Double inverter concept for high-speed drives without motor filters

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Abstract

It is known that high-speed machines have high power and loss densities [1]. The additional losses in the rotor caused by harmonics are particularly critical, as they act in the center of the machine. This paper shows an approach to reach small additional losses without a filter between inverter and machine.

Introduction

High-Speed drives become an important key technology to gain sustainable solutions in many applications. Water treatment, processes in food industry or high-performance pumps and blowers [2] require high rotational speeds. Direct drives, build with Permanent Magnet Synchronous Machines (PMSM) and equipped with magnetic bearings, avoid mechanical transmissions. Thus, they offer much higher energy efficiency and less wear resulting in lower operation and maintenance costs compared to conventional drives systems. Also regenerative energy systems require these high speed drives; they drive kinetic energy storages or they are used as turbo generators in many processes, like ORC (organic Rankine cycle) processes for e.g. waste heat recovery, biomass or geothermal power plant. However, rotor losses are critical and should be considered carefully. They are one reason why these drives cannot be operated by standard inverters without additional measures. One standard measure for reducing rotor losses is to use standard two-level inverters with medium switching frequencies in combination with *LC* motor filters to smooth the current ripple. Because these filters are cost intensive, heavy and can have negative impact on robustness and performance, they should be avoided. For development of high-speed drives without such motor filter some specific effects have to be understood, leading to a special design of the drive system, that considers the interaction of inverter hardware and software and the electrical machines, as discussed in the following. Especially the effects of the switched output voltage of an inverter on the electrical machine are manifold. The high rates of voltage rise lead to overvoltage at the winding, inhomogeneous voltage distribution in the winding, bearing currents and electromagnetic interference. However, these problems will not be considered here. The focus is on the understanding of the additional losses in the rotor, which are excited by harmonic waves and oscillations. The harmonic oscillations are caused by the inverter. The spectrum of the output voltage contains numerous harmonics in addition to the desired fundamental oscillation. These lead to a current with harmonics, whereby harmonics near twice the switching frequency appear particularly dominant in the spectrum. Finally, the winding generates pulsating fields and rotating fields from the harmonics, which have speeds different from the mechanical speed of the rotor. In contrast to the fundamental wave field circumventing with the rotor, the harmonic fields generate time-varying inductions in the rotor. Due to the electrical conductivity of the solid components in the rotor, eddy currents are excited causing corresponding additional losses. In addition to the converter, the winding itself also generates harmonics, even if they are supplied by sinusoidal currents. The reason for this is that the coils are mounted in slots. The resulting staircase-shaped distribution of the magnetomotive force generates corresponding harmonics. Another source of harmonics are the slot openings. This changes the magnetic resistance at the circumference, so that the generated fields are modulated. The next section discusses the reduction of harmonic losses by using suitable inverter topologies. Then it will be shown how the losses in the electrical machine can be reduced by supplying them with several inverters. The knowledge gained is then verified by experimental measurements. Finally, a suitable inverter with further possible areas of application is presented.

Methods for reducing the harmonic content at the inverter output

Increasing the switching frequency: This method is often seen as the first option for reducing additional losses. In the power range up to a few 10 kW, converters have been developed that operate with switching frequencies of up to 100 kHz [2]. With the new but cost-intensive wide bandgap (WBG) semiconductor materials SiC and GaN, these high switching frequencies can be achieved even for higher power levels [3]. Note, that in nearly all applications high-speed drives, as considered here, operate in quasi-stationary mode. This is different from the requirements in servo drives and one reason, why such developments are not the cost optimized and best solution. Other reasons for this are:

- The speed is limited to approx. 45,000 rpm for power ratings above 100 kW. This results in fundamental frequencies of max. 1500 Hz. An increase of the switching frequency beyond 20 kHz reduces the losses only slightly.
- Inverters with conventional silicon semiconductors generate very high losses at the high switching frequencies, are large and correspondingly expensive.
- Inverters with WBG semiconductors are much more cost-intensive than a standard inverter with corresponding sinusoidal filters. The greater control dynamics of the filterless variant is not required in the applications.

