APPLICATION NOTE

MOTOR EFFICIENCY AND VARIABLE SPEED DRIVES

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SUMMARY

A great deal is spoken and written about energy efficiency. Occasionally something even gets done. There is now a second classification system for the efficiency of electric motors, designed to exploit their full potential. To that end, the new standard also lays down prescriptions for the use of frequency inverters such as *Variable Speed Drives* (VSDs). This raises questions such as what exactly does such an inverter do and how does it achieve what it achieves? Which motors save energy and which do not? And which must achieve additional energy savings according to the new standards? This Application Note sheds a light on the answers to all of these questions.

INTRODUCTION

Two things have made it difficult for the improved electric motor to penetrate the market. Firstly, the efficiencies of electric motors are already high:

- A diesel engine with a nominal power of 90 kW produces at least 120 kW of heat loss
- An electric motor with a nominal power of 90 kW produces at most 7 kW of heat loss

It seems that it is not obvious that the 7 kW reduction mentioned above contains an appreciable potential saving that pays off. Instead, you have to more or less spell it out to users that the extra cost of a better 3-phase AC standard motor can pay for itself within a year. If you point out to a pragmatist that 3% of the operating costs of an industrial motor consist of the purchase price, 1% maintenance, and 96% electricity, it becomes plausible[1].

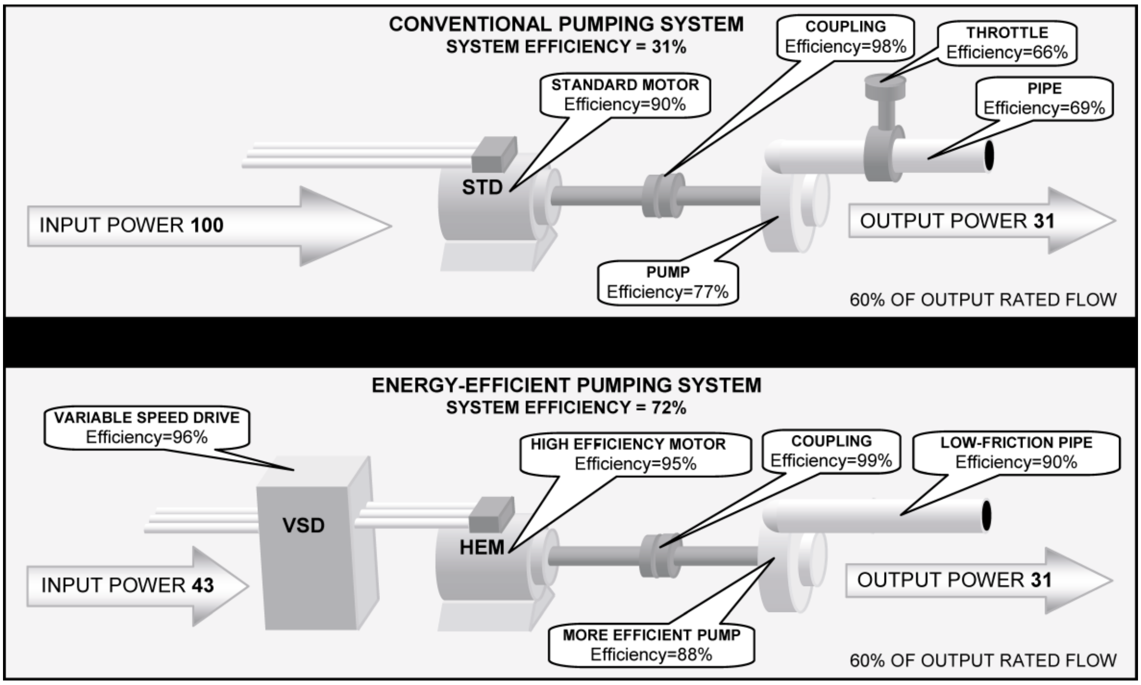

Figure 1 – In a typical industrial drive train, more than 50% of the potential energy savings are hidden.

The second difficulty is the fact that significantly more energy can be saved using a frequency inverter than with a better motor. Savings of up to 60% can be achieved by replacing braking controls using throttles and valves with a variable speed device. Around 8% of Europe’s entire energy consumption could be saved in this way, whereas improving motors only produces a 1.3% saving. This is because the motor is intrinsically already much more efficient than the average industrial process it drives (Figure 1). The inverter, however, is also several times more expensive than the cost of a high-quality motor. The payback times of both measures are therefore similarly short; and both measures are equally justified. In addition, the gap between simple and improved motors becomes even greater if motors are operated by inverter. This is due to the fact that the incomplete reconstruction of the sinusoidal voltage at the inverter output leads to increased supplementary load losses in the motor. This increase is greater if the supplementary load losses are already higher.

