



Comparative Loss Analysis of an Axial-Flux PMSM Fed by a Modular Multilevel Inverter (BM3) Versus a Two-level Inverter (SVPWM)

Tobias Manfred Högerl, Julian Estaller, Johannes Buberger, Wolfgang Grupp, Andreas Wiedenmann, Nina Sorokina, Wolfgang Bliemetsrieder, Sebastian Pohlmann, Christian Rothmund, Manuel Kuder, et al.

► To cite this version:

Tobias Manfred Högerl, Julian Estaller, Johannes Buberger, Wolfgang Grupp, Andreas Wiedenmann, et al.. Comparative Loss Analysis of an Axial-Flux PMSM Fed by a Modular Multilevel Inverter (BM3) Versus a Two-level Inverter (SVPWM). The 26th European Conference on Power Electronics and Applications, GDR SEEDS France & EPE Association, Mar 2025, Paris, France. 10.34746/epe2025-0191 . hal-05105873

HAL Id: hal-05105873

<https://utc.hal.science/hal-05105873v1>

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

Comparative Loss Analysis of an Axial-Flux PMSM Fed by a Modular Multilevel Inverter (BM3) Versus a Two-level Inverter (SVPWM)

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

Universität der Bundeswehr München

Werner-Heisenberg-Weg 39

Munich, Germany

Tel.: +49 89 60043734

E-Mail: tobias.hoegerl@unibw.de URL: <https://www.unibw.de/>

Index Terms—Axial Flux, Efficiency, Electrical Machine, Modular Multilevel Converters (MMC), Total Harmonic Distortion, Core Losses, Iron Losses, Copper Losses, Excess Losses, Electric Machine Losses, Permanent Magnet Synchronous Machine.

Abstract—Loss reduction of up to 11 % in an AFPM machines is achieved using a Modular Multilevel Converter, enhancing efficiency and extending the range of electric vehicles. Simulations highlight significant advantages in reducing THD by up to 16 %, contributing to increased sustainability and resource conservation in all sectors of electric vehicles.

I. INTRODUCTION

Electromobility is becoming a key technology in addressing climate change, significantly contributing to the reduction of greenhouse gas emissions [1]. Battery Electric Vehicles (BEVs) play a central role in this effort. In order to increase the attractiveness and competitiveness of BEVs, intensive efforts are being made to increase their range and efficiency. A promising technology in this area is the Multilevel Inverter (MLI), which has, among other benefits, the potential to significantly improve the efficiency of the electric machine in the drivetrain of BEVs. The MLI is based on the technology of the Modular Multilevel Converter (MMC) [2] from the field of grid-connected high-voltage converters, whereby the energy storage is not represented by a battery cell but rather by capacitors.

The MLI is characterised by its ability to generate almost perfect sinusoidal voltage waveforms, which leads to a reduction in losses in the electric machine. This

also classifies it as an inverter, as it converts the battery DC voltage to AC voltage to drive the electric machine. This increased efficiency can either be utilised directly to extend the range or, alternatively, to contribute to the conservation of resources by reducing the installed battery capacity. In this context, it is of great importance to investigate the influence of MLIs on the efficiency of electric machines [3]–[5].

The increased motor efficiency, achieved by the better modulated voltage sine wave generated by MLIs, is the focus of this investigation. To validate the theoretical assumptions, a Finite-Element-Method (FEM) simulation of an axial-flux permanent-magnet (AFPM) [6], [7] is carried out using *Ansys Electronics Desktop*. The results of these simulations are promising and show that losses can be reduced by up to 30 %. However, this reduction is highly dependent on the type of machine, the size of the machine, the materials used, and its rotational speed and torque [3], [8]–[10]. As the research group is currently working on the planning, construction, and testing of a research vehicle for testing an optimised multilevel inverter drivetrain, it is necessary to examine the selected machine (EMRAX 268 MV).

In this paper, the remaining system components, such as battery cells, power electronics and connecting cables, are deliberately excluded in order to focus on the behaviour of the electric machine. However, these powertrain subcomponents should also be taken into account if a holistic representation of a multilevel system is intended, as they react differently to the generated voltage and current curves. The architecture of modules

and submodules also has a major influence on the efficiency of the overall system, leading to pros and cons for certain topologies [11]–[14].

The knowledge gained could further increase the efficiency and range of BEVs, making an important contribution to sustainability and resource conservation in the transport sector.

II. STATE OF THE ART

This section gives a brief introduction into the current state of modular multilevel inverter technology, Space Vector Pulse Width Modulation (SVPWM), electric machines and their loss types, as well as its Total Harmonic Distortion (THD).

A. Modular Multilevel Inverter

MLIs have gained significant attention in the automotive sector, particularly in electric and hybrid powertrains, due to their scalability, high efficiency [4], and superior performance in producing high-quality voltage waveforms [15]. MLIs, as depicted in Fig.1, are distinguished by their ability to generate multiple voltage levels using a series of modular Submodules (SMs), allowing for fine control of the output waveform and reduction of harmonic distortion [16]. This technology has become increasingly relevant as the automotive industry pushes toward electrification, demanding power electronic systems that offer high efficiency, reliability, and flexibility [17].

