



## Cost and Efficiency Optimization for a Reconfigurable E-Bike Battery System for EPE'25

Julian Estaller, Nina Sorokina, Wolfgang Grupp, Johannes Buberger, Tobias Högerl, Andreas Wiedenmann, Sebastian Pohlmann, Manuel Kuder, Thomas Weyh

### ► To cite this version:

Julian Estaller, Nina Sorokina, Wolfgang Grupp, Johannes Buberger, Tobias Högerl, et al.. Cost and Efficiency Optimization for a Reconfigurable E-Bike Battery System for EPE'25. The 26th European Conference on Power Electronics and Applications, GDR SEEDS France & EPE Association, Mar 2025, Paris, France. 10.34746/epe2025-0189 . hal-05105927

**HAL Id: hal-05105927**

**<https://utc.hal.science/hal-05105927v1>**

Submitted on 10 Jun 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY 4.0 - Attribution - International License

# Cost and Efficiency Optimization for a Reconfigurable E-Bike Battery System for EPE'25

Julian Estaller, Nina Sorokina, Wolfgang Grupp, Johannes Buberger, Tobias Högerl, Andreas Wiedenmann, Sebastian Pohlmann, Manuel Kuder, Thomas Weyh

Universität der Bundeswehr München

Werner-Heisenberg-Weg 39

Munich, Germany

Tel.: +49 89 60043734

E-Mail: [julian.estaller@unibw.de](mailto:julian.estaller@unibw.de) URL: <https://www.unibw.de/>

***Index Terms***—Cascaded H-Bridge, Cost Analysis, CHB, E-Bike, Efficiency, Micromobility, Multilevel, Modular Multilevel Converters (MMC), RBS, Reconfigurable Battery System.

***Abstract***—This study optimized and evaluated the module voltage level of an e-bike's reconfigurable battery system for efficiency and costs against a conventional powertrain. For micromobility applications, findings indicate that with today's semiconductor switches, these systems remain less competitive than a conventional, two-level inverter powertrain, with a 5% efficiency and 18% cost disadvantage.

## I. INTRODUCTION

Reconfigurable Battery Systems (RBS) are gaining interest in research and development, as they promise a number of advantages. Within the scope of this work, RBS refers to a modular battery storage system, whose modules can be reconfigured with the help of semiconductor switches - in other words, battery cells are not arranged in a fixed way as in conventional battery storage systems. The battery modules can be electrically reconfigured so quickly, that a sinusoidal output voltage of a module string can be obtained - which makes additional power electronics for supplying a load with AC superfluous. In a nutshell, this so-called multilevel (direct) inverter (MLI) promises the following advantages [1]:

- Higher Efficiency
- Lower Cost
- Better Electromagnetic Compatibility (EMC)
- Lower Total Harmonic Distortion (THD)
- Redundancy
- Safety

- Increased usable capacity.

The design of the modules, in particular the number and arrangement of the battery cells per module, has a decisive influence on whether the advantages mentioned can actually be realized. To investigate this, an electric powertrain of an e-bike will be optimized as a case study, where the total number of battery cells will be kept constant, but the number of cells per module - and therefore the number of modules in the powertrain - will be varied. The systems efficiency and part costs will be evaluated and compared for each setup of the multilevel powertrain.

The aim of this work is therefore to provide a methodology for the optimization of module sizes for RBS concepts, which is also of interest for other applications such as stationary energy storage, the automotive industry or electric aviation. Furthermore, the first ever concept for a multilevel-based e-bike is to be presented in order to evaluate the relevance and readiness of this technology for electric micromobility vehicles.

The following section II describes the structure of a conventional e-bike. The drive concept for a multilevel e-bike is then explained in section III. Section IV deals with the methodology, i.e. how the efficiencies of the different concepts were determined and how the cost comparison was carried out. Section V presents the results, followed by a conclusion in section VI.

## II. CONVENTIONAL E-BIKE

An e-bike is a bicycle that supports the rider when pedaling by providing additional torque via an electric powertrain. A purely electric riding mode that eliminates the need for the rider to pedal is not usually provided [2].

For most e-bikes, the supporting torque of the electric drivetrain is combined with the muscle-generated torque in a gearbox; its magnitude is determined by a riding mode selected by the user, and the amount of muscular torque generated at any given time. Assistance is generally only provided up to a legally prescribed maximum speed of, for example, 25 km/h in the (European Union) EU [3]. Energy recovery through recuperation of kinetic energy during braking is not usually implemented. The electric powertrain of an e-bike typically consists of the following components:

- Battery System
- Controller and Inverter
- Electric Motor
- Gearbox.

The components of the conventional e-bike are briefly described in the following to illustrate the difference to the multilevel concepts.

#### A. Battery System

Figure 1 shows a commercially available, conventional e-bike battery system built by Bosch.

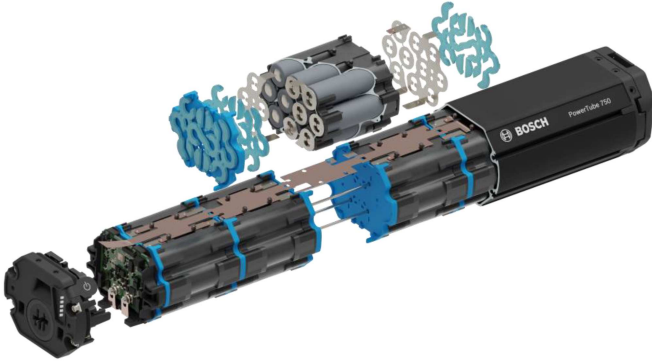


Fig. 1. Conventional battery system of an e-bike [4].