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[1] Stefan Fassbinder: Eff1, IE3 – und was dann? de 20/2011, p. 60, de 21/2011, p. 60, and de 22/2011, p. 68

BENEFITS AND POSSIBILITIES OF THE FREQUENCY INVERTER

The German association of electrical engineering and electronics ZVEI (Zentralverband Elektrotechnik und Elektronikindustrie) puts the number of all drives that could benefit from speed control at 50%. At present, however, only 12% of all motors are so equipped. There is nevertheless no sense in refitting every three-phase asynchronous motor without exception with an inverter. Inverters are expensive, increase the losses in the motor, and even have their own losses. These losses are, however, minimal, and even smaller than those found in a highly efficient motor. Thus, as soon as even a minor change in speed results in an improvement in the process, it is advisable to use a frequency inverter. A conversion of 50 Hz to 50 Hz, on the other hand, never makes any sense. Or does it? It seems that there are in fact two instances in which even this makes sense.

FROM SINGLE-PHASE TO THREE-PHASE AC

In Germany, three-phase current is omnipresent. Even apartments are increasingly supplied with three-phase power. Almost every electric oven is connected to three-phase. This fact however should not be taken simply at face value. In the UK and in countries subject to British influence—typically those that drive on the left—it is considered dangerous to deliver a voltage of 400 V to a home. In some emerging countries, even small businesses have to cope with single-phase current. While it does not matter to an electric oven whether it is supplied with 3*16 A or 1*48 A, single-phase induction motors are by their nature inefficient. Problems with start-up can also occur if the creation of a third phase using a starting capacitor does not produce the starting torque expected of a genuine three-phase AC motor. The Pfeiffer Vacuum Company reports that in such cases, inverters of 50 Hz to 50 Hz would be used, as well as devices converting 50 Hz single-phase AC to 50 Hz three-phase current[2]. The other benefits of an inverter then appear as mere side-effects.

FROM THREE-PHASE TO SINGLE-PHASE AC

Electric railways are operated with single-phase AC or with direct current, since trials with three-phase pantographs proved to be inadequate as long as 100 years ago. This is in spite of the fact that at the time these systems led to record runs of 200 km/h. Today, DC is the medium of choice for trams and light rail systems. For long-distance travel however it has the disadvantage that you have to manage with relatively modest voltages up to 3 kV, since DC cannot (or could not) be transformed. AC traction vehicles are always fitted with a transformer.

Several countries have provided a separate single-phase AC network to power their national railways. These networks are generally operated at a different frequency than the public infrastructure (Germany, Austria, Switzerland, Sweden, and Norway 16.7 Hz, USA 25 Hz). Others, such as the small Benelux countries, as well as larger ones like Poland, use DC—thus accepting the necessarily high number of infeed points and the accompanying high losses. Still others, such as France, draw single-phase current or two-phase current via a transformer from the high-voltage network. This raises the question of how the high unbalance of such large and extremely unsteady loads can be brought back into balance. The so-called Steinmetz connection can serve as a supporting measure here[3]. In reality however, the actual measure consists of periodically changing phases,

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[2] www.pfeiffer-vacuum.de

[3] www.leonardo-energy.org/**introduction-unbalance** – see title page

and is irrevocably linked to inevitable compromises such as separate sections with insulated wire pieces on which the train must never come to a halt or employing costly automatic changeovers[4].

So what would be more logical than the solution currently being implemented by the Chinese state railways? Their new network is fed from large inverters of 50 Hz to 50 Hz—but this time 50 Hz three-phase current (3AC) at 50 Hz single-phase AC (1AC)[5]. This measure is obviously beneficial, but was previously only possible using costly mechanical inverter sets. Here too, the electronic power inverter is a major step forward. It reduces consumption and also saves energy, since it is appreciably more efficient than the old mechanical devices nicknamed *copper mines*. This originally disrespectful name has now taken on genuine significance at a time of scarce supplies of iron and copper. The scrap value of the installations that are currently being dismantled on a massive scale is considerable. In addition, unlike modern electronic installations, this antiquated approach could not offer the option in France or China of feeding one phase directly into the traction current grid and only converting the other two—purely on the basis of phase angle and not frequency.

The obvious question is how long it will be before the inverter also replaces the traction transformer and tracks can be fed directly with, for instance, 15 kV or 25 kV direct voltages. However, little or nothing is heard or written about what is in fact a fairly obvious idea, this despite everything the inverter is currently able to do, up to and including high-voltage applications such as HVDC transmission.

ON THE FUNCTION OF THE FREQUENCY INVERTER

As seen in Figure 4, an inverter consists in principle of not more than one rectifier (of any type—single-phase, three-phase, 12-pulse, et cetera) and six switches. By simply switching on and off however, only the DC voltage of the intermediate circuit would be commutated at regular intervals and thus feed at one time one winding and at another two windings connected in series in the motor. For reasons of clarity, the operating sequence in Figure 6 is shown on a unipolar synchronous machine (with a permanent magnet rotor). No one would actually build in this way because they would be giving away the rearward pole of each winding; however such a construction would still run.

