LUT University

High-Speed Megawatt-Scale Induction-Motor Drives: Efficiency Maps and Drivetrains

Vostrov Konstantin, Aarniovuori Lassi, Pyrhönen Juha

This is a Final draft version of a publication

published by IEEE

in 2022 International Conference on Electrical Machines (ICEM)

DOI: 10.1109/ICEM51905.2022.9910826

Copyright of the original publication:

© 2023 IEEE

Please cite the publication as follows:

Vostrov, K., Aarniovuori, L., Pyrhönen, J. (2022). High-Speed Megawatt-Scale Induction-Motor Drives: Efficiency Maps and Drivetrains. In: 2022 International Conference on Electrical Machines (ICEM), Valencia, Spain, 2022, pp. 745-751. DOI: 10.1109/ICEM51905.2022.9910826

© 2022 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

This is a parallel published version of an original publication. This version can differ from the original published article.

High-Speed Megawatt-Scale Induction-Motor Drives: Efficiency Maps and Drivetrains

K. Vostrov, L. Aarniovuori, J. Pyrhönen

Abstract –**Selection of a proper drivetrain for a certain application is an important and challenging task. To make the right choice, several factors must be considered. The performance of an electrical drive system is among the crucial factors responsible for decision making. Although the performance at rated speed and torque is usually given, to estimate the losses under various operating scenarios it is necessary to know the efficiency values at different possible combinations of torque and speed. The paper focuses on megawatt-power range applications, where high-speed rotation is required. Efficiency maps showing the efficiency as a function of load torque and rotational speed are determined for the drivetrains with a gearbox and direct drive, as well as for their constituent parts. Presented results are intended to be useful for loss determining at a certain operating point, and for making a choice between different drivetrains.**

Index Terms—**Drivetrains, Energy efficiency, High-speed drives, Induction motors, Mechanical power transmission, Performance analysis, Variable speed drives.**

I. Introduction

In modern industry there are plenty of applications, where high-speed and high-torque loads must be driven. For example, oil and gas pumps require 5700…10000 Nm at 5-15 krpm [1], flywheel motor-generators need 1270-2500 Nm at 7.5…15 krpm [2], hydrogen and air compressors operate at 11 krpm and require 2200…2600 Nm torque [3]. All these loads must be driven with multimegawatt (2…15 MW) electric motors.

Even though there are different types of electric motors available, induction motors are the most popular in industrial use nowadays. Moreover, induction motors require a minimal amount of rare-earth elements, and this factor further enables their popularity [1]. This trend works also for megawatt-scale applications, where the vast majority of machines are asynchronous ones. Induction machines with a power range up to 5 MW and with a speed up to 20 krpm are most highly demanded in the industry [4].

In the latest decades, the question of usage of different drivetrains has been arisen in different areas and industries and remains an open question for all power ranges. Currently, for instance, washing machines, electric bicycles, wind turbines, oil pumps, screw compressors, and other small and large-scale devices are available driven with geared or direct drive systems.

Similarly, with other power ranges, in megawatt-scale applications, there are several possible drivetrains.

The first drivetrain is a direct-on-line (further – "DOL") regular-speed motor attached to a step-up gearbox. This has been the most convenient setup. The advantages of it are low price and moderate efficiency at the rated load. However, direct online motors cannot be used in applications where adjustable speed is required. Utilization of a step-up gearbox brings a bunch of cons: it needs a large amount of oil, an oil-circulating, -filtering and -cooling system, regular service, requires extra space for placing, produces high losses and noise, and affects the overall reliability of the system.

The second possible drivetrain is a regular-speed drive supplied via frequency converter with a step-up gearbox (further – "RS+GB" drivetrain). This setup operates at an adjustable speed and has slightly lower system efficiency at the rated operating point than the "DOL" system, but enable speed control. In addition to the drawbacks caused by the gearbox, frequency converter utilization makes the given drivetrain more expensive and less reliable. Also, overall efficiency drops, when speed or torque are below the rated values.

Finally, the third possible drivetrain is a direct drive high-speed motor supplied via a frequency converter (further – "HSDD" drivetrain). This drivetrain has several advantages: its speed is adjustable, it needs no gear-box servicing, it is compact and highly reliabile. Because the number of components in a direct-drive system is minimal, its efficiency is the highest. With direct drive, recuperation is always possible with the highest efficiency. Moreover, not all gearboxes offer two-way torque transmission at all.

Abovementioned drivetrains are schematically shown in Fig. 1.

From a global perspective, high-speed machines are a promising potential way for further efficiency increase since they have higher power density. In the future, number of high-speed machines is predicted to grow. The environmental trend is named as one of the driving forces behind this growth. Rising energy needs, increasing cost of energy, rising environmental concerns, the trend of electrifying future transportation systems, and different environmental regulations and restrictions, are considered to be the driver for the development towards high-speed applications.