Besides the housing, cylindrical battery cells, often in the 18650 format, can be seen. A battery pack of this size typically has a cell configuration of four cells connected in parallel, and ten to twelve cells connected in series, resulting in a nominal voltage of 37 to 45 V and a capacity of approximately 444 to 540 Wh. In addition to the battery cells, a battery management system (BMS) is integrated, which monitors and passively balances the voltages of the serially connected cell units.

#### B. Controller and Inverter

Controller and inverter are usually integrated on a single PCB. A MOSFET-based six-pulse three-phase inverter is supplemented on the DC side by DC-link

capacitors for battery current smoothing. In the case of the PCB shown in Fig. 2 (Bosch Active Line 3 drive unit), for example, there are four 100  $\mu$ F capacitors in parallel.

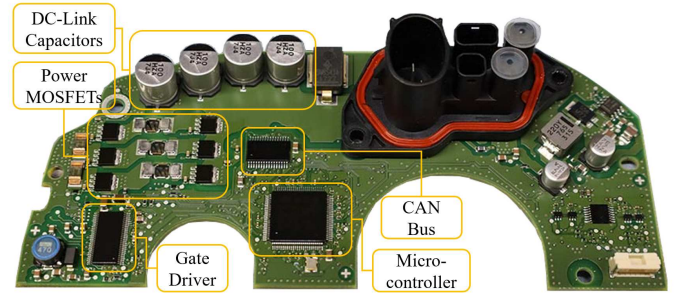


Fig. 2. Combined controller and inverter of a Bosch Active Line 3 drive unit [5].

The controller typically regulates the motor current via a sinusoidal pulse-width modulation (PWM).

#### C. Electric Motor and Gearbox

Permanent magnet synchronous machines (PMSM) are typically used in e-bikes [6]. These are in the range of approximately 600 W maximum power, 5 Nm maximum torque and a maximum speed of approximately 6,000 rpm, even though much lower rotational speeds are sufficient to reach the speed limit of 25 km/h. The output power of the motor is converted to a lower speed and higher torque level with a fixed transmission ratio of around 15. Figure 3 shows an exploded view of the Bosch Active Line 3 drivetrain with motor and gearbox.

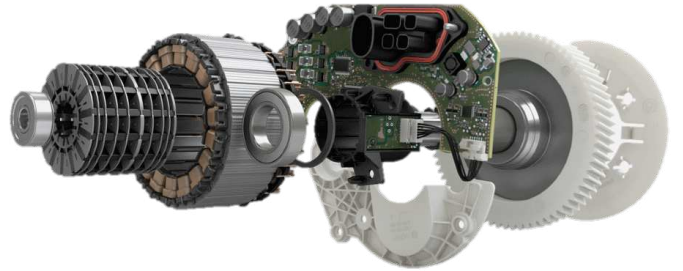


Fig. 3. Exploded view of the Bosch Active Line 3 drivetrain [5].

### III. MULTILEVEL E-BIKE

The electric motor and gearbox remain unchanged for the conversion to a multilevel-based electric drivetrain. The inverter and the DC-link capacitor are omitted. Instead, the battery cells are all connected to a PCB, which houses the semiconductors for reconfiguring the cells. The number of battery cells remains constant. The

cells are distributed evenly across three strings, each of which feeds one motor phase. The other side of the strings is connected to a neutral point. Within a string, the cells are again divided into modules. This is where the actual parameter variation takes place: Concepts with many modules per string can be chosen, which reduces the number of cells per module, resulting in a low module voltage, and increases the total number of semiconductors required. The other extreme would be only one module per string, which requires fewer semiconductors at a high module voltage. The different variants and their specific advantages are discussed in more detail in section IV-A.

Cascaded H-Bridges (CHB) are used for the module topology. This topology allows four-quadrant operation and a bypass of battery cells, but without the option of connecting battery cells from different modules in parallel [7]. Figure 4 illustrates one of the three strings with the CHB topology.

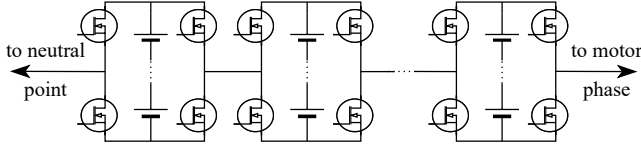


Fig. 4. One of three multilevel strings with CHB modules.

The reason for choosing this topology is that four-quadrant operation is essential in order to be able to generate a high voltage amplitude with few cells, which for example cannot be realized with a half bridge topology [8]. Topologies that allow a parallel connection of adjacent modules, such as a Modular Multilevel Series Parallel Converter (MMSPC), were not considered for this usecase, as the additional complexity of such topologies, and the doubled semiconductor costs per module compared to CHB, do not justify the potential efficiency advantage for an e-bike.

#### IV. METHODOLOGY

This section describes which concepts for the multilevel powertrain are evaluated and what state-of-the-art concept they are compared against. Furthermore, it is explained how the efficiency and cost comparisons were carried out.

A conventional battery system with a 12S4P configuration is used as a reference, which is connected to a six-pulse three-phase inverter with a DC-link capacitor. This results in a total number of 48 cells. Figure 5 shows the schematic structure of the concept.

