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Novel Recuperation Capability for Variable Speed Drives

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Abstract—**Efficiency and recuperation capabilities of modern electrical drives have become very important features within variable speed drive applications. Regenerative electrical drives are therefore usually equipped with cost extensive pulsed active front end topologies for the recuperation mode. Contrarily, the much cheaper fundamental frequency switched front end is used. It has no electrolytic capacitor with its limiting effect on the operating temperature and lifetime. Additionally to the converter topology, the used squirrel cage induction or alternatively the permanent magnet based machine shows different advantages with respect to the efficiency-torque characteristic within variable speed drives.**

Index Terms—**Variable speed drives, Converter topologies, Energy recuperation options.**

I. Introduction

Modern electrical variable speed drives, as shown in Fig. 1, can consist of different electrical machines – based on synchronous or even asynchronous energy conversion – in conjunction with various special control algorithms and different novel power converter topologies [1-4]. Additional to the given technical requirements, the optimal drive is almost chosen with respect to economical reasons. Thus, significant electrical energy saving potentials due to the usage of very high efficient machine and converter components itself as well as the recuperation capability of electrical power into the grid became very important aspects.

Fig. 1. Controlled variable speed drive systems consisting of electric motors driven by power converters.

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There are several possibilities available for realizing braking or recuperation options within the drive system. Over synchronous braking e.g. leads to an energy flow back into the DC link of Fig. 2, whereas the braking chopper and resistor limits the voltage rise and converts the remaining energy into heat. A more favorable alternative is to feed back the recuperation energy into the mains by a line side inverter in combination with a line-side choke as shown in Fig. 3 [5-7]. Additional features of such topology are the sinusoidal current waveform in the mains and its unity power factor as well as the control of the DC link voltage. The complexity of the control for the active front end in Fig. 3 is comparable with the complexity of the field oriented control of the DC-AC inverter for the motor. The line-side and motor side inverter sections are thereby almost stressed by switching losses in the same amount.

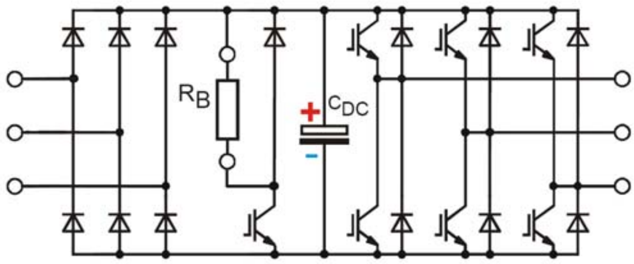

Fig. 2. AC-AC converter with AC-DC diode rectifier, DC-link capacitor with brake resistor and brake chopper as well as DC-AC drive inverter.

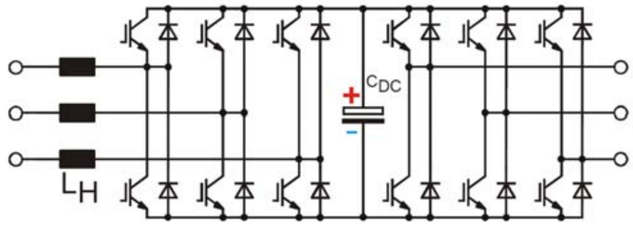

Fig. 3. Drive converter with line-side step-up inverter (active front end), DC-link and DC-AC drive inverter.

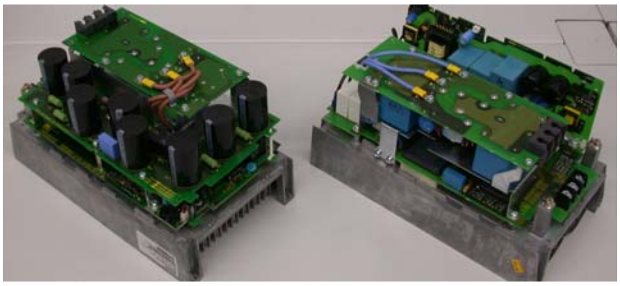

Fig. 4. State-of-the art DC-link design (left) versus the novel line-frequency switched rectifier without DC-link (right) topology.