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[4] Arnaud Bastian, Christian Courtois, Alexandre Machet, La Plaine Saint Denis: *Phase separation sections – passing with minimum constraints*. eb Elektrische Bahnen und Verkehrssysteme 4-5/2011, p. 197

[5] Uwe Behmann: *Umrichterwerke bei 50-Hz-Bahnen – Vorteile am Beispiel der Chinese Railways*. eb Elektrische Bahnen und Verkehrssysteme 1-2/2011, p. 63

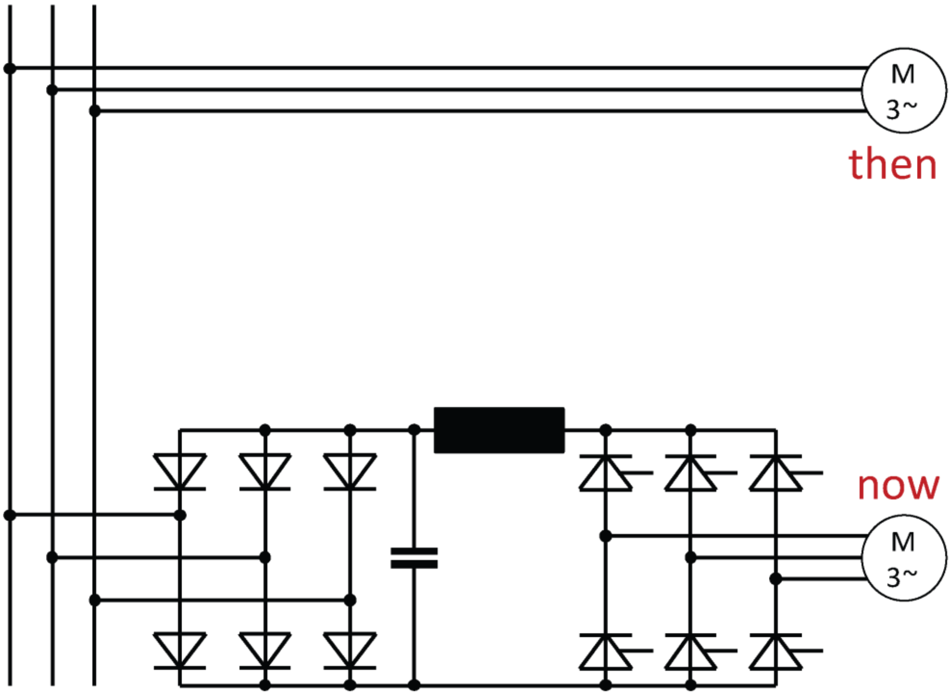

*Figure 2—Supply of induction motors, then and now: **Then** only directly possible with the mains frequency, **now** with variable speed thanks to artificially produced frequency.*

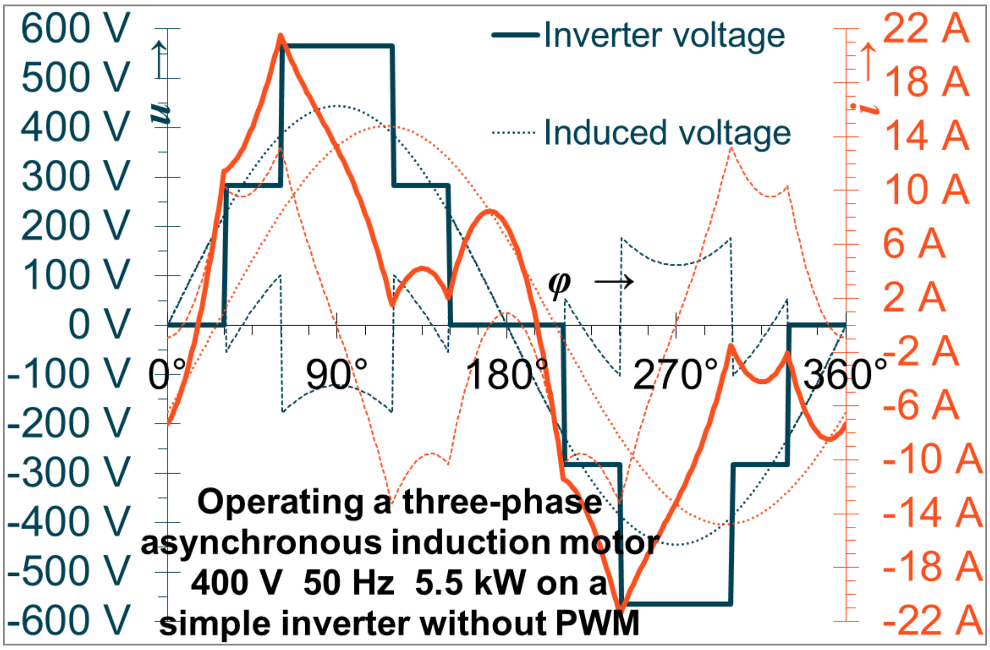

Figure 3—According to Figure 6, simple switching produces rectangular voltage characteristics at the inverter output and therefore a significant divergence from the induced voltage at the coils of the running motor and corresponding compensating currents.