However, to make a weighted choice between different possible drivetrains, it is worth considering efficiency at different operating points, i.e., when speed and torque differ from the rated values.

This work was supported by the Academy of Finland's Centre of Excellence in High-speed Electromechanical Energy Conversion System' (HiECS).

K. Vostrov, L. Aarniovuori, and J, Pyrhönen are with LUT University, Lappeenranta 53850 Finland (e-mails: konstantin.vostrov@lut.fi, lassi.aarniovuori@lut.fi, juha.pyrhonen@lut.fi).

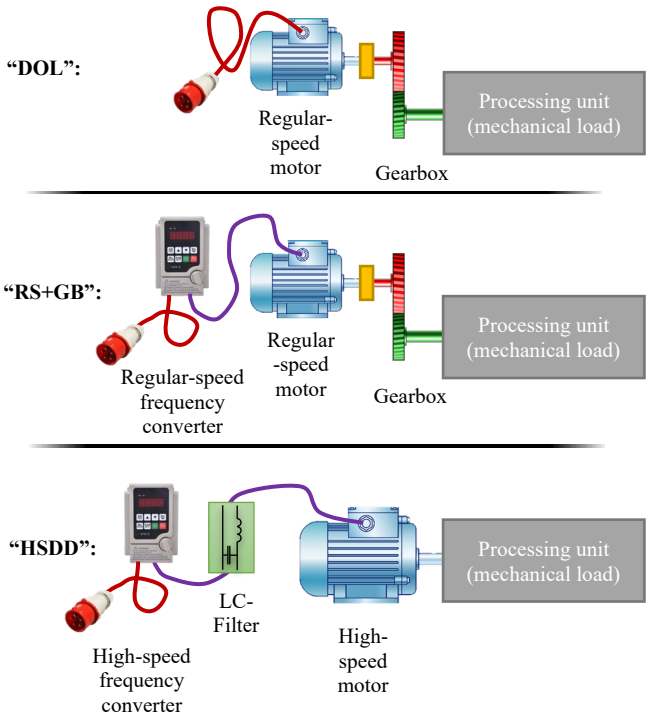

Fig. 1. The schematic representation of three drivetrains being under consideration.

In the current paper, we will compare the abovementioned drivetrains employed to run a high-speed load in a megawatt power range. The main contribution of the paper is building the "efficiency maps", showing the efficiency of drivetrain components and overall system as a function of speed and torque.

In megawatt-scale drive systems efficiency is crucial because even a small fraction of efficiency percentage turns into tens of kilowatts of losses in absolute numbers. Because of that, the choice of the proper drivetrain must be done responsibly. That means, that not only the rated efficiency must be taken into account, but the whole efficiency map covering the full range of speed and torque values planned to be used according to the load scenario is needed.

The efficiency maps built in the current work can be used as reference data when the question of a suitable drivetrain for a high-speed multimegawatt load arises.

Since the efficiency behavior and efficiency values of the machines in the megawatt-range change very insignificantly [5], presented efficiency maps are applicable for any machine, component, or drivetrain within the power range of 1…5MW.

The paper is structured as follows. The paper starts with the Introduction chapter, where the state of the art and scope of the paper are given. In Chapter II "Methods", the way of efficiency surfaces plotting is described, and efficiency maps for all components constituting the different drivetrains are presented. Chapter III "Results" show the resulting efficiency maps for whole drivetrain systems being analyzed. Chapter IV "Discussion" points out practical aspects of the findings, and gives the interpretation of the results. The last chapter "Conclusion" gives a brief summary and wraps up the paper.

II. Methods

The purpose of the current work is to find and show the efficiency of three possible drivetrains as a function of speed and torque.

According to [6], there are several specific points taken for determining the losses and efficiency of converter-fed AC induction motors. These points are shown as round red dots in Fig. 2. To build a more relevant surface plot, we have supplemented the recommended points with some extra points. They are shown in Fig. 2 as green squares.

Exact efficiency values in that points were calculated as starting points for the efficiency maps building and collected in Table I. Based on those points, the efficiency maps were built using linear interpolation in a MATLAB environment. The efficiency maps cover the whole range of possible operating points within 25…100% from the rated load torque and 25…100% from the rated shaft speed.