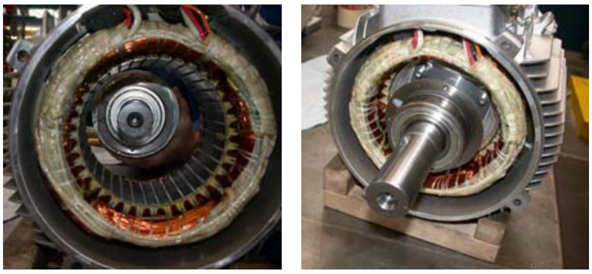

Fig. 5. A typical 5.5kW low voltage 4-pole squirrel cage induction (left) and buried permanent magnet (right) machine design.

The Fig. 4 shows a comparison of different power modules. The main electrical characteristics of the used converter are listed in Table I. Between the line and the rectifier there is an additional filter, comprising a three-phase inductor and three capacitors. In case of an increased pulse-frequency in Table I of up to 8 kHz, a significant reduction of the continuous output current reduction from 18 A to 12 A has to be considered.

TABLE I
ELECTRIC CHARACTERISTICS CONVERTER

Rated power	Pulse-frequency	Output current	Output frequency	Power-factor
[kW]	[kHz]	[A]	[Hz]	[1]
7.5	4	18	0…200	0.95

TABLE II
CHARACTERISTICS FOUR POLE ASM-MACHINE AT 1500 RPM

Rated power	Copper losses	Iron losses	Friction, fan losses	Remaining losses
[kW]	[W]	[W]	[W]	[W]
5.5	524	168	38	11

TABLE III
CHARACTERISTICS FOUR POLE IPM-MACHINE AT 1500 RPM

Rated power	Copper losses	Iron losses	Friction, fan losses	Remaining losses
[kW]	[W]	[W]	[W]	[W]
5.5	435	130	45	21

The interior permanent magnet design in Fig. 5 allows the usage of reluctance torque effects within special control algorithms. Table II and Table III include main characteristics of both machines. The knowledge of the relation between different loss contributions at the rated speed gives a first idea about the efficiency versus speed characteristic behavior.

II. CONVERTER WITH LINE-FREQUENCY SWITCHED RECTIFIER

The novel regenerative drive converter consists of a line-side three-phase rectifier and a motor-side three-phase inverter, but its operational behavior is completely different to the well known state of the art designs shown in Fig. 2 or Fig. 3, because the novel topology in Fig.6 uses a DC link with no additional components [8]. Neither a temperature sensitive electrolytic capacitor or simple inductor, nor a braking resistor with chopper, are necessary [9].

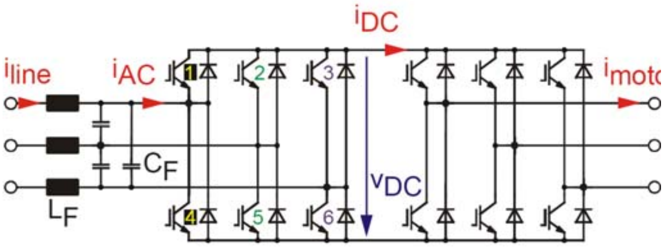

Fig. 6. Converter with line-frequency switched rectifier but without DC-link components.

Anti-parallel to the rectifier diodes in Fig.6 there are six IGBTs, which conduct the DC link current, if it flows from the inverter to the rectifier in regeneration mode. Between the line and the rectifier in Fig. 6 there is a line filter. Its main purpose is to keep currents with the switching frequency of the inverter away from the mains. As the motor-side inverter is a normal inverter with a normal pulse pattern, the output current is sinusoidal as usual, too.

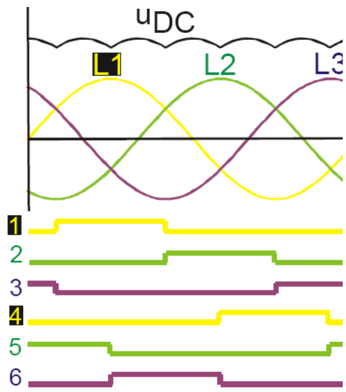

Fig. 7. Line voltage synchronizes the switching pattern for the anti-parallel IGBTs of the rectifier.