This would create a voltage on the motor windings consisting of square blocks (shown in blue in Figure 3). However, the reverse voltage induced in the motor is and remains sinusoidal. This is a basic principle of electrical engineering, as long as electric potential is generated from rotary movements, since the voltage is proportional to the rate of change of the number of magnetic field lines permeating the coil, and this number is proportional to the sine or cosine of the angle between coil and field. Sine and cosine are trigonometric functions, and the voltages thus produced always run sinusoidally or cosinusoidally. Since this also applies to the inverse voltage induced in the motor (blue in Figure 3), there would be significant compensating alternating currents, since the connected voltage and the inverse voltage generated by the motor itself would diverge considerably at almost any point in a given period of the alternating current—now in the one direction, now in the other (red in Figure 3). The consequence would be significant extra heating. This is only acceptable in very small—and above all—fast-running synchronous motors (brushless DC machine or electronically commutated motors). The main disadvantage is the additional losses due to harmonic currents. However, with these applications, e.g. CPU fans and fans in PC power packs[6], these can be accepted in favour of low levels of wear and the clear improvement in reliability if the functioning of an important installation depends on such a small, apparently insignificant component.

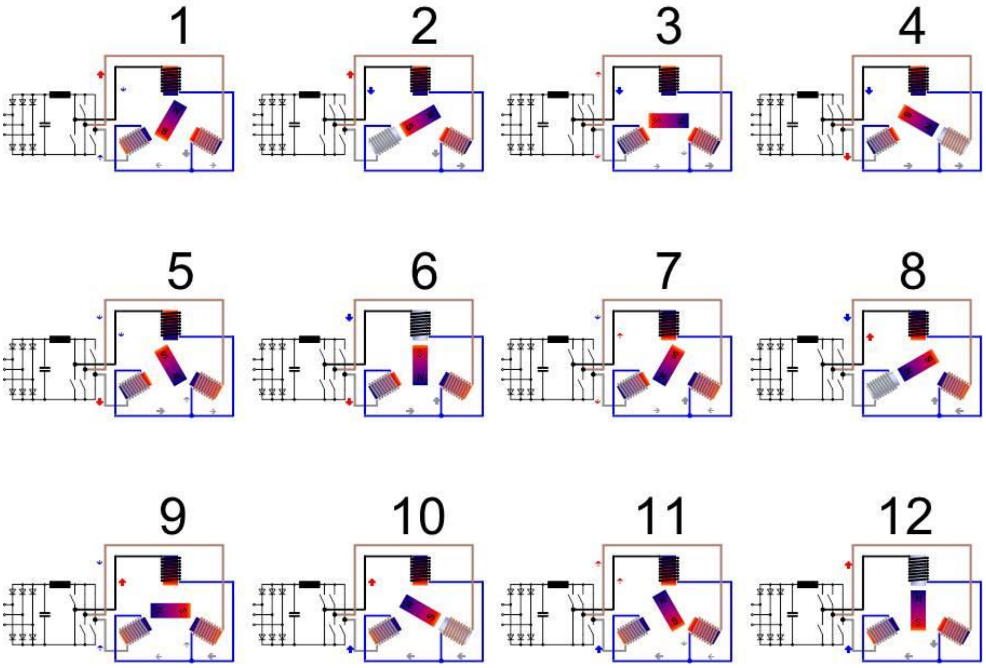

Figure 4 – Principle representation—for reasons of clarity, the operating sequence of the inverter to generate a rotary movement is shown here on a unipolar synchronous machine (with a permanent magnet rotor).

However, as soon as the power of the motor exceeds a few watts, the output frequency of the inverter is superposed by a significantly higher frequency that can be controlled by pulse width modulation. This means that the ratio of make-time to break-time can be continually varied. The inductance of the motor windings smooths out the current more or less back into the region of a sinusoidal current. Viewed up close, however, this is still jagged (red line in Figure 5): if the controllable power semiconductor in the inverter is open, the current increases, and if the valve is closed, the current decreases again. Therefore, these main semiconductors are always bridged with a reverse-poled, non-controllable freewheeling diode (not shown in Figure 2 for the sake of clarity).

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[6] http://leonardo-web.org/de/strom/edv

Because the smoothing out of the curve—and therefore the avoidance of additional losses—is not entirely successful, the current has to be reduced somewhat compared to operation directly in the power grid. However, this loss of power can often be more than compensated for by allowing the motor to run faster at the inverter than if it were running on the 50 Hz grid. Typically, 87 Hz is used in this instance. Efficiency can sometimes also be increased by increasing the power, since the losses do not necessarily increase at the same rate as the power (speed) of the motor.

DEALING WITH POSSIBLE PROBLEMS WITH FREQUENCY INVERTERS

In principle, any three-phase asynchronous motor previously connected directly to the mains can be retrofitted with an inverter. This should be done wherever and whenever this measure is economical.

In practice, however, it has been shown that the extremely fast switching times of the inverter lead to ringing and overshoot of the voltage in the motor windings. This places a greater load on the insulation of the winding wire. The better an inverter, the more stringent the additional requirements on the insulation of the motor windings, as is apparent from Section 1 above. Today, motor manufacturers counter this by using double enamel-insulated wire, stronger insulation, and other measures. If, however, an old motor suffers damage or failure following a retrofit with an inverter, rewinding is recommended. The repair workshop should be made aware of the altered operating conditions.