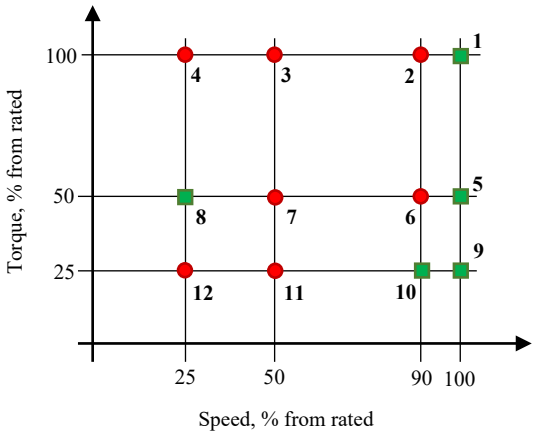

Fig. 2. Standardized operating points map (red dots) with extra points added (green squares).

To find the efficiency maps of the listed drivetrains, efficiency maps for each component will be drawn. The total efficiency of the considered drivetrains will be found as a combination of its components' efficiency maps.

A. Motors

Using data available from [7], [8], [9], and calculation technique described in [10] capable to show the efficiency for any combination of load and speed for induction motors, the efficiency in the operating points 1…12 for regular-speed megawatt-scale motors was found. The efficiency values in the given points are shown in Column (2) of Table I and were found by averaging the numbers available from the sources mentioned above. The efficiency map for the regular-speed motor is shown in Fig. 3a. The motor has highest efficiencies near the rated operation point. The maximum efficiency is with the load torque values from 50% to 75% and 90% speed. The lower efficiency can be found with low speed and high torque.

With the data available for high-speed machines [11], [12], [13], their efficiencies in points of interest were found in a similar manner and collected in column (3) of Table I. The efficiency map showing the efficiency as a function of speed

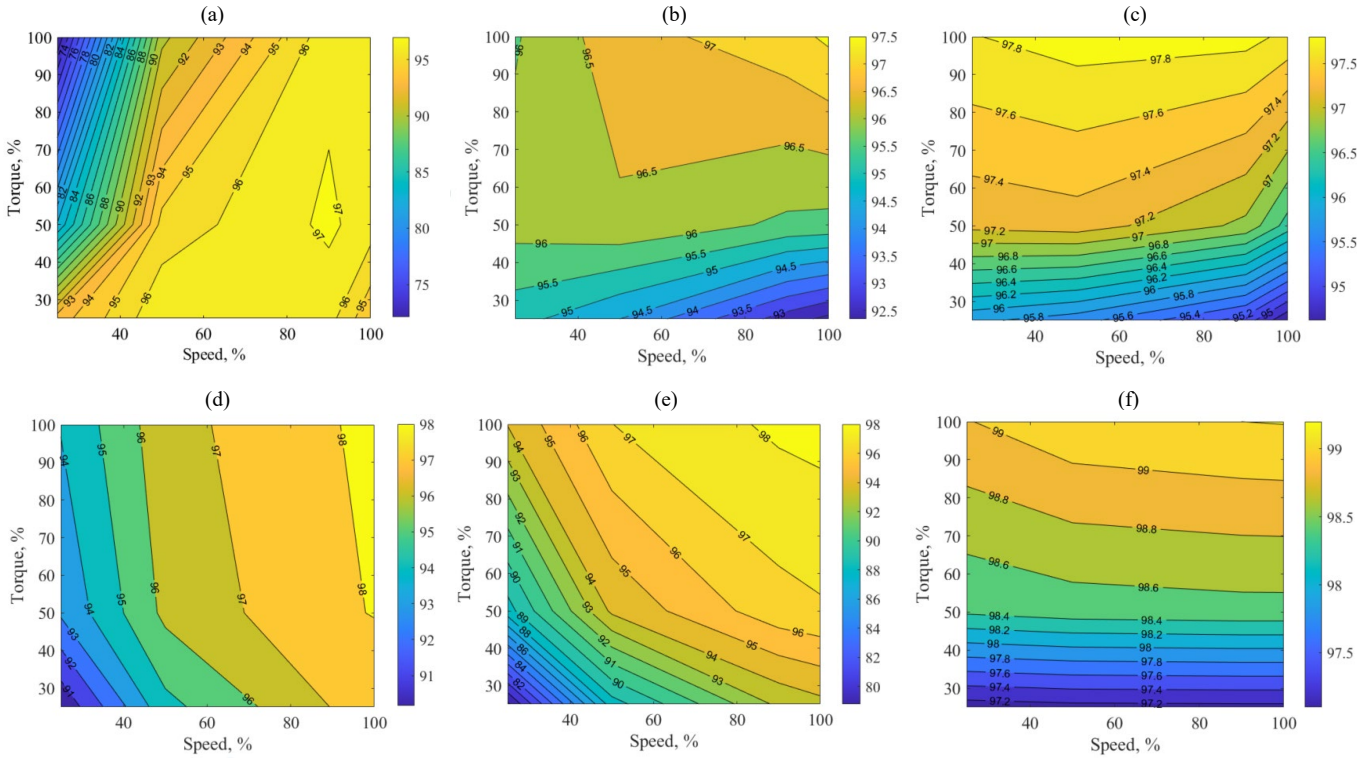

Fig. 3. Efficiency maps: a) - regular-speed megawatt-scale induction machines, b) – high-speed megawatt-scale induction machines, c) – speed-up gearbox, d) - frequency converters designed for regular speed operation, e) - frequency converters designed for high-speed operation, f) – LC-filter.