Under the present conditions, inverters built with ordinary silicon semiconductors and switching frequencies between 10 kHz ... 25 kHz seem to be an ideal compromise between requirements from the application and costs. In the following, the influence of the frequency ratio on the harmonic losses is to be shown with measurements on motors with relatively low power ratings. Fig. 1 shows the measured harmonic losses of a standard asynchronous machine and a fast rotating permanent magnet synchronous machine. The measurements of the asynchronous machine are taken from [5]. Table 1 shows the machine data.

Table 1: Data of the used machines

Parameter	Asynchronous Machine	Synchronous Machine
Rated power	7.5 kW	35 kW
Rated speed	2900 rpm	54 000 rpm
Rated frequency	50 Hz	1800 Hz

If we look at the harmonic loss curves, we see that the loss proportion is much smaller for permanently excited high-speed machines. Above frequency ratios of 25, hardly any reductions are possible. With standard asynchronous machines, the harmonic losses can be decreased significantly up to frequency ratios around 150. The difference in loss reduction can be suspected from the fact that in the asynchronous machine a large part of the additional losses occurs in the cage winding. In the synchronous machines considered here, however, this is not existing. Due to the small improvements and the problems arising in the inverter to achieve high frequency ratios at high fundamental frequencies, a large increase in the switching frequency does not make sense.

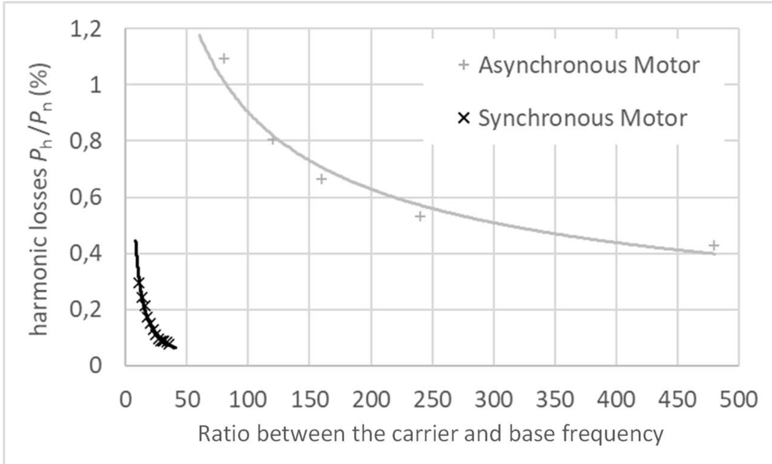

Fig. 1: Harmonic losses normalized to the rated power as a function of the switching frequency

Multi-level inverters: Another possibility to reduce the harmonic content is to increase the number of switching levels. Since the number of components used increases strongly with the number of switching levels, only three-level converters can currently be used effectively in the low-voltage range. In the meantime, there are many semiconductor modules available for this inverter topology, so that the module costs have been greatly reduced in recent years. The switching voltages at the inverter output are only half as large as those of the standard two-level inverter. This means that at the same switching frequency, the current ripple and the harmonic fields excited in the machine are also halved. According to [4, 6], the magnetic induction is squared in the magnetic losses. Therefore, by using inverters with three-level technology, the additional losses in the rotor and stator caused by the converter are reduced by factor 4. This fact was also confirmed by measurements [5]. The loss reduction through three-level inverters is very strong and sufficient for many applications [16].

Interleaved inverter

Use of coupling inductors: An interleaved inverter is built by connecting n inverters of the same type. Fig. 2 shows such a setup with two inverters. The fundamental oscillations are given out synchronously, but the carrier signals C_1 and C_2 of the modulation have phase offsets by $2\pi/n$ to each other. Fig. 3 shows the pulse patterns of two interleaved switching sub-inverters. The output currents i_1 and i_2 show the typical ripple of an inverter feeding an inductor. However, the sum results in a current that contains smaller harmonic amplitudes with double the frequency. The harmonic components of each sub-inverter are therefore not reduced by interleaving. The harmonics, which are no longer present in the total current, flow as circulating currents. The limitation of these harmonics must be done with correspondingly large chokes L_1 and L_2 [7]. Fig. 4 shows an example of the spectrum of the output voltage of an interleaved inverter with two sub-inverters.