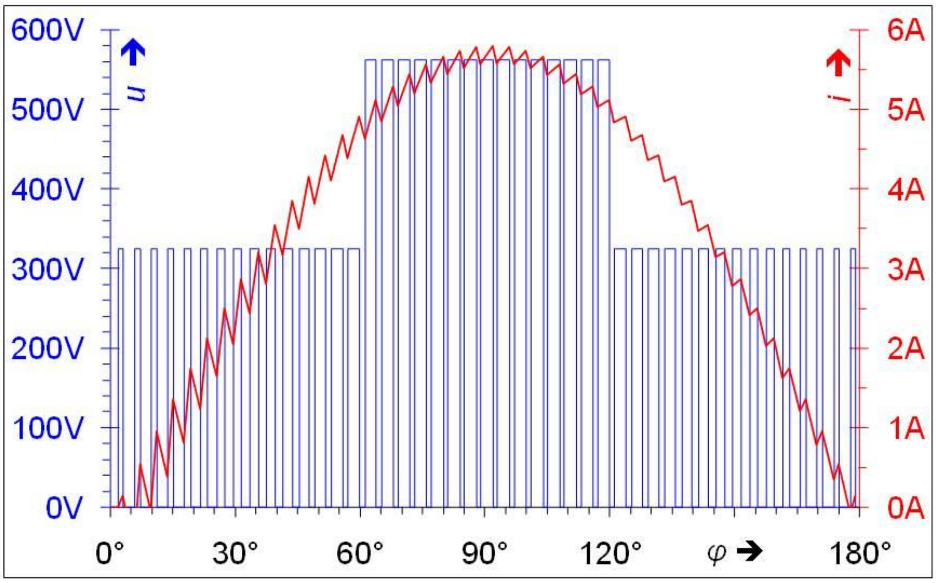

Figure 5—The switching in Figure 6 is superposed by pulse width modulation.

GUARANTEEING EMC BETWEEN MOTOR AND INVERTER

Inverters are available for centralized installation in the switch cabinet or for decentralized installation directly on the motor. Decentralized installation offers clear advantages in terms of electromagnetic compatibility (EMC), as well as during installation and commissioning. At the same time, EMC in fact presents a problem for inverters, since these operate more efficiently the higher the superposed clock frequency and the steeper the switching slopes, i.e. the faster the semiconductor switches are able to switch from a blocking to a conducting state and back again, because:

- The higher the clock frequency, the better the restoration of the sinusoidal curve of the motor current, and the smaller the extra additional losses of the motor.
- In practice, losses only occur in the power semiconductors of the inverter during the transition between the blocking and conducting states. In a blocked state, the current is zero. In a conducting state, the voltage drop at the semiconductor valve is almost zero. A significant power loss only occurs between the two states, as a result of through-current times voltage drop at the valve. The steeper the slopes, the faster this loss area will therefore pass through.

Note that the higher the clock frequency and steepness of the slopes, the higher the spectrum of high-frequency interference, which has to be filtered at considerable cost. The shorter the connection between inverter and motor, the easier it is to rectify the problem. This therefore presents a clear advantage for an integrated drive.

GUARANTEEING EMC ON THE MAINS SIDE

All of this concerns high frequency EMC on the output side of the inverter (between the motor and the inverter). The possible interference on the mains side is of quite a different kind, and has to do with the properties of the rectifier. Harmonics occur here, as has already been frequently discussed elsewhere. The harmonic load is currently on the decline in residential buildings, since more and more electronic devices, especially computers and televisions, are equipped with active power factor correction (PFC). In non-residential buildings however, it is reported that inverter drives up to and including fairly large powers still have simple, passive B6 rectification at the input and the harmonic emissions are at best attenuated by smoothing out coils and possibly capacitors. In very large units this is accomplished by a 12-pulse rectifier circuit. Overall however, it seems more viable economically to continue to tackle harmonics at network level by creating networks that are able to cope with this, simply because it works.

GUARANTEEING HF-EMC

Conversely, things look bad for the problem of high-frequency filter currents that are disposed of by inverters for suppression purposes via the earth wire. Here the main problem is that the PE earth wire has to be kept free from operating currents, since RCD functioning is sabotaged otherwise. No attempt will be made at further discussion of this problem in this paper simply because there is currently no solution. One author, who hitherto had a record of two feedback responses per publication, received no fewer than fourteen letters in response to a corresponding presentation[7] of this problem. The spectrum extended from overwhelming approval to blatant rejection—which in itself shows that no practicable solution is in sight.

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[7] Stefan Fassbinder: *Entstörfilter – Verursacher von Schutzleiterströmen*. Elektropraktiker 12/2010, p. 1039

THE NEW CLASSES OF MOTOR

A new standard[8] for motors is solely concerned with three-phase squirrel cage motors. These easily account for the biggest proportion of all electrical drives (Figure 6). These motors are now divided into four classes instead of the previous three (Figure 7 and Table 1). To this end, the diagram is the other way round, no longer capped, but expandable at any time to include further improvements as they occur. The lowest class, IE1, roughly corresponds to the old class EFF2. The new best class, IE4, is, however, a pie in the sky classification and not yet fixed. It is also not limited to asynchronous motors. The new draft of IEC 60034-30 notes that IE5 is planned to appear in the next edition of the standard.