and load torque is built and shown in Fig. 3b. The prefomance of the high-speed machine is relatively high in any opeationg point, and the lowest possible value of 92.4% can be found under full speed and minimal torque operation. The highest output of high-speed motor is at the rated point, i.e., with full load at full speed.

Fig. 4 show simultaneously plotted efficiency surfaces for regular-speed and high-speed machines.

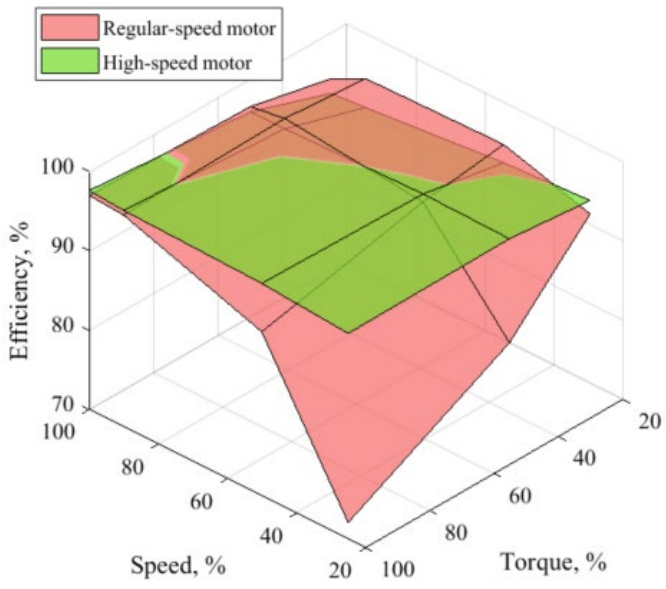

Fig. 4. Comparison of efficiency maps for regular-speed and high-speed megawatt-scale induction motors.

B. *Gearbox*

To run a high-speed load, a step-up gearbox must be used in “RS+GB” drivetrains powered by regular-speed motors.

The efficiency map showing typical behavior of the speed-up gearbox designed for multimegawatt load is shown in Fig. 3c, and exact values in operating points of interest being found by summarizing data from [14], [15], [16] are shown in Column (4) of Table I. The gearbox effitiency mainly depends on the applied load torque and represents a and is directly dependent on it. Maximum gearbox pefomance is achieved at the maximum load, and with speed at the level of 50…90% from the rated one. The worst prfomance is observed at full speed and low torque.

C. *Frequency converters*

A frequency converter must be employed in both “RS+GB” and “HSDD” systems to enable variable speed operation.

Efficiency values in key points were found based on [17], and efficiency maps representing frequency converters designed to supply regular-speed and high-speed motors were built and shown in Fig. 3d and Fig. 3e respectively. The exact efficiency values in key points for both regular- and high-speed converters can be found in Table I.

For both converters, the maximum effitiency can be reached at the rated point, and the opposite operating point of lowest torque at minimal speed shows the smallest effitiency.

Fig. 5 shows simultaneously plotted efficiency surfaces for regular-speed and high-speed converters.

TABLE I
EFFICIENCY VALUES AT CERTAIN OPERATING POINTS BEING FOUND FOR DIFFERENT DRIVETRAINS AND COMPONENTS

Operating point	Motor		Step-up gearbox	Frequency converter		LC -Filter	Total efficiency for drivetrains:		
	Regular-speed	High-speed		Regular-speed	High-speed		"DOL"	"RS+GB"	"HS DD"
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	97.0%	97.6%	97.8%	98.1%	98.4%	99.2%	94.82%	93.02%	95.27%
2	96.7%	97.3%	97.9%	98.0%	98.2%	99.2%	-	92.75%	94.78%
3	90.7%	96.8%	97.9%	96.6%	97.0%	99.1%	-	85.77%	93.05%
4	72.1%	95.9%	97.8%	94.1%	94.1%	99.0%	-	66.35%	89.34%
5	96.5%	95.8%	96.5%	98.0%	96.9%	98.5%	93.13%	91.27%	91.44%
6	97.2%	95.9%	97.0%	97.9%	96.6%	98.5%	-	92.26%	91.25%
7	95.4%	96.4%	97.3%	96.2%	94.2%	98.5%	-	89.31%	89.45%
8	83.1%	96.2%	97.3%	93.1%	88.6%	98.4%	-	75.25%	83.87%
9	94.2%	92.35%	94.6%	97.3%	93.7%	97.2%	89.13%	86.73%	84.11%
10	96.4%	92.75%	95.1%	97.0%	93.2%	97.2%	-	88.94%	84.02%
11	96.8%	94.5%	95.7%	94.7%	88.5%	97.1%	-	87.71%	81.21%
12	93.5%	95.19%	95.9%	90.1%	78.8%	97.1%	-	80.75%	72.83%