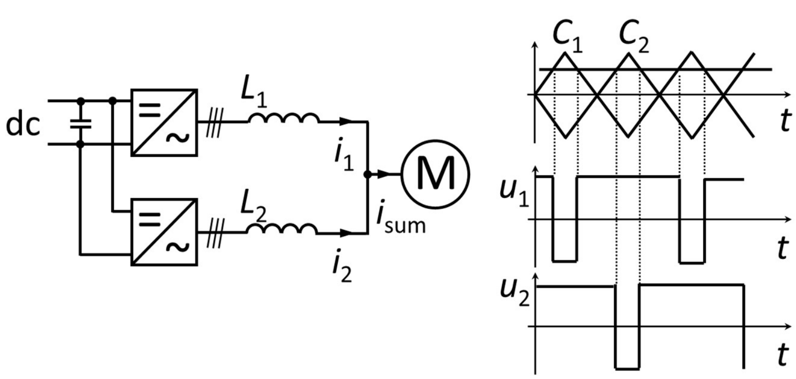

Fig. 2: Interleaved inverter

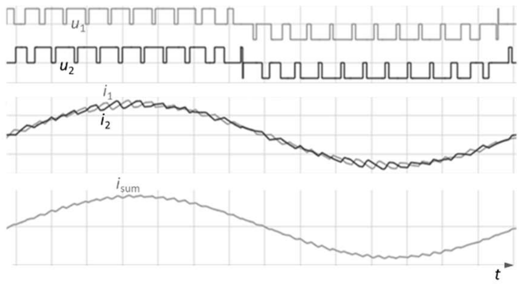

Fig. 3: Inverter outputs and their sum current one

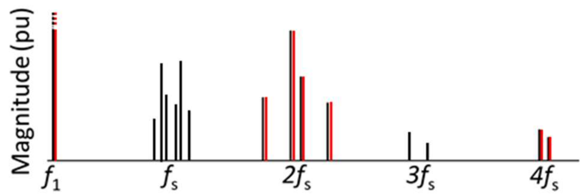

Fig. 4: Frequency spectrum of the output voltage of inverter (black) and the sum of both inverters (red)

The harmonics and their sidebands with multiples of 1, 3, 5, ... of the switching frequency, which are present when only one inverter is working, can be suppressed. However, the particularly dominant harmonics with twice the switching frequency cannot be influenced. Because the density of the spectrum decreases with $1/n$ through n interleaved switching inverters, it can be assumed that the harmonic losses decrease with the same ratio.

Direct connection of the winding: If the armature winding is divided into several galvanically separated partial windings, a correspondingly large number of interleaved converters can be connected directly to them. The separate wiring between the inverter and the machine with several three-phase cables has further additional advantages:

- At high currents and frequencies, the current displacement losses in the cables are no longer negligible. A division into several three-phase cables reduces the current displacement. For this reason, [8] also recommends such cabling.
- The balancing of the currents is achieved by the positive temperature coefficient of the conductors. If the cables are connected to separate winding sections, the current is distributed more homogeneously among the cables.

In this configuration the circular currents are now limited by the inductances of the individual partial windings. Fig. 5 shows this situation for a winding with two parts. First, the circuit currents are limited by the leakage inductances of the two winding parts. Furthermore, the coupling of the winding parts by the main flux is not complete, so that the main inductance is modelled with 3 equivalent elements. L_{m1} and L_{m2} stand for the leakage inductances not chained to the main flux. L_m stands for the main inductance linked to the main flux. The effect of the winding resistances on the circulating currents can be neglected.

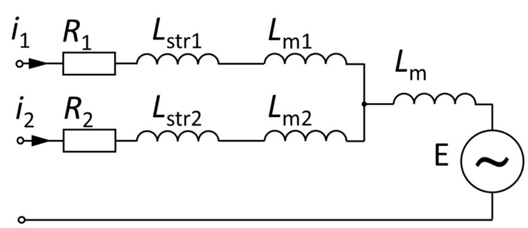

Fig. 5: Simplified equivalent circuit diagram for a synchronous machine fed by 2 inverters

In the following it will be shown how the winding construction influences the coupling of the winding parts. For simplicity, only windings with two partial windings are considered. In general, however, these statements can also be applied to several sub-windings.