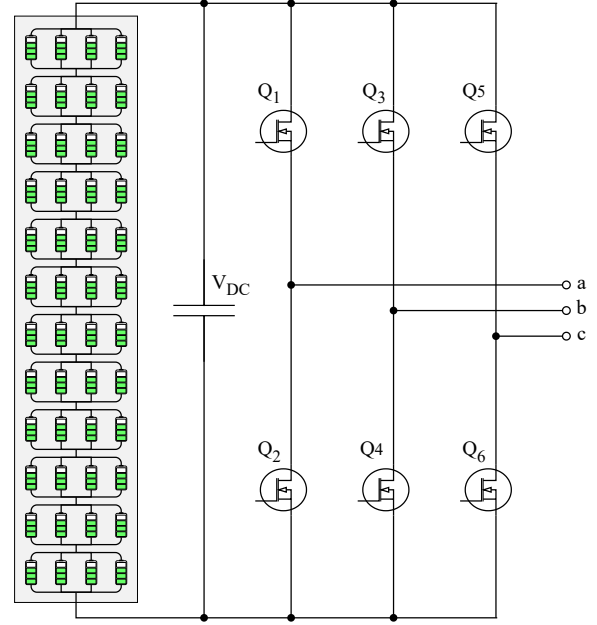


Fig. 5. Conventional battery system with 12S4P configuration and a MOSFET-based six-pulse three phase inverter as a reference to compare the multilevel concepts against.

For a fair comparison, the number of cells for the multilevel concepts is also set to 48, resulting in 16 cells per phase. The conventional battery system achieves a peak voltage per phase of  $48V/\sqrt{3} \approx 28V$  when space-vector modulation is used to control the motor. This corresponds to approximately eight serial cells per phase for the multilevel concepts, so that the peak phase voltage output is comparable. This also means that all modules have a 2P configuration. If only identical modules are to be used in all phases, the following module configurations are conceivable: 1S2P, 2S2P, 4S2P and 8S2P. The resulting concepts are shown in Figure 6.

The following nomenclature is introduced for simple naming of the concepts: xM-yS-zP, where x is the number of modules in the entire drive train, and y and z are the number of serial and parallel connected battery cells per module.

##### A. Efficiency Analysis

In order to facilitate an efficiency comparison, three operating points (P1 to P3) for each concept for the electric powertrain are evaluated in Matlab Simulink, and the resulting losses are compared. Of particular interest are the battery, conduction and switching losses. Point P1 represents a point with high torque but low speed, P2 is in the middle range for both parameters, and P3 is

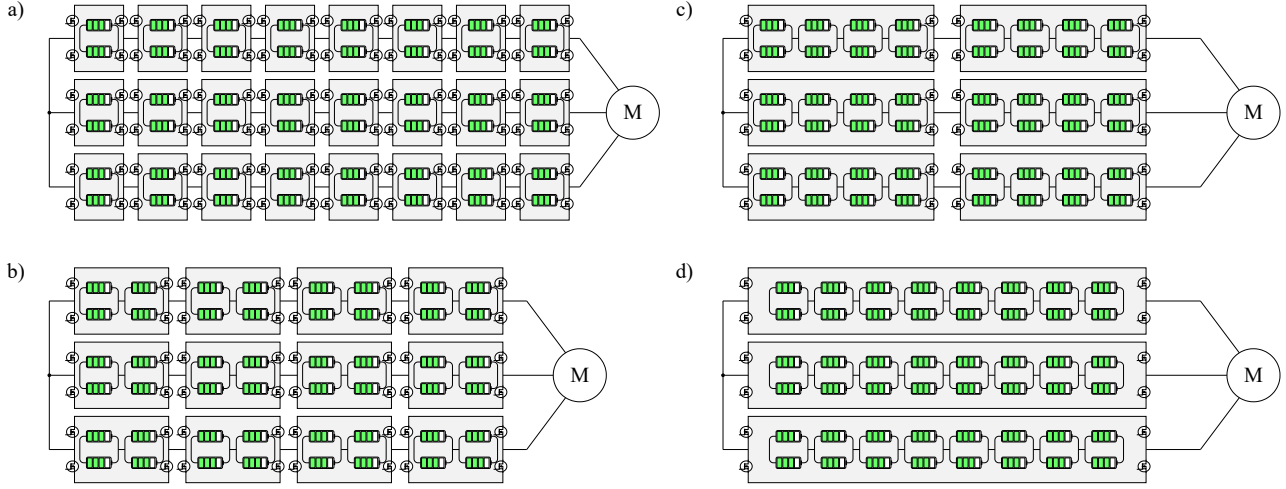


Fig. 6. Concept overview of the different module sizes: a): 24M-1S-2P, b): 12M-2S-2P, c): 6M-4S-2P, d): 3M-8S-2P.

an operating point with high speed and low torque. The points are shown in the characteristic map of a fictional e-bike motor in Fig. 7.

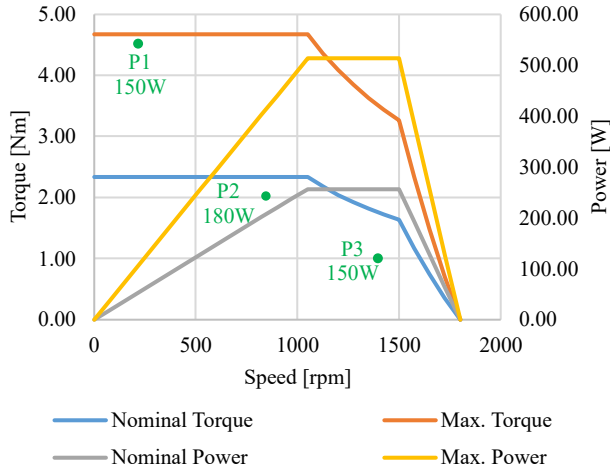


Fig. 7. Motor map of a typical e-bike PMSM with the three operating points P1 to P3.