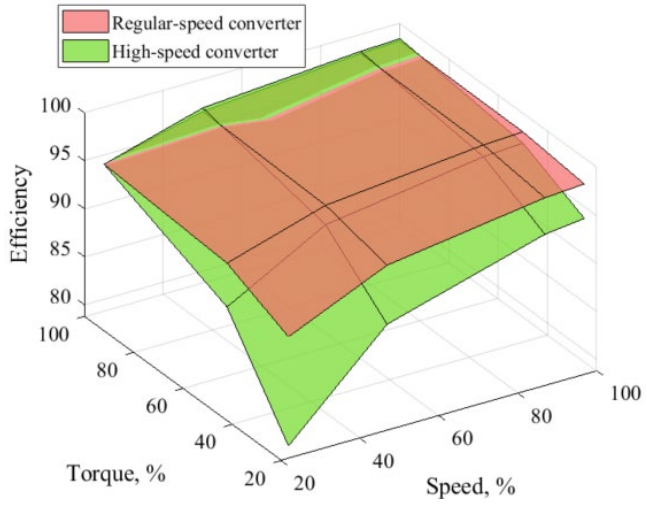

Fig. 5. Comparison of efficiency maps for frequency converters designed for regular-speed and high-speed applications.

D. *LC-filter*

In a high-speed direct drive system, where the motor is supplied with a frequency converter, there are especially strong negative effects caused by fast-switching PWM modulation. Especially rotor surface losses get high. To mitigate the switching frequencty related harmonics and its multiples, and reduce harmful d*u*/d*t* values, a specific high-frequency LC-filter must be used.

Losses of high-frequency LC-filters at different regimes were analyzed based on data available in [18], [19], written down in Column (7) of Table I, and presented as a corresponding efficiency map in Fig. 3f. The behaviour of LC-filter performance depends mainly on torque. However, if the speed is higher than half of the rated, it also affects he filter performance in direct relation. The LC-filter is utilized with the highest effitiency at the raded point.

III. RESULTS

Efficiency values found for different components are collected in Table I. Total efficiencies of all three drivetrains being under consideration in specified operating points are calculated and shown in the three rightmost columns of Table I.

Overall efficiency was calculated as a multiplication of efficiencies found for the drivetrain's constituent parts.

For the "DOL" operation, only columns (2) and (4) were taken. The resulting efficiencies are given in Column (8). For motor operated in direct online mode, speed adjustment is not available. Because of that, the first drivetrain's efficiency only depends on load torque. The remaining two drivetrains are equipped with frequency converters, and are capable to adjust rotational speed.

"RS+GB" drivetrain includes components listed in Table I under columns (2), (4), and (5) resulting in overall efficiency numbers given in column (9).

Drivetrain "HSDD" consists of high-speed motor (column (3)), high-speed converter (Column (6)), and filter (Column (7)). The total efficiency of the direct drive system is given in Table I, Column (10).

Fig. 6 shows a family of curves, where one can compare the efficiencies of different drivetrains over the whole range of speed and at three levels of load torque.

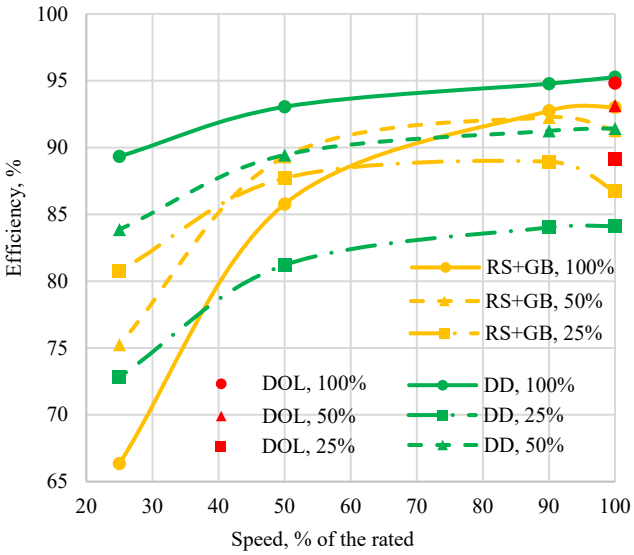

Fig. 6. Efficiency vs. speed curves for 100% load, 50% load, and 25% load for different drivetrains.