Case a) The coils of the partial windings lie on top of each other and in the same slots:

In this case, very small stray inductances of the partial windings result. The magnetic coupling is at a maximum. As a result, very high circulating currents are generated through the two windings and inverters. Usually the inductances are too small, so that additional external inductances are necessary. The construction of such windings is difficult, as there are always two coils to be insulated, one on top of the other in the winding. However, the suppression of the harmonic content is maximum with this type of winding. It can be assumed that the same results are achieved as with interleaved converters connected by coupling chokes.

Case b) Partial windings with coil groups shifted by 360°:
Fig. 6 shows the position of the two coil groups of a phase in a 4-pole machine. From the indicated field lines it can be seen that the coil groups are not chained via the main flux. This means that there are no circulating currents between the two inverters. Due to the lack of coupling, however, the full harmonic spectrum of an inverter reaches the rotor, so that no reduction in losses can be expected with this arrangement.

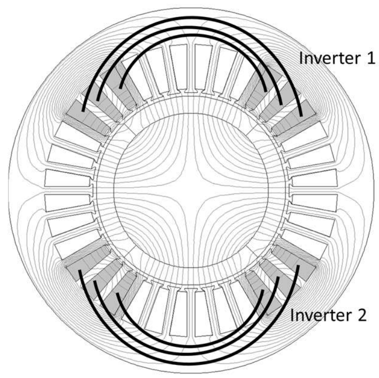

Fig. 6: Position of the coil groups shifted by 360° in a 4-pole machine

Case c) Partial windings with coil groups shifted by 180°:
Fig. 7 shows the placement of the coil groups. Since here, too, each slot magnetomotive force is generated by both inverters, the harmonics, eliminated by interleaved operation can also be suppressed. The end windings that are not directly on top of each other increase the leakage inductance, so that the circular currents in this case are smaller compared to case a (coils are on top of each other). However, to suppress winding harmonics, chorded coils are often used so that the coil groups do not lie exactly in the same slots. Fig. 8 shows such a possible position. The field shown results from the circular current. As can be seen, the circular current forms fluxes that only partially reach the rotor. For this reason, the suppression of harmonics is not as good as in an interleaved inverter with coupling chokes or in the case of windings where the two parts of the winding are placed in the same slots. On the other hand, in this case there is a considerable inductance that limits the circulating currents, so that additional chokes can be omitted. As a rule, if the suppression of the additional losses caused by the inverter is sufficient, this variant with chorded coils is forced in an interleaved concept, since no additional chokes are necessary.

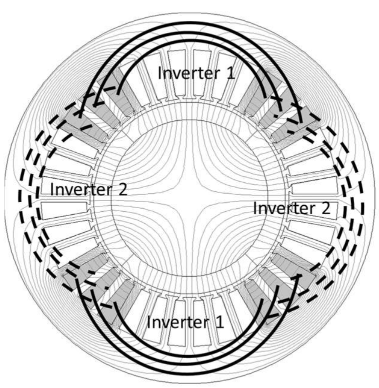

Fig. 7: Position of the coil groups shifted by 180° in a 4-pole machine

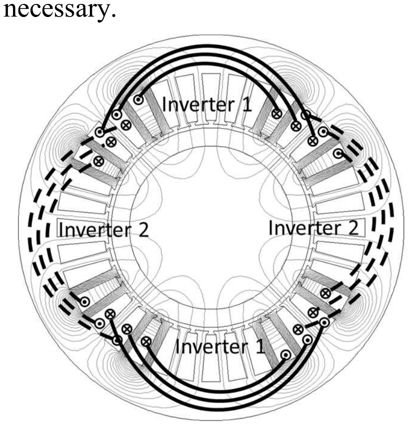

Fig. 8: Position of the coil groups shifted by 180° with chorded coils in a 4-pole machine