MLIs consist of several identical SMs. Typically, half-bridges, full-bridges or customised circuits with a local energy storage element, usually realised by a capacitor or a battery. These SMs are connected in series to form each phase leg of the inverter. Each submodule can be individually controlled to contribute either its full voltage, zero voltage, or in the case of more advanced topologies, intermediate voltages to the output. In automotive applications, the modular nature of MLIs allows for highly efficient and reliable operation under varying load conditions typical of vehicle operation. The inverters generate output voltages that closely approximate sinusoidal waveforms with minimal filtering, reducing costs and losses associated with harmonic distortion [18] as can be seen from the exemplary comparison in Fig. 2.

The modular design allows MLIs to be scaled easily for different voltage and power levels, making them suitable for a wide range of automotive applications, from small passenger vehicles to heavy-duty trucks [2], and even electric aircraft applications [19]. This flexibility also enables the use of MLIs-technology in

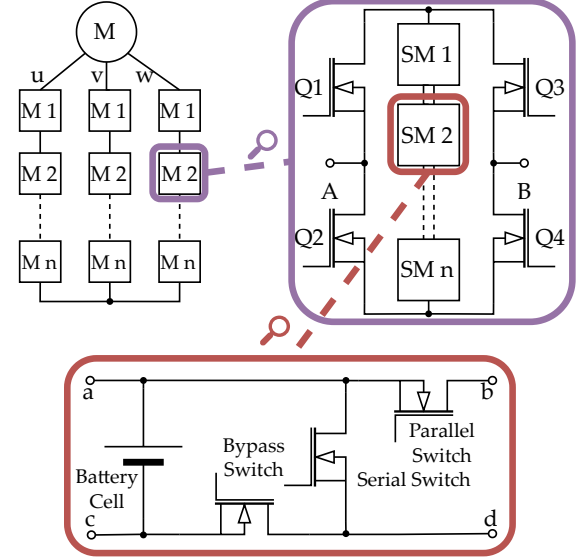


Figure 1. Exemplary hierarchical structure of a three phase BM3 incl. the macrotopology (top left) with multiple modules (M), its mesotopology (top right) with multiple SM and a three-switch (BM3) microtopology.

various other applications, such as onboard chargers and auxiliary power systems. MLIs can efficiently manage bidirectional power flow, a critical feature in regenerative braking systems in BEVs and Hybrid Electric Vehicles (HEVs). This capability helps maximise energy recovery during braking, improving the overall energy efficiency of the vehicle [18], [20], [21].

In this paper, a battery-based MLI, utilising the BM3 topology [18], [22], [23], is used, as depicted in Fig. 1. This variant has two further hierarchical layers in addition to the macrolevel. These specify how the SMs are connected (mesolevel), and the microlevel (submodule level), defining which features the inverter has. This enables the inverter to add features to the submodule level without adding too much complexity to the overall topology. For example, the inverter shown in Fig. 1 can change the output polarity of a module using switches Q1 to Q4. A BM3 SM alone is not capable of doing this natively. It is fair to say that the structure or architecture of a comparable MLI mesolevel has no influence on the efficiency of the electrical machine as long as the resulting pulse or sinusoidal patterns (machine input side) correspond to each other. A comparable system means having the same number of stages or, for example, the ability to generate positive and negative output signals.

The topology is able to switch its batteries in series, parallel, and bypass to generate an arbitrary voltage output. If the MLI uses Li-ion batteries as a voltage source. The lowest possible voltage steps are dependent on the State of Charge (SoC) of the SM's batteries, which lead to a typical range of 2.7 V to 4.3 V, depending on the cell chemistry. The easiest way to control the MLI is the Nearest Level Control (NLC) approach without any Pulse Width Modulation (PWM) to generate intermediate voltage steps.

The full potential has not yet been exploited here, as the individual cells can still output any intermediate values of the cell voltage via a PWM control method, especially in the low speed or low-frequency range. This is done by adjusting the duty cycle, which brings the output voltage even closer to a sine wave. The disadvantages and dangers with regard to Electromagnetic Compatibility (EMC) are also acceptable here due to the very low voltage level.

With the BM3 topology, a THD below 5 % at low currents and below 1 % can be achieved at high currents [16], [24], [25]. This paper shows the impact of lower THD by using MLIs on electric motor efficiency.