IV. Discussion

With defined efficiencies of different components for gear-box-powered and direct-drive drivetrains, it turns out to be possible to conduct a comprehensive efficiency analysis of presented drivetrains and define the most suitable option for a certain application.

This information and further considerations are intended to be valuable for energy systems engineers and specialists in industrial plants planning.

If comparing regular- and high-speed induction motors of megawatt-scale (Fig. 4), we can notice that regular-speed motors show a significant efficiency drop when the speed is reduced. Especially dramatic drop is seen at the lowest speed with rated torque. The efficiency surface of high-speed motors is much steadier – there are no significant dips over the entire area. High-speed motors show in general higher efficiency than regular-speed ones, except running at full speed and low torque.

The efficiency surfaces of megawatt-scale frequency converters designed for regular and high-speed motors supply (Fig. 5) show the following features. Regular speed converters have almost flat efficiency surface with nearly constant efficiency at all regimes, while high-speed converter has a notable efficiency decrease when torque and speed are at minimal levels. If we consider the converters separately from the entire drive system, high-speed converters have the only advantage at full torque operation regardless of speed. However, a comparison of efficiencies of entire drivetrains should be done to find out the most suitable one for a certain application.

In Fig. 6 we can notice that the simplest “DOL” drivetrain with a regular-speed motor and a speed-up gearbox has the best efficiency at operating points with reduced torque. Thus, a drivetrain based on a regular-speed direct-on-line motor can be considered as an adequate option in applications, where speed is constant, but torque is varying. Even though at full load “DOL” system is not on the top in efficiency, at half- or quarter- torque this simplest drivetrain shows significantly higher efficiency, than other options.

In cases, when adjustable speed is required, a system fed via frequency converter must be taken. Here we have a choice between direct-drive “HSDD” and gear-boxed “RS+GB” drivetrains.

Fig. 7 shows resulting efficiency surfaces built for two listed drivetrains in the same coordinates. An arithmetic difference between the surfaces is shown in Fig. 8, where positive deviation means that the “HSDD” drivetrain has higher efficiency, and negative values mean the “RS+GB” drivetrain is more effective in a certain point.

From those figures, we can notice that a high-speed direct-drive motor has better performance at all speeds, when the torque does not drop below about half of its rated value. However, in points where the high-speed direct-drive is inferior in efficiency, its lag is only a few percents, whereas the maximum positive effect happening at full torque and minimal speed operation is more than 20%.

It is recommended, that direct-drive must be used in applications, where load torque rarely drops below 40% of the rated value. Otherwise, if the load scenario involves long periods of operation at nearly idle torque, a drivetrain with a regular-speed motor and speed-up gear-box can be an appropriate solution as well.

In the current paper, the choice between different drivetrains was considered only from the efficiency point of view. In final decision making, all factors, such as CAPEX and OPEX costs, budget, availability of parts, available space, service access, reliability and noise requirements, and other characteristics must be taken into account.

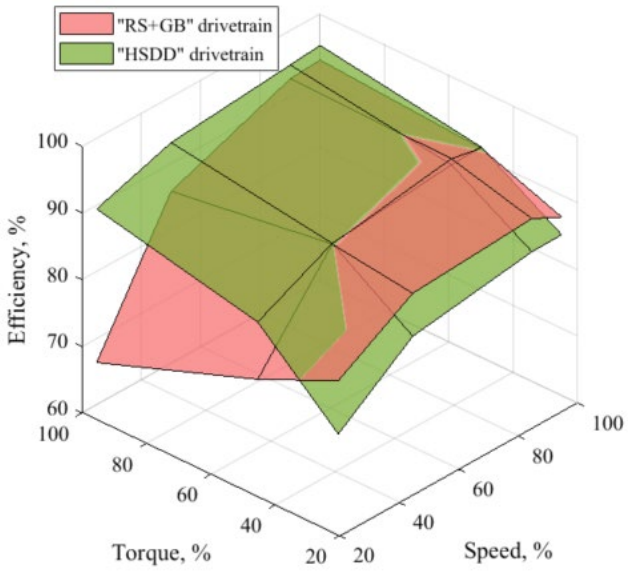

Fig. 7. Efficiency maps for “RS+GB” and “HSDD” drivetrains.