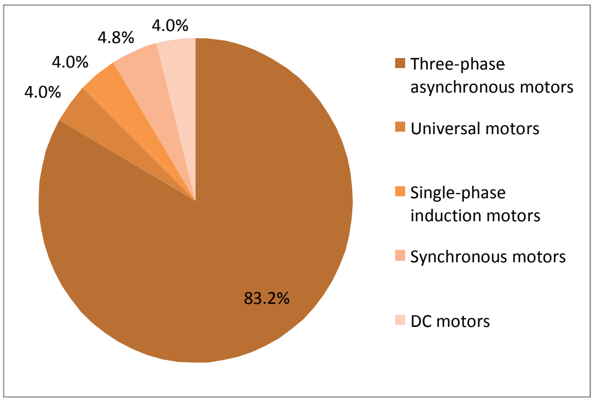

Figure 6—Breakdown of the motor market in Germany in 2008.

THE NEW REGULATION

On 11 March 2009, the EU Member States adopted a new regulation regarding Minimum Energy-Efficiency Performance Standards with the new classification scheme for the motor efficiencies of two-pole to six-pole industry standard motors of power classes 0.75 kW to 375 kW for 50 Hz. The regulation now includes 60 Hz as well, so these limits also apply to North American motors as well. The dates for entry into force were/are:

- IE2 since 16.06.2011
- IE3 since 01.01.2015 for 7.5 kW to 375 kW motors (or IE2 + frequency inverter)
- IE3 from 01.01.2017 all power ranges (or IE2 + frequency inverter)

Consideration was given to the fact that the use of a frequency inverter can produce far more savings than a better motor if the process imposes variable requirements. In such a case, the standard prescribes that an IE2 motor must either be replaced by an IE3 motor or fitted with an inverter in the medium term. On 27 March 2009 the European Commission also made a binding determination that a maximum Energy Efficiency Index value must be applied to all circulating pumps:

- ≥ 0.27 kW since 01.01.2013
- ≥ 0.23 kW since 01.01.2015

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[8] DIN EN 60034-30 (VDE 0530-30):2009-08: Rotating electrical machines – Part three-phase AC motors with squirrel cages at full load, excluding pole-changeabl

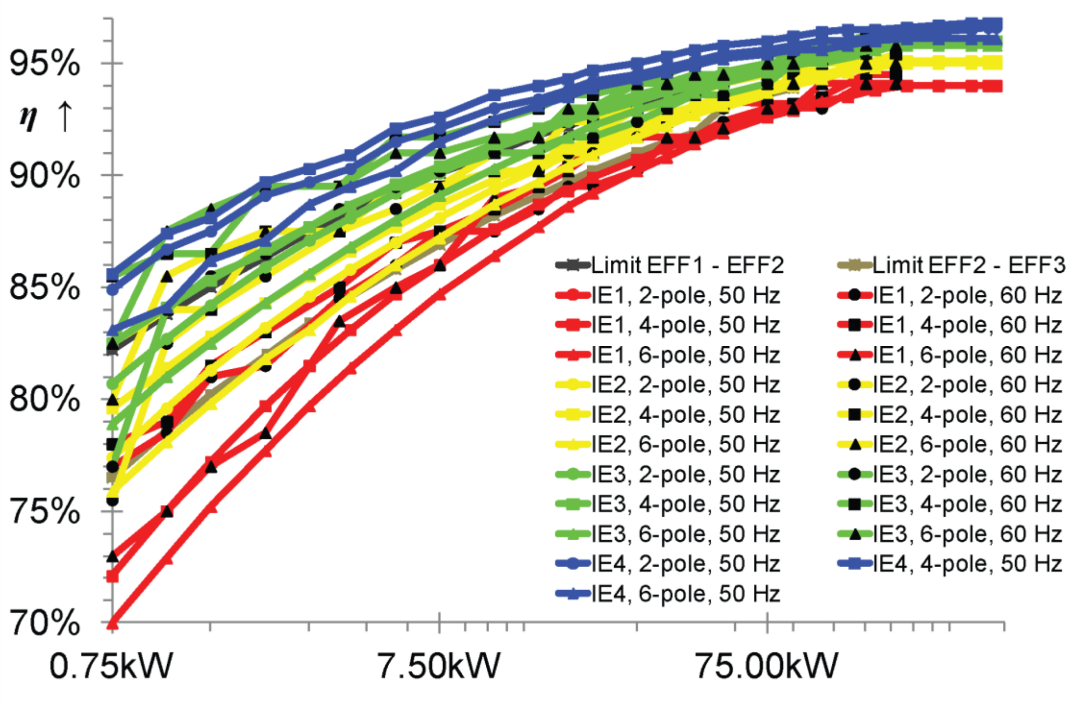

Figure 7—The new efficiency curves according to IE Code in graphic form (IE4 provisionally).

It had been discovered that the approximately 30 million heating pumps installed in Germany in the power range below 200 W consume around 3.5% of all electrical energy used in Germany. That astonishing figure is as much as the entire electrical rail traffic consumption. This only becomes plausible when you realize that these motors are operating almost continuously. Many an old pump pumps cold water round the circuit throughout the summer, and no one notices, no one knows[9]. The latest electronically controlled heating pumps use up to 50% less energy than modern standard pumps with asynchronous motors and up to 70% less than the uncontrolled pumps still often found in older HVAC systems.