The map shown in Fig. 7 serves as a reference for further calculations. It displays a constant torque range up to a speed of 1,100 rpm. This is followed by a field-weakening range up to 1,500 rpm, after which the electric assistance is reduced up to a speed of 1,800 rpm. This corresponds to a speed of 25 km/h. The overload factor between nominal and maximum power is 2. Table I presents the three operating points P1 to P3 again in numerical form, supplemented by the parameters power factor, phase voltage and electrical frequency.

The simulation model for the efficiency analysis

TABLE I  
OPERATING POINTS P1 TO P3

| Operating Point | Parameter |            |           |
|-----------------|-----------|------------|-----------|
|                 | Power $P$ | Torque $T$ | Speed $n$ |
| P1              | 150 W     | 4.77 Nm    | 250 rpm   |
| P2              | 180 W     | 2.15 Nm    | 1400 rpm  |
| P3              | 150 W     | 1.02 Nm    | 1800 rpm  |

| Operating Point | Parameter              |                         |               |
|-----------------|------------------------|-------------------------|---------------|
|                 | Power Factor $\lambda$ | Phase Voltage $\hat{V}$ | Frequency $f$ |
| P1              | 0.87                   | 2.0 V                   | 29.2 Hz       |
| P2              | 0.95                   | 11.2 V                  | 163.3 Hz      |
| P3              | 0.83                   | 14.4 V                  | 210.0 Hz      |

consists of a simple motor model, as well as battery models at module level and MOSFET models. These models are described in more detail in the following.

1) *Motor Model*: The motor is modeled as a three-phase inductive-resistive load. Therefore, a single series RL element represents each of the three motor phases, whereby all three RL elements are connected to a neutral point. To ensure that the correct current flows at the correct phase offset when the required phase voltage is applied for each of the three operating points, the RL elements must be parameterized for the specific operating point. This calculation is derived in the following eqs. (1 - 5).

Based on the active power  $P$ , the apparent power  $S$  can be calculated using the power factor  $\lambda$ ,

$$S = \frac{P}{\lambda} \quad (1)$$

and the peak phase current  $\hat{I}$  can be derived from  $S$  by the peak phase voltage  $\hat{V}$  in each of the three symmetrical motor phases as

$$\hat{I} = \frac{S}{3 \cdot \hat{V}} \quad (2)$$

Phase current and phase voltage are related via the impedance  $Z$  of a phase, see eq. (3). Based on the power factor, the impedance can be divided into the resistive component  $R$  of the RL element, and the reactance  $X_L$  according to eq. (4 - 5). Taking the frequency  $f$  into account, the inductance  $L$  of the RL element can be calculated, see eq. (6).

$$Z = \frac{\hat{V}}{\hat{I}} \quad (3)$$

$$R = Z \cdot \lambda \quad (4)$$

$$X_L = \sqrt{Z^2 + R^2} \quad (5)$$

$$L = \frac{X_L}{2\pi f} \quad (6)$$

2) *Battery Model*: The battery model consists of an ideal voltage source and a series resistor. The model serves two purposes: To provide the cell voltages  $V_{\text{Cell}}$  and to determine the battery losses  $P_{\text{Loss, Cell}}$  resulting from the battery current  $I_{\text{Cell}}$  and internal resistance  $R_{\text{Cell}}$  according to eq.(7)

$$P_{\text{Loss, Cell}} = I_{\text{Cell}}^2 \cdot R_{\text{Cell}} \quad (7)$$

and is therefore kept as simple as possible. Balancing, thermal management and ageing of the cells are not of interest. Adding RC-elements to the model would improve the dynamic behavior of the cell models at the expense of computing time, but would have no significant influence on the loss determination and was therefore omitted. The cylindrical battery cell LG HG2 by LGChem in the 18650 format was selected to determine a cell voltage of  $V_{\text{Cell}} = 3.7\text{V}$ , a capacity of  $C_{\text{Cell}} = 3\text{Ah}$  and an internal resistance of  $R_{\text{Cell}} = 25\text{ m}\Omega$ . The data is taken from [9].

3) *Switch Model*: The semiconductor model for the simulation is based on a MOSFET model from Simscape Electrical [10]. This model can be parameterized with data sheet values and has a body diode and a snubber. Using the gate input as well as current and voltage measurements on the MOSFET, the model was extended by including a loss calculation, whereby a distinction

was made between conduction losses and switching losses. The calculation is based on eq. (8) and (9)

$$P_{\text{Loss, On}} = I_{\text{MOSFET}}^2 \cdot R_{\text{DS, on}} \quad (8)$$

$$P_{\text{Loss, Sw}} = \frac{1}{6} t_{\text{sw}} U_{\text{Fet}} I_{\text{Fet}} f_{\text{sw}} \quad (9)$$

where  $t_{\text{sw}}$  is the sum of the switching times for turning the MOSFET on and off,  $f_{\text{sw}}$  is the switching frequency, and  $U_{\text{Fet}}$  and  $I_{\text{Fet}}$  are the mosfets' current and voltage whilst a switching event.