High phase windings

Similar to the interleaved concept, several 3-phase inverters feeding a corresponding number of galvanically separated winding parts are used here. In contrast to interleaved system, in which the carrier frequencies are shifted, the phase position between the fundamental oscillations is shifted here. As a result, the winding parts must also be shifted arranged in the stator. This known method [9-11] has the following advantages:

- Increase of the fundamental winding factor, so that 8-12 % winding losses can be reduced with the same material usage.
- The lower winding losses reduce the winding temperature and indirectly also the critical rotor temperatures.
- Reduction of the harmonic content of the winding, so that the losses in the rotor decrease.
- The rotor losses generated by harmonics oscillations can be well suppressed by using shielding sleeves [12]. However, this solution produces higher winding harmonic losses. If such an arrangement is to be used effectively, low-harmonic windings must be used accordingly. This goal can be achieved well by using high phase windings.

The ideal phase shift α_i between the 3-phase systems depends on the number n of winding systems used:

$$\alpha_i = \frac{60°}{n}.$$

The number n of systems influences the harmonic content, which can be described by the coefficient of differential leakage [12, 13]. The influence of the number of systems is shown in the example of a 2-pole winding with 72 slots (Table 2). It is noticeable that the fundamental winding factor can be increased when two three-phase systems are used. A further increase in the number of winding systems, on the other hand, neither increases the fundamental winding factor, nor reduces the coefficient of the differential leakage. Investigations in[14] show that the winding losses decrease quadratically to the fundamental winding factor.

Table 2: Properties of the high phase windings

number of 3-phase systems	1	2	3	4
phase shift (deg)	-	30	20	15
nuber of slots per pole and phase	12	6	4	3
coil pitch (slots)	30	33	34	35
fundamental winding factor ξ_1	0.9227	0.9805	0.9915	0.9965
$(\xi_{1,3\sim} / \xi_1)^2$	1	0.886	0.866	0.8573
differential leakage factor (%)	0.0928	0.065	0.0639	0.0638

With two shifted three-phase systems, the winding losses can be reduced by approx. 11 %. If four systems are used, the winding losses are reduced to approx. 14 %. As can be seen, an increase to more than two three-phase systems hardly results in any advantages. In addition, such high-phase systems often require an impracticably high number of slots. Apart from the loss considerations, there is another advantage with these windings. Due to the high frequency and power, the number of coil turns are very small, so that an adjustment to the ideal number of turns is not possible. Furthermore, the required large conductor cross-sections tend to cause large current displacement losses, which can only be avoided by twisted strands with very thin individual wires. This results in a poor slot fill factor [15]. Both problems can be reduced if the number of parallel armature paths is increased. It is known that three-phase windings can have a maximum of as many parallel armature paths as this winding has poles. In the case of windings constructed by n systems, this applies to each system. Accordingly, such windings can be constructed by $2p{\cdot}n$ parallel interacting armature paths. In addition, the 5th and 7th harmonics can be suppressed so that the generated torque pulsates less. Typically, such harmonics occur in V/f controlled operation. This can disturb the start-up. Due to the effective suppression when using two inverters shifted by $30°_{el}$, the start-up can take place much less critically. This mode of operation is no more up-to-date today. Nevertheless, it is used for sensorless control in the lower speed range when there are only small differences between the d- and q-axis inductances in synchronous machines.

Measurement results

All measurements were done on permanently excited 300 kW machines, which can be operated as motors or generators. The tests were made in the speed range between 18 000 rpm and 22 000 rpm.

Reduction of losses through 3-level inverter and interleaved operation:

The power loss reduction was measured in no-load operation, as this can be determined directly via the power consumption. To measure the power consumption, a power meter with sufficient bandwidth was used between the inverter and the electric machine operated as a motor. Table 3 shows the losses measured in this way. Comparing the two interleaved measurements, it can be seen that the harmonic losses can be reduced to approx. ¼ by the 3-level control. The loss reduction is much weaker when comparing non-interleaved and interleaved operation in 3-level mode. The loss reduction is less than ½. In chapter II it was derived that the losses decrease proportionally with the number of inverters in interleaved operation. In the measurement, two inverters were used. However, the currents were not added by a coupling inductor. Both converters fed one winding part each. Their windings are shifted by 180°. As described above, the power loss reduction is less than ½, in this case 0.4. Fig. 9 shows the influence of interleaved operation on the rotor temperatures under load with nominal torque. These comparative measurements were also carried out with 3-level inverters. The rotor temperatures were measured at 6 axial points during operation. Data transmission was carried out using near-field telemetry. Here, too, it was shown that the rotor temperatures could only be reduced slightly by approx. 3 K through the interleaved drive.