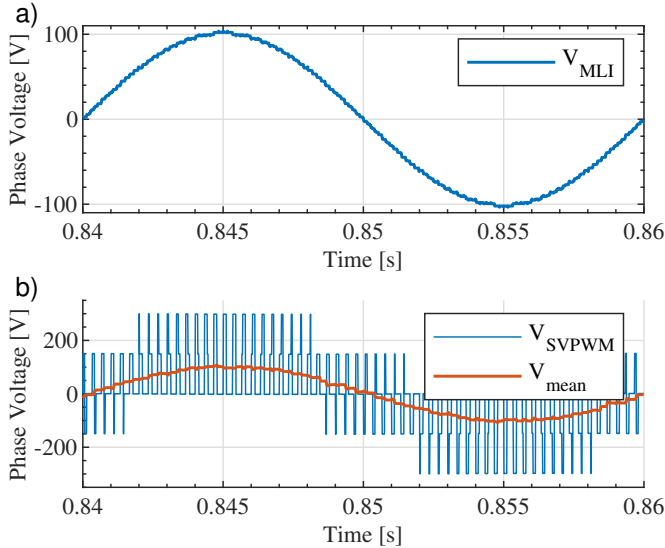


Figure 2. Exemplary phase voltage of a) MLI for comparison with the phase voltage of a b) SVPWM based inverter.

B. Space Vector Pulse Width Modulation

SVPWM [26] is a technique widely used in power electronics to control the output voltage and frequency of conventional 2-Level Inverters (2LIs) as depicted in Fig. 2 b). It is currently one of the most efficient control methods, which is why it is compared with

MLIs in this paper, as exemplarily depicted in Fig. 2 a). Applied to motor drive applications, SVPWM is known for its efficiency and ability to achieve higher voltage amplitudes compared to conventional PWM methods like sinusoidal PWM, making it a preferred choice for three-phase voltage source inverters.

The SVPWM is based on the concept of space vectors, which represent the instantaneous values of the three-phase voltage system as a single rotating vector in a two-dimensional plane. This method uses the switching states of the inverter to approximate the desired output voltage vector, thereby generating sinusoidal output currents. The continuous modulation pattern of SVPWM reduces the THD of the output current, resulting in improved performance of the motor drive system. Other advantages of SVPWM over sinusoidal PWM methods are maximised utilisation of the Direct Current (DC) link voltage, which enables a higher output voltage in comparison. Among other things, this improves the efficiency of the 2LI and the connected motor due to lower switching losses.

Although SVPWM offers considerable advantages, it also poses challenges such as a comparatively increased complexity due to the mathematically precise calculation and real-time processing of the dwell times. In addition, there is an increased computational effort, which means that fast microcontrollers or Digital Signal Processors (DSPs) are required for the intensive calculations, especially at high switching frequencies. Despite its complexity and superior control characteristics, SVPWM is still a preferred choice for high power applications. Therefore, this paper compares the MLI control method for operating electrical machines with the SVPWM method.

With SVPWM, voltage jumps occur due to the fast switching processes of the power semiconductors in the inverter as depicted in the comparison in Fig. 2. These jumps occur when the inverter passes through the various switching states, particularly during the transition between the active and zero vectors. The maximum voltage steps for SVPWM are as large as the full DC bus voltage i.e. if a DC bus voltage of 600 V is applied, the voltage jumps can be up to 600 V for each switching operation. Factors influencing this are the switching frequency and the modulation index.

The switching frequency is typically in the range of 2 kHz to 20 kHz, depending on the application and design of the inverter. This high switching frequency helps to minimise the THD in the output current, but increases the number of voltage transients per second. A higher modulation index leads to larger active time components of the switching vectors and therefore po-

tentially higher voltage jumps on the motor terminals. However, the voltage step remains limited by the DC bus voltage.

The current slope, also referred to as the rate of current change ($\delta i/\delta t$), is a critical parameter as it influences the EMC and the load on the motor windings.

The rate of current change depends directly on the magnitude of the voltage jumps and the impedance of the motor. Typical values for the current steepness are in the range of several 100 A/ μ s to 1000 A/ μ s, depending on the power of the motor and the switching frequency of the inverter. To control the current slope and minimise EMC problems, output filters (LC filters) are used to smooth the voltage jumps, and thus reduce the current slope. A higher switching frequency also helps to reduce the current ripple, but leads to higher switching losses in the power electronics as well as in the electrical machine.

High current gradients put a strain on the insulation of the machine windings and lead to increased heat generation due to losses in the laminations and windings as well as to a degradation of the insulating material due to partial discharges. This can have a negative impact on the service life of the machine, which is why it is important to optimise switching strategies and filter designs.

C. Electric Machine

Electric machines are fundamental components in numerous industrial and commercial applications, particularly where high efficiency, precise control, and dynamic performance are crucial.

The EMRAX 268 MV is an AFPM machine with a 18T20P configuration, characterized by its compact structure and high power density. This special machine was used in this work because it is also used in the research project being carried out by the research group. The machine was chosen because of its high power density and the associated small installation space. The specific arrangement of the stator and rotor disks allows for efficient magnetic flux utilisation, minimising losses and enhancing overall performance.

Composed of laminated iron cores and windings, the stator efficiently captures the magnetic flux and minimises current losses. Its design focuses on maximising the magnetic coupling with the rotor. The rotor includes evenly distributed permanent magnets arranged along the machine's axis, providing a uniform flux distribution and high torque density. The axial flux configuration provides superior magnetic coupling between the rotor and stator due to the axial alignment of the magnetic path, resulting in higher power density and reduced core losses.