The different module voltages also require different drain to source voltages  $V_{\text{DSS}}$ , so that a different MOSFET with specific parameters must be used for each module configuration. The corresponding parameters can be found in Tab. II.

TABLE II  
MOSFET PARAMETERS

| Concept   | $V_{\text{DSS}}$ | $R_{\text{DS, on}}$ | $t_{\text{sw}}$ | Manufacturer Code |
|-----------|------------------|---------------------|-----------------|-------------------|
| 24M-1S-2P | 25 V             | 0.30 m $\Omega$     | 25 ns           | IQDH29NE2LM5CG    |
| 12M-2S-2P |                  |                     |                 |                   |
| 6M-4S-2P  |                  |                     |                 |                   |
| 3M-8S-2P  | 45 V             | 0.95 m $\Omega$     | 62 ns           | XP4NAR95CMT-A     |
| 1M-12S-4P | 60 V             | 4.80 m $\Omega$     | 58 ns           | BUK7Y4R8-60E      |

The semiconductor switch for the state-of-the-art concept (1M-12S-4P) is taken from a teardown of the Bosch Active Line 3 drivetrain [5]. For each of the multilevel concepts, a best-in-class MOSFET was selected that offers the lowest on-resistance for the required drain-source voltage. 25V MOSFETs were used for the 24M-1S-2P and 12M-2S-2P concepts, although MOSFETs in lower voltage classes, e.g. 8V and 12V, are also available. However, to date there are comparatively few applications for these voltage classes, which means that they are not technologically mature with regard to their on-resistance. The best-in-class 8V MOSFET (SI7100DN-T1-E3), for example, features an  $R_{\text{DS, on}}$  of 3.5 m $\Omega$ , which, in combination with the high number of modules, would lead to an unsustainably high string impedance. The lack of technological maturity in low-voltage MOSFETs results in higher prices of the multilevel concepts, as the 25V MOSFETs are more expensive than low-impedance 8V and 12V MOSFETs could be. Only one MOSFET was ever selected for each switch position instead of installing several higher-ohmic MOSFETs in parallel. This is due to the fact that a single MOSFET with a defined  $R_{\text{DS, on}}$  is usually cheaper than

installing several MOSFETs with the same effective  $R_{DS,on}$  in parallel.

### B. Cost Comparison

In addition to efficiency, the costs of the systems must also be taken into account for a meaningful comparison of the multilevel concepts with each other and with the state of the art. For this purpose, 6,500 MOSFET data sets were downloaded from the online distributor platform *DigiKey* in order to establish a correlation between drain-source voltage, on-resistance and price. The data is shown in Fig. 8.

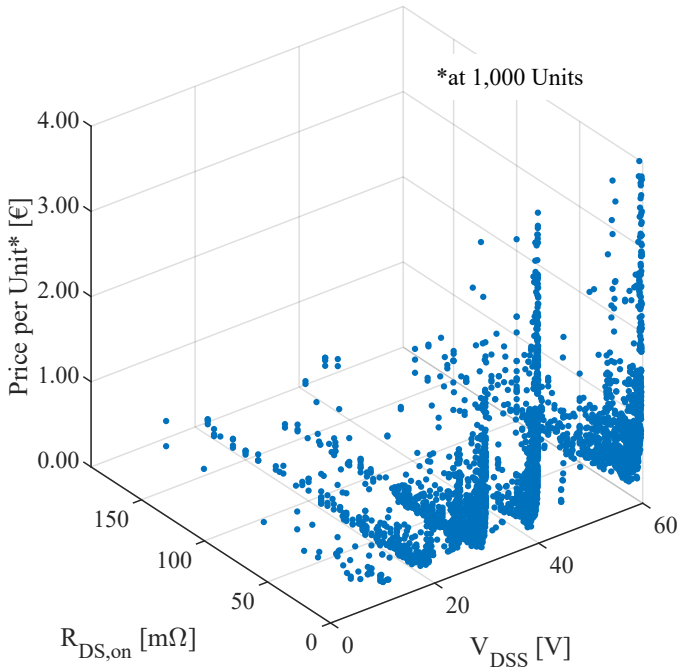


Fig. 8. Scatterplot of all MOSFET Data.

The unit prices shown here are given for a purchase of 1,000 units. The following filters were applied for selecting relevant MOSFETs:

- Surface Mounted Device
- Drain-Source Voltage  $\leq 60$  V
- Active Product Status
- N-Channel.

Surprisingly, there is a noticeable gap for the price range 0.90€ and 1.60€ to 1.70€ - no MOSFETs are offered in these price regions. This is presumably due to the distributor's internal pricing policy. There is also a clustering into the voltage classes 8V, 12V, 20V, 25V, 30V, 40V, 55V and 60V. In addition, there are smaller clusters of less frequently offered voltage classes. The data suggests that MOSFETs are in particularly high demand in the 20V, 30V, 40V and 60V voltage classes,

as the supply is particularly high here. In addition, the expected trend can be seen that MOSFETs with a low  $R_{DS,on}$  tend to be more expensive.

Based on the MOSFET data set, pareto fronts were identified for the voltage classes, which show what is technologically possible in terms of the resistance of the MOSFETs according to the state of the art, and what must be paid for a MOSFET with certain properties. The pareto fronts are shown in Fig. 9.