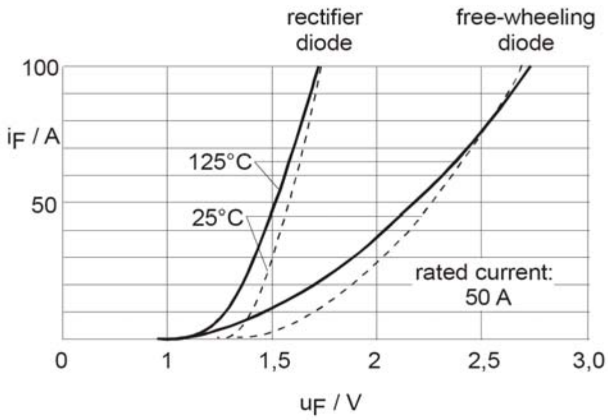

Fig. 8. Different voltage drops of rectifier and switching diodes.

The DC link voltage in Fig.6 has the waveform according to Fig 7, because there are no smoothing elements in the DC link. The waveform is composed of sections of the phase-to-phase voltages of the line.

As the anti-parallel IGBTs in Fig.6 are switched with line frequency as shown in Fig.7, their switching pattern is very simple, because it is synchronized with the line voltage. The IGBTs in Fig.6 are switched on and off in synchronization with the line voltage.

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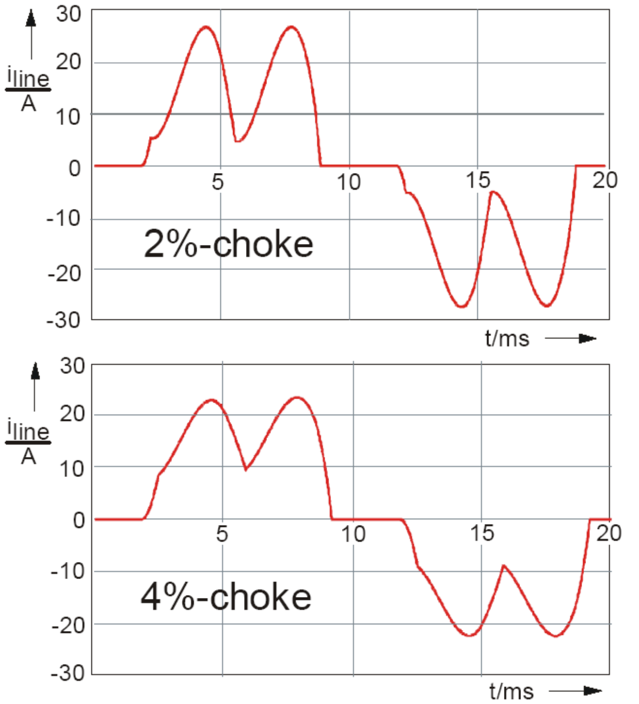

Fig. 9. Schematically line current waveforms of the standard rectifier with 2% and 4% choke.

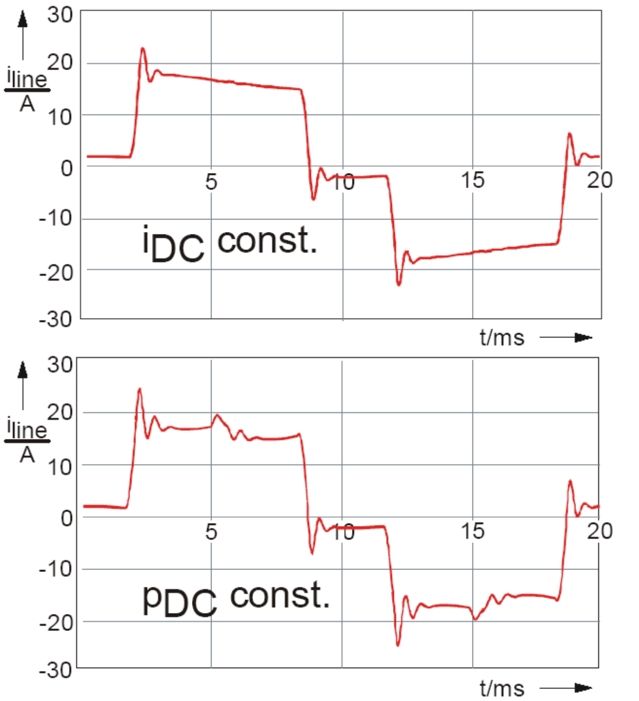

Fig. 10. Schematically line current waveforms of the fundamental frequency front end converter with line filter.