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[9] Stefan Fassbinder: Geld zahlen fürs Nichtstun? de 10/1998, p. 915

Minimum efficiencies for three-phase asynchronous motors according to EN 60034-30																					
Class	**IE1**						**IE2**						**IE3**						**IE4**		
Poles	**2-pole**		**4-pole**		**6-pole**		**2-pole**		**4-pole**		**6-pole**		**2-pole**		**4-pole**		**6-pole**		**2-pole**	**4-pole**	**6-pole**
Rated frequency	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**50 Hz**	**50 Hz**
0,75kW	72,1%	77,0%	72,1%	78,0%	70,0%	73,0%	77,4%	75,5%	79,6%	82,5%	75,9%	80,0%	80,7%	77,0%	82,5%	85,5%	78,9%	82,5%	84,9%	85,6%	83,1%
1,10kW	75,0%	78,5%	75,0%	79,0%	72,9%	75,0%	79,6%	82,5%	81,4%	84,0%	78,1%	85,5%	82,7%	84,0%	84,1%	86,5%	81,0%	87,5%	86,7%	87,4%	84,1%
1,50kW	77,2%	81,0%	77,2%	81,5%	75,2%	77,0%	81,3%	84,0%	82,8%	84,0%	79,8%	86,5%	84,2%	85,5%	85,3%	86,5%	82,5%	88,5%	87,5%	88,1%	86,2%
2,20kW	79,7%	81,5%	79,7%	83,0%	77,7%	78,5%	83,2%	85,5%	84,3%	87,5%	81,8%	87,5%	85,9%	86,5%	86,7%	89,5%	84,3%	89,5%	89,1%	89,7%	87,1%
3,00kW	81,5%		81,5%		79,7%		84,6%		85,5%		83,1%		87,1%		87,7%		85,6%		89,7%	90,3%	88,7%
3,70kW		84,5%		85,0%		83,5%		87,5%		87,5%		87,5%		88,5%		89,5%		89,5%			
4,00kW	83,1%		83,1%		81,4%		85,8%		86,6%		84,6%		88,1%		88,6%		86,8%		90,3%	90,9%	89,5%
5,50kW	84,7%	86,0%	84,7%	87,0%	83,1%	85,0%	87,0%	88,5%	87,7%	89,5%	86,0%	89,5%	89,2%	89,5%	89,6%	91,7%	88,0%	91,0%	91,5%	92,1%	90,2%
7,50kW	86,0%	87,5%	86,0%	87,5%	84,7%	86,0%	88,1%	89,5%	88,7%	89,5%	87,2%	89,5%	90,1%	90,2%	90,4%	91,7%	89,1%	91,0%	92,1%	92,6%	91,5%
11,00kW	87,6%	87,5%	87,6%	88,5%	86,4%	89,0%	89,4%	90,2%	89,8%	91,0%	88,7%	90,2%	91,2%	91,0%	91,4%	92,4%	90,3%	91,7%	93,0%	93,6%	92,5%
15,00kW	88,7%	88,5%	88,7%	89,5%	87,7%	89,5%	90,3%	90,2%	90,6%	91,0%	89,7%	90,2%	91,9%	91,0%	92,1%	93,0%	91,2%	91,7%	93,4%	94,0%	93,1%
18,50kW	89,3%	89,5%	89,3%	90,5%	88,6%	90,2%	90,9%	91,0%	91,2%	92,4%	90,4%	91,7%	92,4%	91,7%	92,6%	93,6%	91,7%	93,0%	93,8%	94,3%	93,5%
22,00kW	89,9%	89,5%	89,9%	91,0%	89,2%	91,0%	91,3%	91,0%	91,6%	92,4%	90,9%	91,7%	92,7%	91,7%	93,0%	93,6%	92,2%	93,0%	94,2%	94,7%	93,9%
30,00kW	90,7%	90,2%	90,7%	91,7%	90,2%	91,7%	92,0%	91,7%	92,3%	93,0%	91,7%	93,0%	93,3%	92,4%	93,6%	94,1%	92,9%	94,1%	94,5%	95,0%	94,3%
37,00kW	91,2%	91,5%	91,2%	92,4%	90,8%	91,7%	92,5%	92,4%	92,7%	93,0%	92,2%	93,0%	93,7%	93,0%	93,9%	94,5%	93,3%	94,1%	94,8%	95,3%	94,6%
45,00kW	91,7%	91,7%	91,7%	93,0%	91,4%	91,7%	92,9%	93,0%	93,1%	93,6%	92,7%	93,6%	94,0%	93,6%	94,2%	95,0%	93,7%	94,5%	95,1%	95,6%	94,9%
55,00kW	92,1%	92,4%	92,1%	93,3%	91,9%	92,1%	93,2%	93,0%	93,5%	94,1%	93,1%	93,6%	94,3%	93,6%	94,6%	95,4%	94,1%	94,5%	95,4%	95,8%	95,2%
75,00kW	92,7%	93,0%	92,7%	93,2%	92,6%	93,0%	93,8%	93,6%	94,0%	94,5%	93,7%	94,1%	94,7%	94,1%	95,0%	95,4%	94,6%	95,0%	95,6%	96,0%	95,4%
90,00kW	93,0%	93,0%	93,0%	93,2%	92,9%	93,0%	94,1%	94,5%	94,2%	94,5%	94,0%	94,1%	95,0%	95,0%	95,2%	95,4%	94,9%	95,0%	95,8%	96,2%	95,6%
110,00kW	93,3%	93,0%	93,3%	93,5%	93,3%	94,1%	94,3%	94,5%	94,5%	95,0%	94,3%	95,0%	95,2%	95,0%	95,4%	95,8%	95,1%	95,8%	96,0%	96,4%	95,6%
132,00kW	93,5%		93,5%		93,5%		94,6%		94,7%		94,6%		95,4%		95,6%		95,4%		96,0%	96,5%	95,8%
150,00kW		94,1%		94,5%		94,1%		95,0%		95,0%		95,0%		95,4%		96,2%		95,8%			
160,00kW	93,8%		93,8%		93,8%		94,8%		94,9%		94,8%		95,6%		95,8%		95,6%		96,2%	96,5%	96,0%
185,00kW		94,1%		94,5%		94,1%		95,4%		95,4%		95,0%		95,8%		96,2%		95,8%			
200,00kW	94,0%		94,0%		94,0%		95,0%		95,1%		95,0%		95,8%		96,0%		95,8%		96,3%	96,6%	96,1%
250,00kW	94,0%		94,0%		94,0%		95,0%		95,1%		95,0%		95,8%		96,0%		95,8%		96,4%	96,7%	96,1%
315,00kW	94,0%		94,0%		94,0%		95,0%		95,1%		95,0%		95,8%		96,0%		95,8%		96,5%	96,8%	96,1%
355,00kW	94,0%		94,0%		94,0%		95,0%		95,1%		95,0%		95,8%		96,0%		95,8%		96,6%	96,8%	96,1%
375,00kW	94,0%		94,0%		94,0%		95,0%		95,1%		95,0%		95,8%		96,0%		95,8%		96,6%	96,8%	96,1%