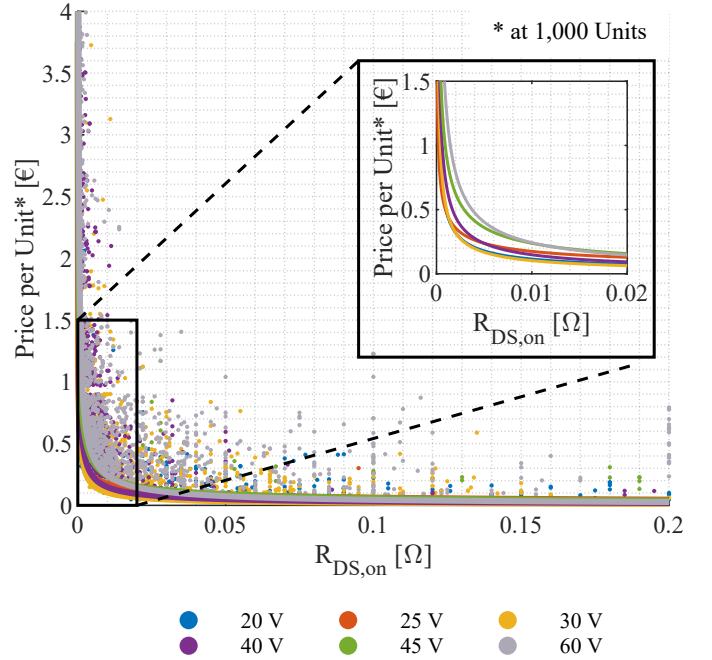


Fig. 9. MOSFET data with interpolated pareto fronts for different voltage classes. Data points have been hidden in the zoomplot for improved readability of the pareto fronts.

A MOSFET located on such a pareto front indicates for a certain voltage class what must be paid for a certain resistance, or also what resistance value can be expected for a certain price. These relationships can be used to determine the prices for the cost analysis of the multilevel and state-of-the-art e-bike concepts. In addition, the relative position of the pareto fronts in relation to each other shows the trend that MOSFETs with a higher drain-source voltage tend to be more expensive if the same  $R_{DS,on}$  is to be achieved. The prices for a single MOSFET of a certain voltage class, given that 1,000 units are purchased, are presented in Tab. III.

From the gradients of the Pareto fronts it can already be seen that, as mentioned before, a single MOSFET at a certain  $R_{DS,on}$  is more favorable than, for example, two MOSFETs with twice the  $R_{DS,on}$  each, which could theoretically be installed in parallel.

TABLE III  
PARETO-OPTIMIZED MOSFET PRICES

| Concept   | $V_{DS}$ | $R_{DS,on}$     | Price  |
|-----------|----------|-----------------|--------|
| 24M-1S-2P | 25 V     | 0.30 m $\Omega$ | 0.83 € |
| 12M-2S-2P |          |                 |        |
| 6M-4S-2P  |          |                 |        |
| 3M-8S-2P  | 45 V     | 0.95 m $\Omega$ | 0.98 € |
| 1M-12S-4P | 60 V     | 4.80 m $\Omega$ | 0.42 € |

The observation that one low-resistance MOSFET is cheaper than several higher-resistance MOSFETs in parallel does not even take into account the fact that several MOSFETs per switching position require additional manufacturing, packaging and driver costs. In addition to the costs for the power MOSFETs, there are other costs for the system:

- Driver Costs
- Battery Costs
- BMS Costs
- Development Costs
- Manufacturing Costs
- After Sales Costs
- Distribution Costs.

How these additional costs were taken into account is described in the following.

1) *Driver Costs*: The costs for the MOSFET drivers are calculated using a simple rule of thumb:

$$C_{\text{Driver}} = \frac{1}{2} C_{\text{MOSFET}} \quad (10)$$

2) *Battery Costs*: For the battery cells, the price of the online distributor *nkon.nl* was set at 2.36€ for a purchase of 1,000 units.

3) *BMS Costs*: BMS units are required for all modules that exceed a number of serially connected battery cells per module  $N_S$  of one. This means that concepts with more modules also require more individual BMS units, which results in additional BMS costs  $C_{BMS}$ . In general, BMS units are cheaper if fewer cells have to be balanced. The following cost model was therefore used to determine BMS costs (eq. 11).

$$C_{BMS} = \frac{1}{2} N_S + 4 \quad (11)$$

This simple cost model is derived from online prices for 12S BMS units, which are in the region of 10€ if 1.000 units are being purchased.

4) *Development, Manufacturing, After Sales and Distribution Costs*: For a rough estimate of the costs for development, manufacturing, after sales and distribution, the parts costs, consisting of costs of battery cells, BMS and drivers are first determined for each concept, and then the corresponding additional costs are calculated using the key shown in Tab. IV. Since the same key is applied to all concepts, a relative cost comparison of the concepts is still meaningful even if the key deviates from reality.

TABLE IV  
MODEL FOR ADDITIONAL COSTS

| Costs for     | Factor | Reference               |
|---------------|--------|-------------------------|
| Development   | 0.2    | Part Costs              |
| Manufacturing | 0.5    | Part Costs              |
| After Sales   | 0.1    | Part Costs              |
| Distribution  | 0.3    | Part Costs of 1M-12S-4P |
| Margin        | 0.3    | Total Costs             |

As the distribution costs are independent from the inverter technology, the same distribution costs are applied here for each concept, based on the distribution costs of the state-of-the-art concept 1M12S4P.