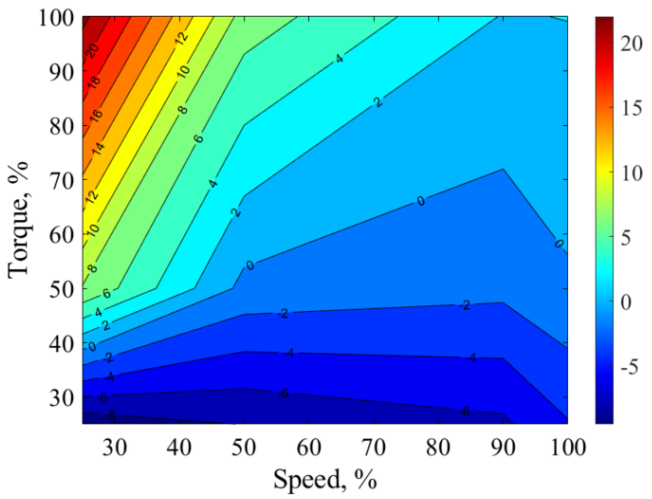

Fig. 8. The difference between the efficiency map surfaces for “RS+GB” and “HSDD” drivetrains. Positive deviation means that the “HSDD” drivetrain has a higher efficiency at a certain point while negative deviation means that the “RS+GB” drivetrain has a better performance.

Direct drive systems are considered by different authors as a more advantageous drivetrain because it has fewer fragile

and wearing parts, can be better and easier balanced, produces less noise and vibrations, requires less lubrication, has less inertia and offers better dynamics, always allows two-way torque transfer, has less maintenance cost, produces a wide range of RPM. Because of reduced drivetrain losses and a high power to mass ratio, the overall efficiency including material efficiency of direct-drive systems is generally higher. All abovementioned should be borne in mind and taken into account together with performance-based considerations.

V. Conclusion

In the current paper, the efficiencies of three different induction motor drivetrains in megawatt-scale high-speed application were compared.

Even though efficiency and losses at the rated operating point are usually given for any drive or system component, finding the performance, when load and speed differ from the rated is not a straightforward task. To fill that knowledge gap, the efficiency maps showing the performance at different combinations of torque and speed for whole considered drive systems and for their constituent parts were presented. The efficiency maps can be utilized to analyze different load scenarios and find corresponding losses. The performance plots shown in the current work are valid with acceptable tolerance for any practical induction machine or drivetrain components within the power range of 1…5 MW.

Investigating the performance of electrical drive systems in different operating points is a multidisciplinary and complex problem. The efficiency of the electric motor, gearbox, converter, and filter must be estimated together and under different conditions. To solve that task analytically or via FEM simulation, a multiphysics problem including electromagnetic, mechanical, and thermal components must be solved. Moreover, due to complicated geometry and assumptions always applied in analytical studies, the result can at some point vary compared to the real system. In multimegawatt scale, every fraction of an efficiency percent matters. Thus, even a small deviation is important. Because of that, a more reliable way of building the efficiency maps for listed drivetrains is to use empirical data. In the present paper, we refer to performance data available from manufacturers of the drivetrain equipment, and to peer-reviewed publications, where efficiency of equipment under certain conditions was reported.

Based on the presented findings, we can conclude that a direct-on-line drivetrain is always the best choice if no speed control is needed, but torque is varying. Especially, in load scenarios, when the load often and continuously goes below the rated value.

In cases, where variable speed is required, the efficiency-based choice between a direct-drive and a gear-box-equipped drivetrain should be done taking real load cycle into account. A direct drive has a notably higher efficiency if the load torque is higher than 40-50% of the rated. At lower speeds, direct-drive system shows the most significant gain in efficiency. At lower load torque, the direct drive has slightly worse performance, compared with the gearbox-based drivetrain. This small efficiency drop, however, can be compensated with other advantages of a direct drive system. But final decisions must be made on a case-by-case basis.

Thus, in variable high-speed applications in the range of 1…5 MW, direct-drive systems definitely have an advantage in efficiency in most cases and are highly recommended to be selected.

VI. References

[1] P. Poso, "Startup Survival in B2B Markets: case ASynRo," M.S. thesis, School of Engineering Science, LUT Univ., Lappeenranta, 2019.

[2] M. T. Caprio, V. Lelos, J. D. Herbst, and J. Upshaw, "Advanced Induction Motor Endring Design Features for High Speed Applications," in *Proc. IEEE Int. Electric Mach. Drives Conf.*, 2005, pp. 993-998.

[3] B. M. Wood, C. L. Olsen, G. D. Hartzo, J. C. Rama, and F. R. Szenasi, "Development of an 11000-r/min 3500-HP induction motor and adjustable-speed drive for refinery service," *IEEE Transactions on Industry Applications*, vol. 33, no 3, pp. 815–825, May-June 1997.

[4] S. Li and B. Sarlioglu, "Assessment of high-speed multi-megawatt electric machines," in *Proc. IEEE Int. Electric Mach. Drives Conf., 2015, pp. 1573-1579*.