AFPM offer higher power density [27] compared to conventional radial flux machines due to better utilisation of magnetic materials and shorter magnetic paths. The flat, disk-like structure allows for use in applications where space is limited, and weight is a critical factor, such as in electric vehicles and aviation.

D. Loss Types

The loss analysis evaluates the core [3] and copper losses under various load conditions for MLI and SVPWM driven machines. Copper losses are a common occurrence in all types of electric machines, including AFPMs. They occur due to the resistance in the stator and/or rotor windings, which causes heat generation when current flows through them. Armature copper losses are inevitable in any machine with current-carrying windings, including the stator of AFPM. It is a significant contributor to overall losses, especially during high current or high load conditions.

Iron or core losses, comprising hysteresis and eddy current losses, are present in all machines that have magnetic cores. These losses occur as a result of alternating magnetic fields within the core material. AFPM experience hysteresis losses due to the repeated magnetisation and demagnetisation of their iron core, just like in radial flux machines. The amount of hysteresis loss depends on the magnetic properties of the core material, such as silicon steel or other soft magnetic materials. Eddy current losses occur within the core material as a result of induced currents from changing magnetic fields. To reduce eddy current losses, the cores of AFPM are often made from thin laminated sheets or powder composites, which minimise the path for these currents and thus reduce the associated heat generation.

Excess losses result from a combination of non-linear electromagnetic interactions, material-dependent effects and operating conditions that deviate from idealised loss models. Depending on the accuracy of the model, the following non-linear but classic loss components are included. The stray magnetic flux and additional eddy current losses occur due to imperfect magnetic circuit designs and non-ideal core geometries, inducing additional eddy currents in machine components. Non-linear hysteresis losses tend to increase disproportionately in certain areas of the machine. They are caused by saturation effects that change the magnetic permeability and lead to increased losses that are not accurately captured in standard core loss models. Harmonic losses, caused by high-frequency voltage harmonics, lead to additional losses in the core and winding. Non-ideal current distribution in the windings, caused by the skin effect at

high frequencies, increases the effective resistance and copper losses beyond what is predicted by DC models. The proximity effect adds to that and leads to an uneven current distribution due to mutual inductance between adjacent conductors. Permanent magnets, especially in high-speed machines, are exposed to time-varying magnetic fields that induce eddy currents in the magnet material, which leads to additional losses in the magnets. There is also a more modern approach, disagreeing with the classic and simplified theory, which assumes that the material is not homogeneously magnetised [28], [29]. The induced electric currents are also inhomogeneously distributed and deviate from Maxwell's equations. Due to the magnetic structure of the domains in electrical steels, these induced electrical currents are not homogeneously distributed in space, but are located around moving magnetic domain walls, leading to additional losses. The movement, and the associated Joule loss of these domain walls, is said to be the origin of these losses [30].

Mechanical losses, also present in AFPM, are similar to those found in other types of electric machines. However, these are not covered in this paper.

E. Total Harmonic Distortion

The THD is a measure of the distortion present in a signal due to the presence of harmonics, which are integer multiples of the fundamental frequency. THD quantifies the degree to which these harmonics alter the original waveform, providing an indicator of the signal's fidelity and quality. It is commonly used in the analysis of electrical systems, audio devices, and power systems to assess performance and efficiency. Mathematically, THD is defined as the ratio of the Root Mean Square (RMS) value of all harmonic components of the signal to the RMS value of the fundamental component. This ratio is often expressed as a percentage, with higher values indicating greater distortion. It is calculated using the following equation:

$$\text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1} \times 100\%$$

In this case, V_n being the n -th harmonic of the fundamental frequency V_1 . The presence of harmonics can cause unwanted effects such as increased losses, overheating, signal degradation, and reduced system efficiency, making minimising THD a critical aspect in the design of many electronic and power electronic systems.

In the context of power electronic systems, THD is particularly significant as it affects both the quality of power delivered and the performance of electrical equipment. Harmonics can be introduced by non-linear

loads such as variable speed drives, inverters, and other power electronic devices, which cause deviations from the ideal sinusoidal waveform.

In the field of electrical machines, this is caused by the additional harmonics of the current, additional copper losses proportional to the square of the current, iron losses (hysteresis and eddy current losses) caused by the additional high-frequency components and excess losses in the form of the coupling of electromagnetic fields that induce eddy currents in conductive parts (e.g. rotor, housing). An additional, mechanical and more indirect loss is caused by the uneven forces in the air gap, which causes vibrations and acoustic losses. The relationship between the losses and the THD is not linear, but the losses increase disproportionately with increasing THD.

Managing THD involves the use of filters, proper circuit design, and active harmonic compensation techniques to ensure that signal integrity is maintained within acceptable limits. A high THD causes additional losses in electrical machines in contrast to ideal sinusoidal signals. Minimising THD is, therefore, essential to maximise the efficiency of electrical machines.