The results of the efficiency and cost analysis are presented in the following section.

## V. RESULTS

This section presents the results of the efficiency and cost analysis, and is divided into two subsections accordingly.

### A. Efficiency Analysis

Figure 10 presents the losses and efficiencies of the powertrain concepts in the three operating points investigated. The losses are divided into battery, conduction and switching losses. In addition, the efficiencies for each setup and operation point are given.

First, a difference in terms of battery losses can be observed. These are comparably high for the multilevel concepts, but significantly lower for the state of the art. This is mainly due to the fact that the battery pack current in the 1M-12S-4P concept is distributed over four battery cells, whereas in the multilevel concepts it is only distributed over two cells per phase. In addition, the electrical power in the conventional system is always drawn at the highest voltage, which minimizes the battery current.

Secondly, conduction losses are the dominant loss mechanism in the 1M-12S-4P concept. In the multilevel

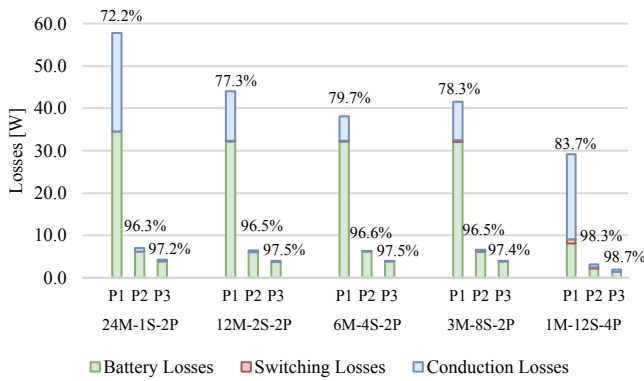


Fig. 10. Loss comparison differentiated by loss type. Efficiencies are given above each bar.

concepts, the conduction losses increase as the number of modules, and therefore the number of MOSFETs in the current path, increases. Contrary to this trend, the on-state losses of the 3M-8S-2P concept are higher than those of the 6M-4S-2P concept, which is due to the higher on-state resistance of the 45V MOSFET compared to the 25V MOSFET.

Finally, there is a clear trend with regard to switching losses. These increase as the number of modules decreases, which is due to the fact that the larger voltage levels increase the switching losses according to eq. (9), and the MOSFETs with higher voltages require longer turn-on and turn-off times (see Tab. II). Accordingly, the switching losses affect the 1M-12S-4P concept particularly severely.

A PWM with a switching frequency of  $f_{PWM} = 10$  kHz was used in all concepts in order to achieve a total harmonic distortion (THD) of less than 5%. Lower THDs were achieved by concepts with lower module voltage levels, resulting in a THD of less than 1% at 24M-1S-2P compared to 2.0% to 3.2% at 1M-12S-4P, depending on the operating point.

Despite the higher switching losses, the 1M-12S-4P concept has the best efficiency overall in all three operating points, as the lower battery current in combination with the low number of MOSFETs ensures significantly lower battery and conduction losses.

### B. Cost Analysis

Figure 11 shows the total costs of the different concepts, as well as a breakdown of the contributions to the total costs.

It turns out that the state-of-the-art 1M-12S-4P is the most cost-effective solution for the electric drive, and the 12M-2S-2P is the most expensive solution. The main

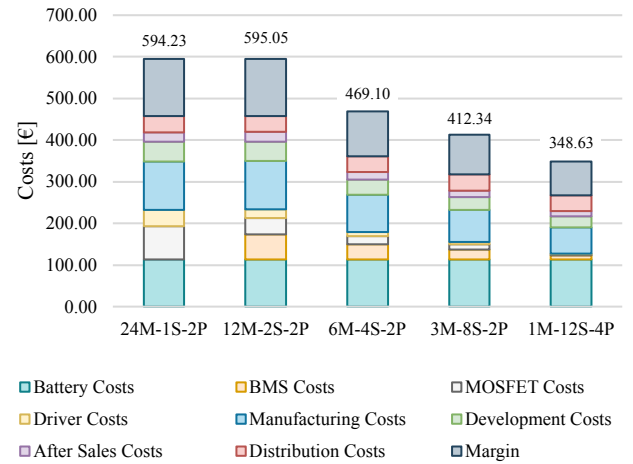


Fig. 11. Cost analysis for the different inverter concepts.

reason for this difference is the BMS. While the 1M-12S-4P concept only requires one BMS for the entire battery system, the 12M-2S-2P concept requires twelve BMS - which drives up the costs. This is where the 24M-1S-2P solution has an advantage - proactive balancing allows the states of charge of the cells to be balanced out via the load, reducing the costs. However, the 24M-1S-2P concept requires significantly more MOSFETs, while the unit prices do not fall in the same proportion as the number of modules increases compared to the 1M-12S-4P MOSFET prices. An additional disadvantage for the concepts with low module voltage is that, as described before, more expensive MOSFETs with a higher  $V_{DSS}$  had to be used in order to achieve reasonable efficiencies due to the technological immaturity of 8V and 12V MOSFETs. As a result, the 24M-1S-2P concept is 24.0% more expensive than the state-of-the-art solution.

Finally, Fig. 12 provides an overview of all concepts and operating points at a cost-efficiency level.