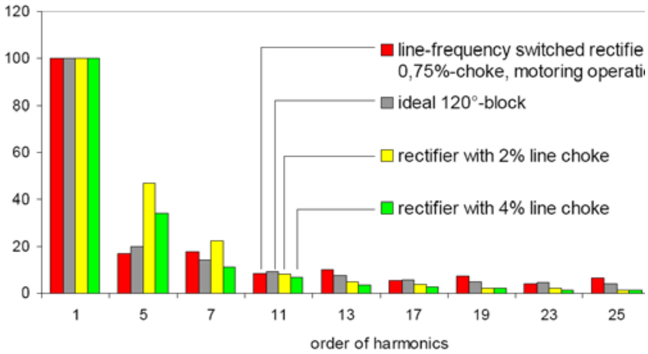

Fig. 11. Spectra of the line current for different rectifier circuits.

The IGBT of the upper three with the highest phase voltage on its emitter gets the ON-signal, the other two get the OFF-signal; with the three lower IGBTs it is the same with the lowest phase voltage. Changes of the switching signals for the six IGBTs occur, while the particular phase-to-phase line voltage passes through zero. Therefore the switching process is soft and the specific loss energy Eon and Eoff is low. Due to the fact, that the switching frequency is the mains frequency, switching losses of the line-side IGBTs are negligible at all. The switching operations occur from phase to phase proceedingly. Switching operations between upper and lower IGBT of one phase in Fig.6 never happen. That is the reason, why rectifier diodes can be used with minimized forward voltage drop.

At the line-side rectifier diodes in Fig.6 with lower conduction losses are suitable instead of freewheeling diodes with optimized switching behavior and higher conduction losses like in the inverter section. Freewheeling diodes in Fig.6 with optimized switching behavior, as exemplarity given in Fig.8 are not necessary. The advantage is less loss in the rectifier section for both reasons: type of diodes and no switching losses of diodes and IGBTs. The principle differences from the fundamental frequency front end converter to the state of the art design can be seen from the comparison of Fig.9 and Fig.10. Fig.9 shows the waveform of the line current for the standard diode rectifier in Fig.2. For the line-frequency switched rectifier in Fig.6, the Fig.10 contains the current shape under different conditions. The content of switching frequency is for simplicity omitted in Fig.9 and Fig.10. If the DC current is constant, the above mentioned current blocks in Fig.10 are overlaid by the current, which flows through the filter capacitors and causes the decreasing ramp instead of a constant current. If the power in the DC link is held constant, the DC link current has an additional content, which compensates the ripple of the DC link voltage. This yields to a superposition like a garland twice during a 120° block in the line current. As the filter is stimulated step-wise the line current shows the step-response of the filter at the beginning and end of each 120° block. The comparison between the harmonic content of the line current in Fig.10 of the fundamental frequency front end converter and in Fig.9 of the rectifier with diodes and a line choke is given in Fig 11. The converter with line-switched rectifier has less current harmonics of low fifth and seventh order opposite to a normal rectifier with a usual 2% or 4% sizing of the line choke. The size of the filter choke of the fundamental frequency front end is about 0.75%. Current harmonics of higher order are similar or slightly higher in Fig.11.

Because of the low additional effort this converter type is very advantageous, when regenerative operation is expected and when low frequency harmonic content of the line current is not critical and does not require a converter with pulsed active front end. The simple switching pattern for the line-side IGBTs can be generated very easily. However, the DC-link voltage is not ideal, but superimposed by the line-harmonics caused by the rectifier. The resulting influences for the motor can be minimized by means of the PWM strategy of the motor-side inverter.

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III. ASYNCHRONOUS DRIVE PERFORMANCE

Because of the missing switching losses of the line-side rectifier in Fig.6 an advantage with respect to the efficiency in motor operation can be expected with the fundamental frequency front end converter. The rectifier has a very high efficiency in the motor operation and in the regenerative operation as well. The reasons for that are the missing switching losses in comparison to an active front-end inverter in Fig.3. However, due to the restricted voltage output of the varying converter topologies, the winding system of both machines has to be adapted for the rated operational state [10].