III. METHODS

For the simulation of the electric machine, a detailed 3D model of the EMRAX 268 MV is created in ANSYS, representing the arrangement of the stator, rotor, windings, and magnets. It is depicted in Fig. 3. To simplify the simulation, only one symmetric half of both, the rotor and the stator, were created, which are displaced against each other with an offset around the Z-axis to show the turn axis. The stator windings are coloured in orange, the stator and rotor core (electric steel) are coloured in grey and the magnets are coloured in red and green to show the alternating orientation of the magnetic poles. The most important data sheet values [31], as well as the model parameters, are given in Tab. I.

A fine mesh, as depicted in Fig. 4, is generated to ensure accurate calculation of electromagnetic fields and thermal distributions. Special attention is given to areas with high flux density or thermal gradients such as the spaces between the windings, the permanent magnets, the core, and the surrounding boundary regions.

Operating conditions such as rotational speed and load torque are defined to simulate realistic operational scenarios in transient load conditions. The lowest speed of 500 rpm represents walking speed and parking manoeuvres with low speed and high torque requirements. This results in high currents to build up the torque, which should lead to a high ratio of copper losses and, because of the low field frequency, to a lower

Table I
DATA AND DIMENSIONS OF THE MACHINE MODEL

Data	EMRAX 268 MV
Machine type	AFPM
Peak Power at max RPM	200 kW
Voltage at max RPM	650 V
Max. Current	400 A
Continuous motor current	190 A
Max. rotational speed	4500 rpm
Max. torque	500 Nm
Continuous torque	213 Nm
Electrical steel	M270-35A
Magnet material	N46SH
Copper and Magnet Temp.	60 °C
Number of pole pairs	10
Number of slots	18
Number of windings	20
Stator outer diameter	259 mm
Magnets outer diameter	250 mm
Inner diameter	130 mm
Air gap	1.5 mm
Phase Resistance	10.5 mΩ
Efficiency	92-98 %

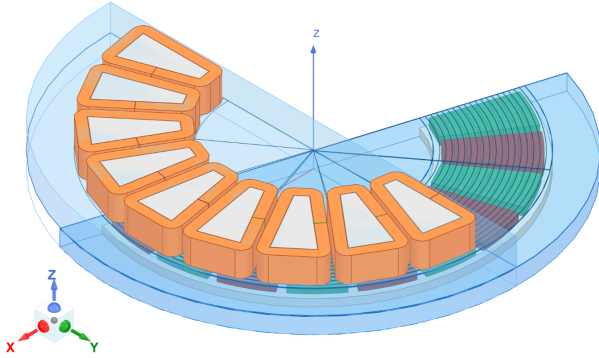


Figure 3. Section through the X/Y-plane of the EMRAX 268 MV model.

ratio of hysteresis and eddy current losses. The average speed of 2500 rpm corresponds to inner-city driving and represents an intermediate range. The high speed of 4500 rpm corresponds to driving on a country road or highway at high speed with low torque requirements. Here, a high share of hysteresis and eddy current losses is expected due to the high field frequency, and a lower share of copper losses due to low current requirements. In order to analyse the machine, the model was current fed with a pre-processed current profile for all three operating points.

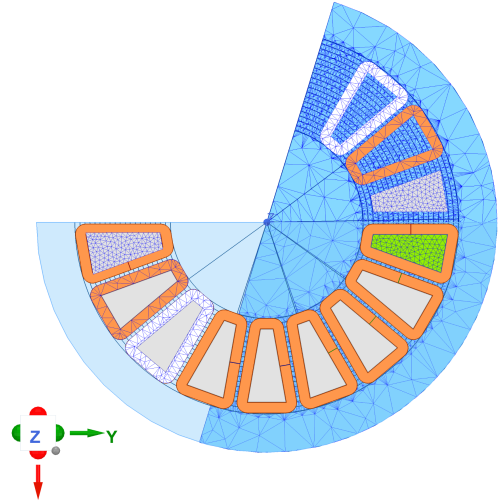


Figure 4. Mesh display as used to simulate the EMRAX 268 MV model.

IV. RESULTS AND DISCUSSION

The THD of the phase current at different rotational speeds is summarised in Tab. II. While the THD is almost similar at about 1.19 % deviation when comparing the two inverters at 500 rpm, the THD increases for the 2LI at higher speeds. The MLI with the small steps of a single cell voltage can maintain almost the same THD across all of the simulated operating points. It can be noted that the MLI causes a smaller THD in all three operating points compared to the 2LI. At 2500 rpm, the THD is 10.84 % lower and at 4500 rpm, a 15.97 % lower THD is achieved with an MLI compared to the SVPWM-controlled 2LI. The results can be explained by the fact that the MLI is controlled with a NLC approach and thus has the same voltage steps independent of the motor's rotational speed. The only thing that is changing is the switching frequency, which is directly proportional to the motor speed. For the SVPWM, the switching frequency stays the same throughout all operating points. For the simulation, a switching frequency of 20 kHz is chosen. This leads to fewer switching operations per wavelength, i.e. a coarser representation of the desired sine wave, at higher speeds for 2LI and thus a higher THD is generated.

