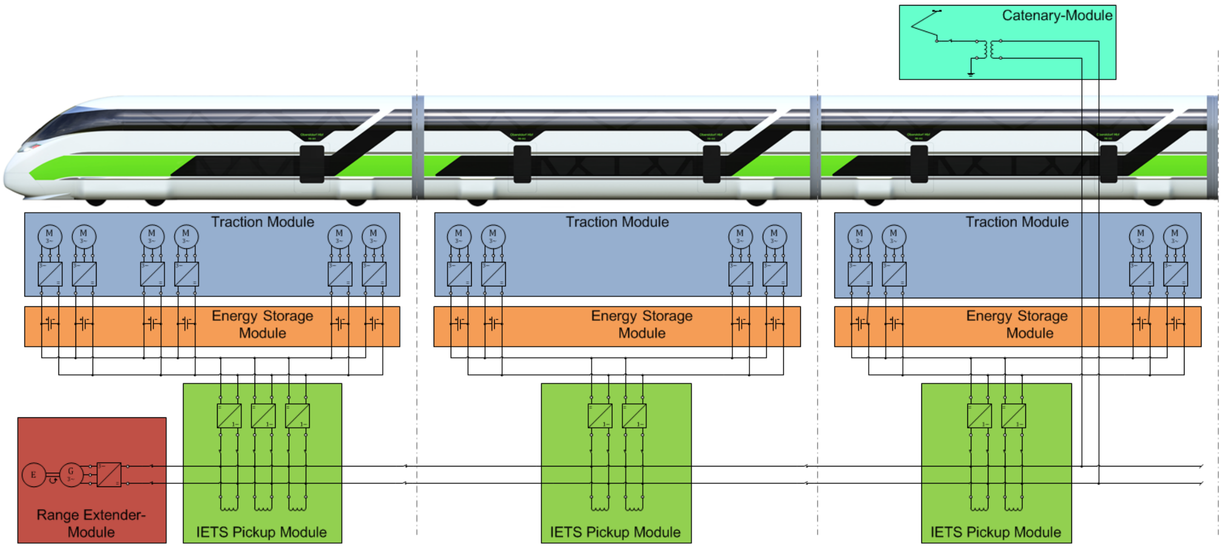


Figure 8: Layout of NGT LINK main current circuit with optional power modules

7 Conclusions and outlook

This paper described design and dimensioning of locally emission free propulsion concepts for non-electrified lines taking the DLR train concept NGT LINK as an example. Three concepts have been developed and the components have been dimensioned for a reference scenario. Analysis of the propulsion concepts with static charging shows, that with an increase of intermediate charging opportunities the on-board energy storage capacity can be reduced significantly. However, in the reference scenario pure static charging at terminal station is not viable for NGT LINK due to mass and volume restrictions.

The dynamic charging concept is the most energy efficient concept due to the fact that the IETS power is used instantaneously for acceleration, while in the other concepts additional losses occur as a result of storing the energy in the ESU. In comparison to concept 1 energy savings of ~1.7 % are achieved. However, this concept requires the highest effort in infrastructure investments for the IETS. With dynamic charging the energy storage capacity may be reduced thus far, that the ESU is not able to provide the required charge / discharge power any more. In this case the storage sizing is dominated by the power requirement; in the concepts with static charging the sizing was done according to the energy demand.

Future work will be done in the field of hybrid propulsion concepts for NGT LINK. The main current circuit demonstrated in this paper is intended to incorporate stand alone electricity sources like fuel cells or power sets based on internal combustion engines. In conjunction with a proper sizing of storage this enables operation of the propulsion system on tracks without any external energy supply. The concept also foresees combination with a catenary based external energy supply for mixed operation on electrified and non-electrified lines.

[1] International Union of Railways – UIC (2013). Railway Statistics – Synopsis 2013. http://old.uic.org/spip.php?article3299 [downloaded on 2016-02-19]

[2] Y. Kono et al., "Catenary and storage battery hybrid system for electric railcar series EV-E301," Proceedings of the Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE-ASIA), 2014.

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[4] David Krüger and Joachim Winter, "High-Speed Feeder Passenger Train − NGT LINK," in *Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance*, vol. 104, Ajaccio, France, 2014.

[5] Stefan Kaimer, Sebastian Streit and Joachim Winter, "High-Speed Passenger Train NGT Link: Propulsion and Electrical Power Supply Concept," in *Proceedings of the Second International Conference on Railway Technology: Research, Development and Maintenance*, Ajaccio, France, 2014.