The efficiency of the complete asynchronous or synchronous drive can be split up for more transparency into the converter and the motor efficiency components. The calculated converter efficiency includes e.g. the losses in the diodes, the semiconductors, the consumption of the electronic power supply unit for the control circuitry and the cooling fan as well. The converters efficiency is strongly depending on the applied load current as well as the chosen pulse-frequency.

The calculated motor efficiency takes account of different loss sources, such as e.g. copper-, iron-, friction-, fan- and various additional-losses [11]. Unfortunately, those different sources of losses are depending on speed and load in a different manner. Some values can be found in Table II and Table III for copper and iron losses at the rated operational state. In case of the squirrel cage induction machine given in Table II, the ratio of iron to copper losses is about 32%. Similarly, the ratio for the permanent magnet assisted machine is about 29%.

A. *Efficiency of converter, machine and complete drive at 1500 rpm rated speed*

The converter fed asynchronous machine is operated at the constant speed of 1500 rpm, whereas the load is varied over a wide range [12]. The system efficiency of the complete drive is derived from measured quantities and split up into the machine and converter efficiency components, which are shown in Fig. 12. For this measurement the electric power consumption was measured at the line and at the output terminals simultaneously. Hence the efficiency of the converter can be obtained.

A changing load at 4 kHz pulse-frequency causes different current consumptions, which mainly governs the invoked copper losses within the converter and the machine at the steady operational state. The efficiency level of the converter lies between the very high ranges of 95% to 97%. The squirrel cage induction machine efficiency is between 85% and 90%.

If the pulse-frequency at the constant speed of 1500 rpm is increased from 4 kHz up to 8 kHz, the behavior shown in Fig 13 is obtained. Thereby, the converter efficiency is significantly reduced due to increasing switching losses. On the other hand, the machine efficiency could be slightly increased due to the reduced higher harmonic voltage content of the applied 8 kHz PWM voltage spectrum. Thus, additional iron losses in the machine due to the applied 8 kHz spectrum could be minimized.

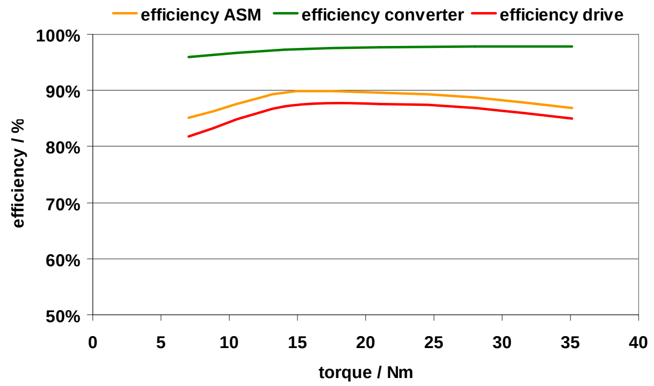

Fig. 12. Efficiency of drive components with 4 kHz pulse-frequency and varying load conditions.

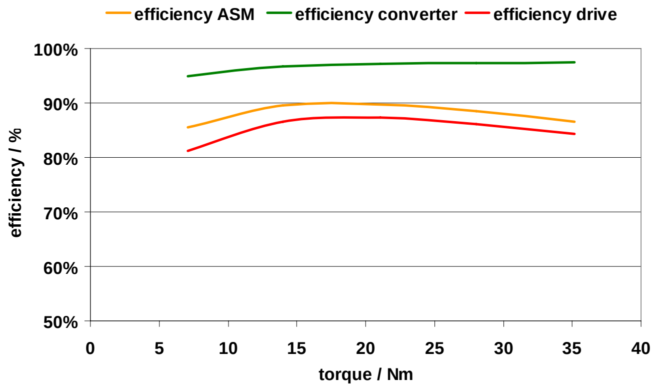

Fig. 13. Efficiency of drive components with 8 kHz pulse-frequency and varying load conditions.