Fig. 5 shows the losses divided into the most relevant fractions. The copper losses have the largest share, but are almost proportionally equal, with slightly lower losses for MLI. The other shares can be summarised as iron or core losses. They comprise eddy current

Table II
COMPARISON OF THE PHASE CURRENT THD

THD of the Phase Current			
n in rpm	500	2500	4500
2LI with SVPWM	6.09	6.73	7.17
MLI 4 V steps	6.01	6.00	6.03
Δ	0.07	0.73	1.15
Δ in %	1.19	10.76	15.79

losses, occurring due to circulating currents induced within the core material by changing magnetic fields in the armature, hysteresis losses, caused by the repeated magnetisation and demagnetisation of the magnetic core material, and the excess losses, which are included and summarised in Tab. III.

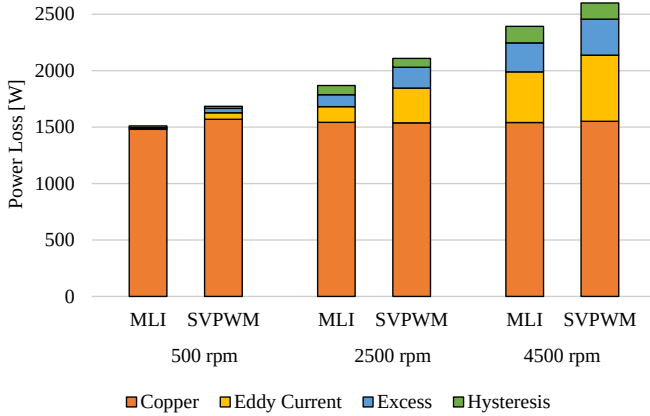


Figure 5. Loss components of an AFPM machine at different speeds, operated with MLI vs. SVPWM-controlled 2LI.

The biggest differences between the two control methods can be seen in the core losses. It can be observed that the MLI is particularly advantageous in the lower speed range, which corresponds to operation in urban areas. This difference decreases with increasing speed, whereby the MLI is more efficient throughout the whole tested speed range. Expressed in figures, this means for a machine with an assumed efficiency of 95 %, when controlled with SVPWM, an improved efficiency of 95.51 % at 500rpm and 95.57 % at 2500rpm. At 4500rpm, the advantage seems almost marginal, but with a loss reduction of 8.0 % it is not negligible, resulting in a machine efficiency of 95.4 %.

Figures 6 and 7 illustrate the core losses of the two systems, including a mean value line at the three simulated operating points. The values clearly show

Table III
LOSS COMPONENTS DATA

	n [rpm]	$P_{L, mli}$ [W]	$P_{L, SVPWM}$ [W]
Copper	500	1479.3	1568.4
	2500	1542.2	1537.0
	4500	1540.7	1550.8
Hysteresis	500	16.0	17.8
	2500	81.3	79.1
	4500	146.4	142.9
Eddy Current	500	5.5	58.3
	2500	138.4	309.2
	4500	447.6	586.4
Excess	500	9.4	38.7
	2500	106.5	183.6
	4500	256.9	318.6
Σ	500	1510.2	1683.1
	2500	1868.4	2108.8
	4500	2391.6	2598.6
$\%$	500	10.3 %	
	2500	11.4 %	
	4500	8.0 %	

lower losses when operating with MLI. However, much more striking is the strong fluctuation or noise of the signals when operating with SVPWM as depicted in Fig. 7.

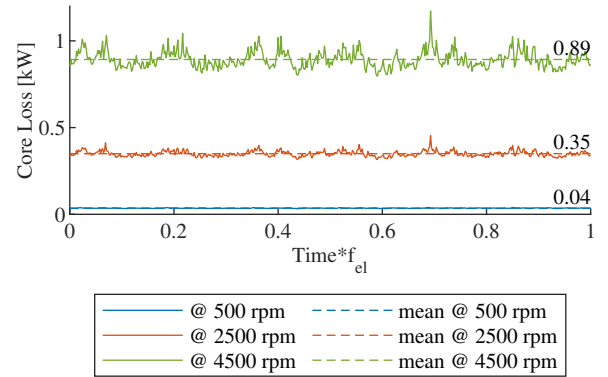


Figure 6. Core losses of an AFPM machine at different speeds, operated with MLI.

Of course, this can be traced back to the level of the voltage stages that are switched by the respective system to drive the motor. Possible consequences of this are the increased losses shown, increased stress on the materials used and the electrical insulation of the cables, as well as increased conducted and radiated noise signals.