Table 3: Measured no load losses

Mode	Total losses (W)	Harmonic current losses (W)
2-Level, interleaved	3583	437
3-Level, not interleaved	3330	184
3-Level, interleaved	3255	109

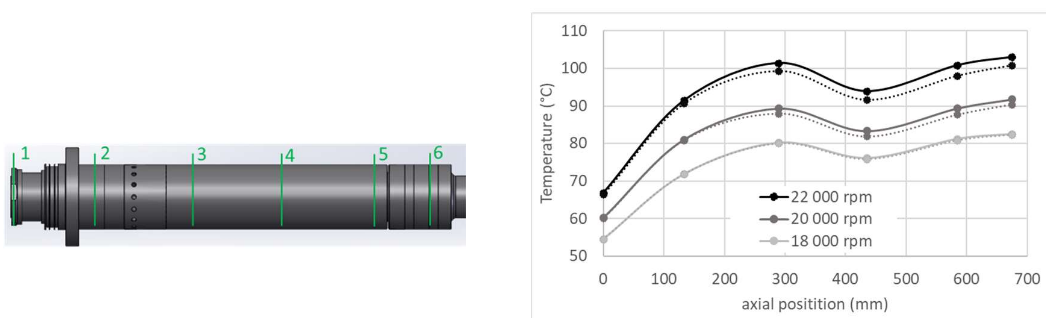

Fig. 9: measured rotor temperatures (interleaved operation is shown with dotted lines)

Winding with two winding parts shifted by 30°:

Compared to the 3-phase standard winding, the measured cold resistance has increased by factor 1.08. The reason for this is that the end windings are 1 slot pitch longer. Since the winding factor also increased from 0.925 to 0.983, the winding losses can be slightly reduced:

$$\frac{P_{\mathrm{cu},6\sim}}{P_{\mathrm{cu},3\sim}} = 1.08 \cdot \left(\frac{0.925}{0.983}\right)^2 = 0.96\,.$$

The smaller winding cross-section results in smaller current displacement losses, which, however, could not be determined by measurements. However, the total losses at 300 kW power could be measured. Table 4 shows the correspondingly determined values for this and the usual 3-phase winding. The total losses could be reduced by approx. 10 % at 18 000 rpm. At 22 000 rpm, more field weakening current has to be provided due to the higher winding factor, so that the loss reduction is lower.

Table 4: measured total losses at 300 kW mechanical power

Winding type	18 000 rpm	22 000 rpm
3-phase standard	5.04 kW	4.74 kW
30° shifted winding parts	4.51 kW	4.56 kW

Inverter concept

Based on the research results discussed above, a multifunctional inverter has been designed as shown in Figure 10. It contains two 3-level inverters operating on one DC link. The two inverters can operate synchronized for driving one motor (interleaved operation, generation of two phase-shifted three-phase systems). However, it is also possible for the two converters to perform different control tasks independently of each other. The inverter is characterized by the following additional features:

- The connectable DC link: The inverter can also be fed or fed back directly into the DC link.
- Braking resistors for safe braking even in the event of a mains failure.
- Input rectifier with thyristors. These can ramp up the DC link voltage in a controlled process. A start via charging resistors with additional external relay is not necessary.
- Integrated power supply unit for magnetic bearings, which is internally fed from the DC link. This means that even in the event of mains failures, the magnetic bearing electronics can work as long as the machine is rotating. In this case the DC link voltage is maintained by braking operation.
- The output power of the two inverters is fed out to four 3-phase terminals. This allows the power to be distributed over several thin cable cross-sections. The thinner cable cross-sections are easier to install and avoid high current displacement at high output frequencies required by high speed drives.
- All 12 phase connections are monitored with current sensors, so asymmetries and cable breaks can be detected.