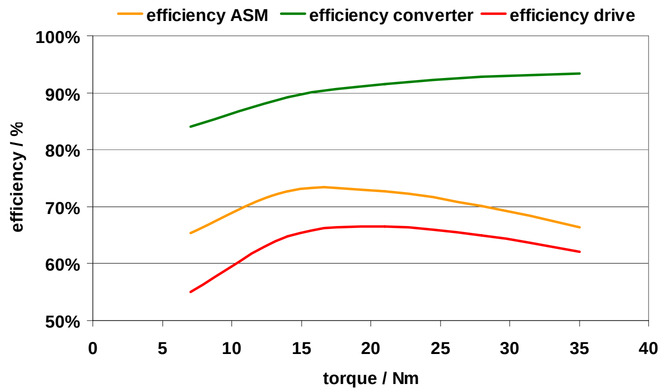

Fig. 14. Efficiency of drive components with 4 kHz pulse-frequency and varying load conditions.

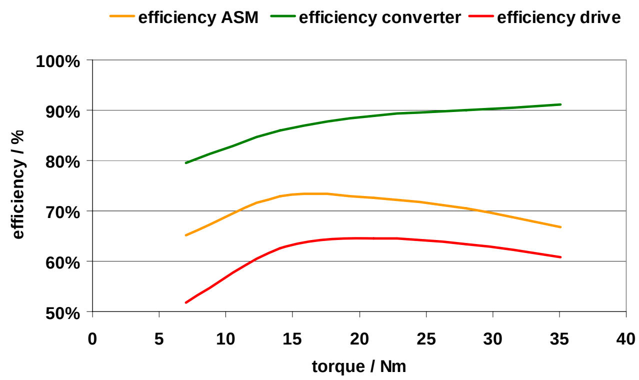

Fig. 15. Efficiency of drive components with 8 kHz pulse-frequency and varying load conditions.

B. Efficiency of converter, machine and complete drive at low speed of 300 rpm

If the asynchronous drive is operated at the lower speed range of 300 rpm with 4 kHz, the reachable efficiency depicted in Fig.14 is generally much lower than in Fig.12. One reason therefore is the fact, that the electrical current at distinct load points in Fig. 12 and Fig.14 is almost the same, whereas the output power is strongly reduced when the speed changes from 1500 rpm to 300 rpm. The effect of a raising pulse-frequency from 4 kHz up to 8 kHz is given in Fig.15. Thus, the converter efficiency is decreased due to increased switching losses at comparable current magnitudes in Fig.14 and Fig.15. In particular at higher torques, the machine efficiency is obviously higher, as it was expected due to the improved PWM spectrum at 8 kHz.

IV. Synchronous Drive Performance

With respect to demanded improved efficiency classes, the utilization of permanent magnet drives makes sense due to the fact, that the squirrel cage losses of the induction machine could be omitted. Moreover, no field constituting current are necessary due to the permanent magnet excitation [13,14].

C. Efficiency of converter, machine and complete drive at 1500 rpm rated speed

The achievable efficiency of the synchronous drive is given in Fig.16 in dependency on the mechanical load, whereas the speed is fixed at 1500 rpm for comparison. The efficiency of the converter varies again between 95% and 97%, as it was also observed in Fig.12 in case of the squirrel cage induction drive. Contrarily, the synchronous machine efficiency is much higher and varies between 82% and 94% in Fig.16. If the pulse-frequency is changed from 4 kHz up to 8 kHz, a significant reduction of the converter efficiency is obvious in Fig.17 in particular for lower loading.

These advantages are especially important with only little space available and restricted cooling conditions like with integrated compact drives.

Unfortunately, the efficiency varies in dependency of the operational state in a wide manner. However, the application of permanent magnet drives enforces a significant improvement of the efficiency levels, even within partial load conditions and lower speed values.

D. Efficiency of converter, machine and complete drive at low speed of 300 rpm

If the speed is reduced from 1500 rpm to 300 rpm, the expected efficiency levels are generally much lower in Fig.18 as it was the case in the comparatively chart of Fig.16. A view to the circumstances of the asynchronous drive in Fig.14 shows almost a system efficiency refinement of at least more than 9%. As expected, a step-up of the pulse-frequency from 4 kHz to 8 kHz invokes in comparison to Fig.18 an significant improvement of the machines efficiency, whereas the converter efficiency decreases.