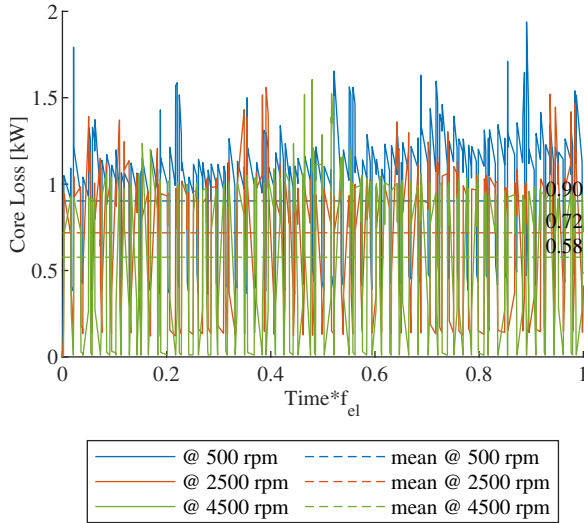


Figure 7. Core Losses of an AFPM machine at different speeds, operated with a classic SVPWM-controlled 2LI at 20 kHz.

V. CONCLUSION

This paper investigated the losses occurring in an AFPM machine while being controlled by a MLI compared to a conventional 2LI. The motor under consideration is an EMRAX 268 MV. A simulation model for the electric motor was built using ANSYS. The THD as well as the core and copper losses were simulated under varying conditions.

The results show that the generated harmonic distortion is lower for the MLI compared to the conventional 2LI across all operating points. Furthermore, the gap in THD increases as the speed of the electric motor increases. This is most likely due to the high flexibility in switching frequency of the MLI compared to the conventional SVPWM-controlled 2LI. The overall AFPM machine losses behave inversely. Although the MLI generates less motor losses, leading to a higher efficiency across all operation points, the difference compared to the losses generated by the 2LI decreases at higher motor speeds. This can be explained by the fact that, at higher speeds, the core losses cannot be mitigated as effectively through the higher quality Alternating Current (AC) input generated by MLI. Therefore, the losses tend to converge at higher rotational speeds. The findings underline the potential of modular multilevel converters in optimising electric motor performance, contributing to the sustainability and competitiveness of electromobility in the automotive industry. Further research could explore the impact of these converters

on different motor configurations, specially customised machine designs and materials and operating conditions to fully harness their benefits.

ACKNOWLEDGMENT

This research is funded by dtec.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] J. Buberger, A. Kersten, M. Kuder, R. Eckerle, T. Weyh, and T. Thiringer, "Total CO₂-equivalent life-cycle emissions from commercially available passenger cars," *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112158, 2022.
- [2] A. Lesnicar and R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range," in *2003 IEEE Bologna Power Tech Conference Proceedings*, vol. 3, 2003, p. 6 pp.
- [3] P. Rasilo, A. Salem, A. Abdalh, F. De Belie, L. Dupré, and J. A. Melkebeek, "Effect of multilevel inverter supply on core losses in magnetic materials and electrical machines," *IEEE transactions on Energy Conversion*, vol. 30, no. 2, pp. 736–744, 2014.
- [4] M. Quraan, P. Tricoli, S. D'Arco, and L. Piegari, "Efficiency assessment of modular multilevel converters for battery electric vehicles," *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2041–2051, 2016.
- [5] 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.
- [6] F. Nishanth, J. Van Verdegheem, and E. L. Severson, "Recent advances in analysis and design of axial flux permanent magnet electric machines," in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, 2021, pp. 3745–3752.
- [7] S. Amin, S. Khan, and S. S. H. Bukhari, "A comprehensive review on axial flux machines and its applications," in *2019 2nd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*. IEEE, 2019, pp. 1–7.
- [8] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel converters for large electric drives," *IEEE transactions on industry applications*, vol. 35, no. 1, pp. 36–44, 1999.
- [9] K. Yamazaki and Y. Seto, "Iron loss analysis of interior permanent-magnet synchronous motors-variation of main loss factors due to driving condition," *IEEE Transactions on Industry Applications*, vol. 42, no. 4, pp. 1045–1052, 2006.
- [10] L. Pei, L. Li, Q. Guo, R. Yang, and P. Du, "A novel rotor eddy current loss estimation method for permanent magnet synchronous machines with small inductance and a conductive rotor sleeve," *Energies*, vol. 12, no. 19, p. 3760, 2019.