## VI. CONCLUSION

The analysis has shown that a MLI concept is not yet a viable option for micromobility vehicles like e-bikes. The state-of-the-art concept with a conventional inverter and battery system is optimal from an efficiency and cost perspective. Among the MLI concepts, the 6M-4S-2P concept has proven to be the most efficient, which is mainly due to the low-resistance MOSFETs in this voltage class. Should MOSFETs in the 8V and 12V voltage range experience a higher demand in the future, it is conceivable that they could also drastically improve the efficiencies of such concepts. The battery losses of MLI concepts could be reduced by using topologies that

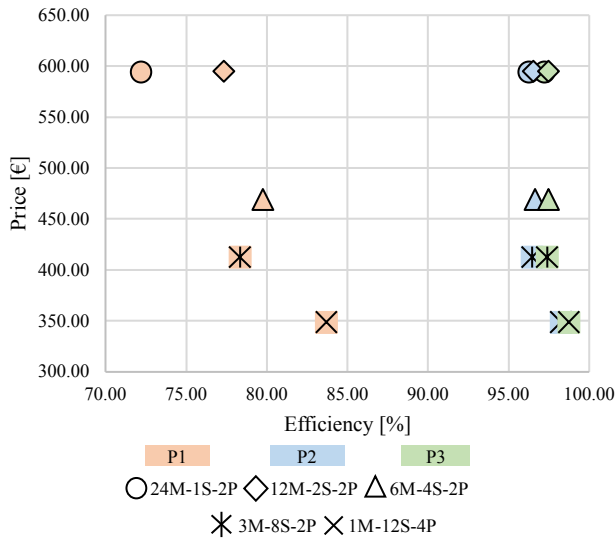


Fig. 12. Overview of the powertrain concepts at cost-efficiency level.

can connect modules in parallel, although this would increase costs and complexity. However, this could be a sensible solution for more expensive powertrains in the automotive and aviation sectors. Furthermore, the 1M-12S-4P concept profits from its DC-Link capacitor, since the battery current is smoothed and the efficiency therefore increased. For the same reason, such capacitors could be installed on the modules of the MLI concepts, further increasing their efficiency. It should be noted that other potential benefits of MLI technology were not included in this paper for reasons of scope. It has been shown that MLI concepts at cell level have a cost advantage over other MLI concepts due to the elimination of BMS. From a cost perspective, concepts with low module voltage would also benefit from the further development of low-voltage MOSFETs. The 1M-12S-4P concept is the most cost-effective solution for the powertrain under investigation, primarily due to the combination of few semiconductors and only one BMS.

#### ACKNOWLEDGEMENTS

This research is funded by dtcc.bw (Digitalization and Technology Research Center of the Bundeswehr) as part of MORE (Munich Mobility Research Campus), which we gratefully acknowledge. Dtec.bw is funded by the European Union – NextGenerationEU.

#### REFERENCES

[1] L. Komsijska, T. Buchberger, S. Diehl, M. Ehrensberger, C. Hanzl, C. Hartmann, M. Hölzle, J. Kleiner, M. Lewerenz,

B. Liebhart *et al.*, “Critical review of intelligent battery systems: Challenges, implementation, and potential for electric vehicles,” *Energies*, vol. 14, no. 18, p. 5989, 2021.

[2] M. Steck and S. Husung, “Systematic optimisation process for an ebike drive unit in a highly variable environment,” *Proceedings of the Design Society*, vol. 3, p. 3305–3314, 2023.

[3] European Parliament and Council of the European Union, “Regulation (eu) no 168/2013 of the european parliament and of the council of 15 january 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles,” 2013, last accessed on September 12, 2024. [Online]. Available: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R0168>

[4] T. Winograd, “Bosch E-Bike Systems sets new Benchmarks in Battery Safety,” May 2022, Press Release, Address : Stuttgart, Germany, Institution : Robert Bosch GmbH.

[5] A. van Dalen, “Bosch active line 3 mid-drive motor tear down,” September 2018, access: 12.09.2024. [Online]. Available: <https://avdweb.nl/solar-bike/hub-motor/bosch-active-line-3>

[6] C. Contò and N. Bianchi, “E-bike motor drive: A review of configurations and capabilities,” *Energies*, vol. 16, no. 1, 2023. [Online]. Available: <https://www.mdpi.com/1996-1073/16/1/160>

[7] A. Kersten, M. Kuder, E. Grunditz, Z. Geng, E. Wikner, T. Thiringer, T. Weyh, and R. Eckerle, “Inverter and battery drive cycle efficiency comparisons of chb and mmsp traction inverters for electric vehicles,” in *2019 21st European Conference on Power Electronics and Applications (EPE'19 ECCE Europe)*. IEEE, 2019, pp. P–1.

[8] T. Högerl, J. Buberger, F. Schwitzgebel, L. Obkricher, J. Estaller, M. Hohenegger, A. Kersten, M. Kuder, R. Eckerle, and T. Weyh, “Battery emulation for battery modular multilevel management (bm3) converters and reconfigurable batteries with series, parallel and bypass function,” in *2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, 2021, pp. 1–8.

[9] J. Estaller, A. Kersten, M. Kuder, T. Thiringer, R. Eckerle, and T. Weyh, “Overview of battery impedance modeling including detailed state-of-the-art cylindrical 18650 lithium-ion battery cell comparisons,” *Energies*, vol. 15, no. 10, 2022.

[10] MathWorks, Inc., *MOSFET (Simcape Electrical)*, 2024, last accessed on September 12, 2024. [Online]. Available: <https://de.mathworks.com/help/sps/powersys/ref/mosfet.html>