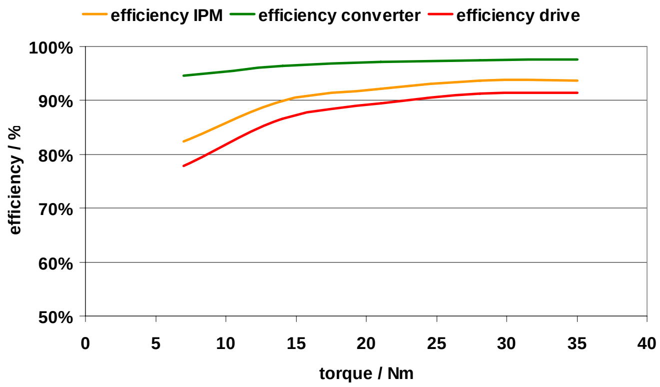

Fig. 16. Efficiency of drive components with 4 kHz pulse-frequency and varying load conditions.

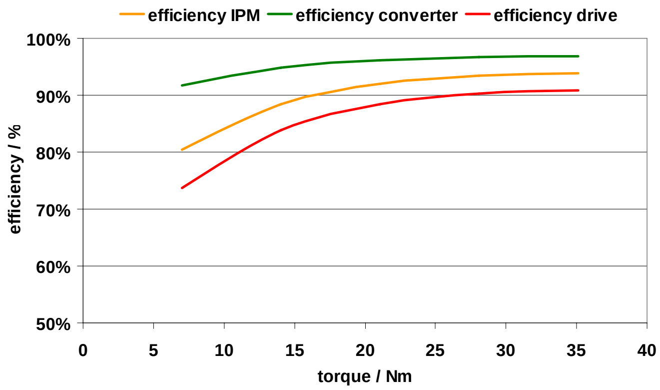

Fig. 17. Efficiency of drive components with 8 kHz pulse-frequency and varying load conditions.

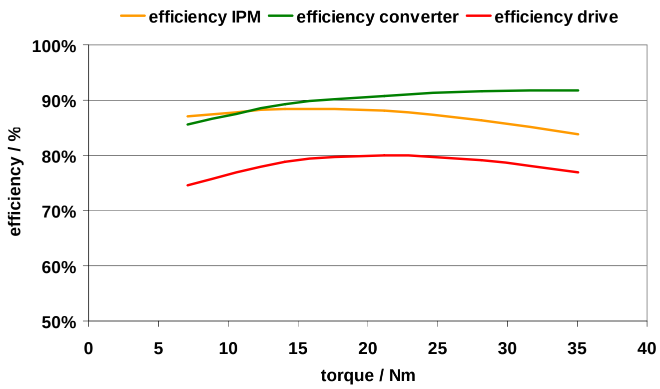

Fig. 18. Efficiency of drive components with 4 kHz pulse-frequency and varying load conditions.

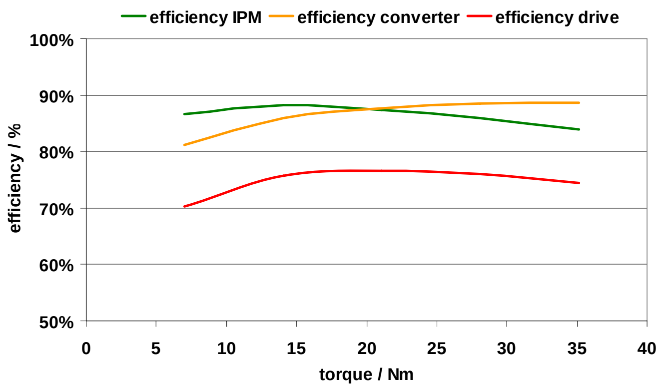

Fig. 19. Efficiency of drive components with 8 kHz pulse-frequency and varying load conditions.

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V. CONCLUSIONS

Efficiency and recuperation possibilities become very important aspects with respect to the green energy conversion. Thus novel approaches for the control and converter topology as well as the industrial machine design have been comparatively investigated in order to get a deeper insight into the complex system interaction.

The presented converter with line-frequency switched rectifier comprises no electrolytic capacitor in the DC link. Thereby a temperature sensitive and bulky passive element is no more necessary. Because of the regenerative capability no brake resistor and no brake chopper are required. The complexity and the costs are low. Efficiency is high, because there are no additional switching losses in the line-side rectifier.

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