- [11] O. Theliander, A. Kersten, M. Kuder, W. Han, E. A. Grunditz, and T. Thiringer, "Battery modeling and parameter extraction for drive cycle loss evaluation of a modular battery system for vehicles based on a cascaded h-bridge multilevel inverter," *IEEE Transactions on Industry Applications*, vol. 56, no. 6, pp. 6968–6977, 2020.
- [12] N. Sorokina, J. Estaller, A. Kersten, J. Buberger, M. Kuder, T. Thiringer, R. Eckerle, and T. Weyh, "Inverter and battery drive cycle efficiency comparisons of multilevel and two-level traction inverters for battery electric vehicles," in *2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*. IEEE, 2021, pp. 1–8.
- [13] A. Kersten, O. Theliander, E. A. Grunditz, T. Thiringer, and M. Bongiorno, "Battery loss and stress mitigation in a cascaded h-bridge multilevel inverter for vehicle traction applications by filter capacitors," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 3, pp. 659–671, 2019.
- [14] T. A. Abdul-jabbar, A. Kersten, A. Mashayekh, A. A. Obed, A. J. Abid, and M. Kuder, "Efficient battery cell balancing methods for low-voltage applications: A review," in *2022 IEEE International Conference in Power Engineering Application (ICPEA)*. IEEE, 2022, pp. 1–7.
- [15] M. Kuder, A. Kersten, L. Bergmann, R. Eckerle, F. Helling, and T. Weyh, "Exponential modular multilevel converter for low voltage applications," in *2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe)*, 2019, pp. P.1–P.11.
- [16] J. Buberger, A. Kersten, M. Kuder, A. Singer, A. Mashayekh, J. Estaller, T. Thiringer, R. Eckerle, and T. Weyh, "Charging strategy for battery electric vehicles with a battery modular multilevel management (bm3) converter system using a pr controller," in *2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe)*. IEEE, 2021, pp. P–1.
- [17] A. Poorfakhraei, M. Narimani, and A. Emadi, "A review of multilevel inverter topologies in electric vehicles: Current status and future trends," *IEEE Open Journal of Power Electronics*, vol. 2, pp. 155–170, 2021.
- [18] M. Kuder, J. Schneider, A. Kersten, T. Thiringer, R. Eckerle, and T. Weyh, "Battery modular multilevel management (bm3) converter applied at battery cell level for electric vehicles and energy storages," in *PCIM Europe digital days 2020; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. VDE, 2020, pp. 1–8.
- [19] N. Sorokina, W. Bliemetsrieder, J. Estaller, D. Karnehm, T. Weyh, and M. Kuder, "Performance analysis of reconfigurable inverter battery systems for aircraft applications," in *2024 24th International Scientific Conference on Electric Power Engineering (EPE)*, 2024, pp. 1–6.
- [20] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel inverters for electric vehicle applications," in *1998 IEEE Workshop on Power Electronics in Transportation, Dearborn, Michigan*, 1998, pp. 79–84.
- [21] L. P. Suresh *et al.*, "A brief review on multi level inverter topologies," in *2016 international conference on circuit, power and computing technologies (ICCPCT)*. IEEE, 2016, pp. 1–6.
- [22] D. Karnehm, N. Sorokina, S. Pohlmann, M. Ackermann, M. Kuder, and A. Gieraths, "High performance simulation framework of three-phase battery modular multilevel management converter system," in *IECON 2022–48th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2022, pp. 1–5.
- [23] A. Wiedenmann, J. Buberger, T. Högerl, W. Grupp, M. Hohenegger, M. Kuder, T. Weyh, and A. Neve, "Proactive balancing for reconfigurable battery systems with automated efficiency analysis," in *2023 International Conference on Smart Energy Systems and Technologies (SEST)*, 09 2023, pp. 1–6.
- [24] J. Buberger, J. Estaller, W. Grupp, F. Schwitzgebel, A. Wiedenmann, A. Mashayekh, M. Kuder, R. Eckerle, and T. Weyh, "Ac and dc charging for electric vehicles with a battery modular multilevel management (bm3) converter system," 05 2022.
- [25] J. Buberger, M. Hohenegger, J. Estaller, A. Wiedenmann, W. Grupp, W. Bliemetsrieder, M. Kuder, A. Lesnicar, and T. Weyh, "Bidirectional charging for bevs with reconfigurable battery systems via a grid-parallel proportional-resonant controller," *Electricity*, pp. 171–184, 05 2023.
- [26] V. Ranganathan, "Space vector pulsewidth modulation—a status review," *sadhana*, vol. 22, pp. 675–688, 1997.
- [27] Z. Hao, Y. Ma, P. Wang, G. Luo, and Y. Chen, "A review of axial-flux permanent-magnet motors: Topological structures, design, optimization and control techniques," *Machines*, vol. 10, no. 12, p. 1178, 2022.
- [28] D. Kowal, P. Sergeant, L. Dupré, and L. Vandenbossche, "Comparison of iron loss models for electrical machines with different frequency domain and time domain methods for excess loss prediction," *IEEE Transactions on Magnetics*, vol. 51, no. 1, pp. 1–10, 2014.
- [29] Z.-Q. Zhu, S. Xue, W. Chu, J. Feng, S. Guo, Z. Chen, and J. Peng, "Evaluation of iron loss models in electrical machines," *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1461–1472, 2018.
- [30] J. Shilling and G. Houze, "Magnetic properties and domain structure in grain-oriented 3% si-fe," *IEEE Transactions on Magnetics*, vol. 10, no. 2, pp. 195–223, 1974.
- [31] *emrax_268_technical_data_table_graphs_5.4*, Version 5.4 ed., EMRAX d.o.o., March 2020. [Online]. Available: https://emrax.com/wp-content/uploads/2020/03/emrax_268_technical_data_table_graphs_5.4.pdf