[5] Gilbert A. McCoy and John G. Douglass, *Premium Efficiency Motor Selection and Application Guide – A Handbook for Industry*, Washington State University Energy Program, USA, 2014.

[6] *Rotating electrical machines - Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors*, IEC TS 60034-2-3:2013.

[7] Baldor Reliance, Product Information Packet: CP500808LR-4, 2015.

[8] M. I. Sunela and R. Puust, "Simple Visual Tool to Analyse Pump Battery Efficiencies for Various Pump Combinations," *Procedia Engineering*, vol. 89, pp. 525–532, Jan. 2014.

[9] R. Chirakalwasan, "Motor Load & Efficiency," *ASHRAE Thailand Chapter Journal 2006 - 2007*, vol. 2, pp. 21-33, 2007.

[10] Y. Li, M. Liu, J. Lau, and B. Zhang, "A novel method to determine the motor efficiency under variable speed operations and partial load conditions," *Applied Energy*, vol. 144, pp. 234–240, 2015.

[11] M. Ahrens, U. Bikle, R. Gottkehaskamp, and H. Prenner, "Electrical design of high-speed induction motors of up to 15 MW and 20000 RPM," in *Proc. Int. Conf. on Power Electron. Mach. and Drives,* Conf. Publ. No. 487, pp. 381-386, 2002.

[12] T. Burress, "Benchmarking State-of-the-Art Technologies," *2013 U.S. Dept. Energy Hydrogen Fuel Cells Program Veh. Technol. Program Annu. Merit Rev. Peer Eval. Meeting U.S. Department of Energy*, 2013.

[13] T. Jokinen, "Losses of high-speed induction motors," Workshop on losses and efficiency in electrical machines, Warsaw, Poland, 4-5.10.2005. editor / "Dzial Informacji Naukowo-Technicznej Sekcja Wydawnictw i Resprografii " Instytut Elektrotechniki. Warsaw, Puola, pp. 71-79, 2005.

[14] P. Jandura, J. Břoušek, and M. Bukvic, "The concept of a highly efficient powertrain for an electric vehicle with respect to vehicle driving dynamics," in *Proc. 2015 Int. Conf. on Elect. Drives and Power Electron. (EDPE)*, pp. 422-429, 2015.

[15] W. Shi, D. Stapersma, H. T. Grimmelius, "Analysis of energy conversion in ship propulsion system inoff-design operation conditions", *WIT Trans. Ecol. Environ*., vol. 121,pp. 449–460, 2009.

[16] Wikov Industry a.s., "Technical annex WGN191247" - unpublished confidential document, 2019

[17] *DriveSize 5.9.0.2.* (2021). ABB.

[18] Siemens, "SIDAC Reactors and Filters – Catalogue LV 60", 2007. [Online], Available: https://www.siemens-pro.ru/doc/documentation/LV60_SIDAC_2007_EN.pdf. [Accessed Mar. 21, 2022].

[19] AQ Trafotek Oy, "Three phase sine filter reactor", technical data sheet - unpublished confidential document, 2020.

VII. BIOGRAPHIES

Konstantin Vostrov was born in Leningrad, Russia, in 1991. He received the B.Sc. degree in the field of Electrical Engineering, Electromechanics and Electrotechnology from Peter the Great St. Petersburg Polytechnic University in 2013, and the double-degree M.Sc from the Peter the Great St. Petersburg Polytechnic University and Lappeenranta University of Technology in 2016. He is currently a doctoral student at Lappeenranta University of Technology. His research interests are in the field of electrical engineering and include electrical machines and electrical drives.

Lassi Aarniovuori was born in Jyväskylä, Finland, in 1979. He received M.Sc. degree in electrical engineering and the D.Sc. degree in electric motors and drives from the Lappeenranta University of Technology (LUT), Lappeenranta, Finland, in 2005 and 2010, respectively. During 2017 – 2019 he was a Marie Curie Fellow with the School of Engineering and Applied Science, Aston University, Birmingham, U.K. He is currently an Adjunct Professor in Electrical Machines and Drives with the LUT School of Energy Systems. His current research interests include the field of electric motors and drives, especially wide band-gap power switches, high-speed machine technology, modulation methods, simulation of electric drives, efficiency measurements, and calorimetric measurement systems.

Juha Pyrhönen (M'06), was born in 1957 in Kuusankoski, Finland, received the Doctor of Science (D.Sc.) degree in Electrical Engineering from Lappeenranta University of Technology (LUT), Finland in 1991. He became an Associate Professor of Electrical Engineering at LUT in 1993 and a Professor of Electrical Machines and Drives in 1997. He is engaged in research and development of electric motors and electric drives. His current interests include different synchronous machines and drives, induction motors and drives, and solid-rotor high-speed induction machines and drives.