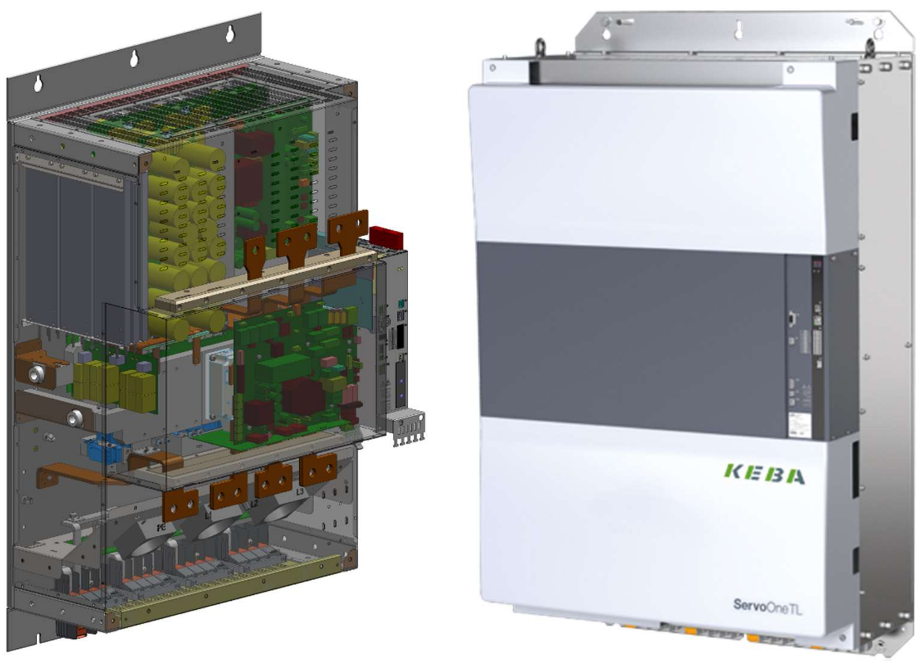

Fig. 10: Double inverter: Basic layout (left) and view of the finished unit (right)

In addition to the high-speed applications, that benefits from the reduction of additional losses caused by the inverter, the modular double inverter can be used in other applications:

- Operation on 2 independently running motors (multi-axis drive)

- Operation as active front end (boost converter) with higher DC link voltages
- Inverters that generate three-phase systems with a multiple of 60°: This does not reduce the losses in the electrical machine. However, common mode is completely avoided, so that the center of the DC link no longer oscillates at 3 times the fundamental frequency. The modulation level can thus be increased at low fundamental frequencies.
- Operation as regenerative converter: One output stage works as an active rectifier. To reduce the output currents and cable cross-sections, it is suitable to use higher DC link voltages in the range between 700 V and 800 V. The other output stage operates as an inverter on the electrical machine. Due to the possible synchronization of both output stages, the undesired overshooting common-mode voltage at the machine terminals can be actively damped [17].

Conclusion

If high-speed machines with high power are fed by an inverter, the harmonics generated cause a problem. Since typical motor filters are very large and expensive, they have to be avoided and other approaches for reducing the harmonic content should be evaluated. In this paper, the approaches of increasing the switching frequency, increasing the number of switching levels, and interleaved converters have been discussed. Like the harmonic oscillations, the harmonic waves generated by the winding also have an impact. Both effects cause an increase in losses and temperature in the most critical component of the electrical machine, the rotor. A further method for loss reduction has been proposed, which makes use of several converters generating phase-shifted three-phase systems. In this method, the winding losses and the losses generated by harmonics are reduced. As a result from this analysis, a multifunctional double converter has been designed. By housing two converters in one unit, each equipped with an own controller, the double inverter provide all operation modes and include most methods, which have been proposed for the reduction of the additional losses caused by the converter. The flexible and modular concept of the inverter allows its use in even more applications than just high-speed drives.

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