These values were taken from NEMA MG1. This is not a typing error

The efficiency of „Energy Efficiency“ is laid down as 95.0 % in the NEMA standard at 185 kW und as 95.8 % at 375 kW

Table 1—The new efficiency limits according to the IE Code in tabular form.

MOTORS NOT COVERED

As already mentioned, efficiency class IE4 (super-premium efficiency), in contrast to classes IE1 to IE3, is not restricted to asynchronous three-phase motors. The efficiencies given here can also be achieved with other electric motors, for example synchronous motors with permanent magnets. It should be borne in mind however, that a frequency inverter is required for this, which brings with it additional losses.

Because the mains frequency and the number of poles of inverter-fed motors are not directly linked to the speed of these motors, they are normally dimensioned for a specific speed range and characterized by torque, not power. Consequently, the limits for IE4 are sorted by torque and named for discrete speed ranges.

In practice, the efficiency of inverter-fed motors can only be determined by the direct method of measuring input/output power, since all single-loss methods require sinusoidal voltage, fixed frequency, and fixed rated voltage. The efficiency thus determined therefore involves a fairly high degree of uncertainty, especially in the case of very high efficiencies, which is what we are dealing with here.

Synchronous motors with permanent magnet excitation and reluctance motors, as well as combinations of these types, have already been developed and are available for specific applications. However, no miracles should be expected—and certainly not the imminent removal of the asynchronous three-phase motor.

DOUBLE-FED SYNCHRONOUS MACHINES

A classic synchronous machine has a standard three-phase stator winding and a rotor winding excited by direct current. A single (two-pole/single-phase) winding therefore suffices for the rotor, as found in current power station generators. However, the rotor can also be designed with for example six poles. The three windings would then be connected in series or parallel and excited with direct current, as before.

However, such a six-pole excitation winding can also be fed on a three-phase basis. This offers the possibility of exciting this winding—again via an inverter—with a very low-frequency three-phase current, with a direct current, so to speak, or rather three direct currents that are continually changing and also swapping their polarities. Therefore, the rotor also constitutes a rotary field, which can, moreover, be inverted as desired. In this configuration, the stator winding is normally operated directly on the three-phase network, and thanks to the flexible feed of the rotor, the speed can be optionally reduced slightly or run slightly above the synchronous speed. The machine therefore no longer runs synchronously; that is merely its name. This principle is applied where only a limited change in speed is required in high-power machines. A classic application is in wind turbines, although the method is in decline here. Its advantage is that the inverter has to be sized not for the entire rated power of the machine, but merely for the speed difference, i.e. the slip power. The disadvantages are the same as those of the classic electrically excited synchronous machine: slip rings are required, and they are wearing parts. The costs of large inverters have now fallen to the extent that it no longer makes economic sense to accept maintenance costs, and certainly not in the case of wind turbines out at sea.

Another application of the principle is in the supply of traction current from the public network. Since the frequency of the single-phase traction current network was increased from $16^2/_3$ Hz to 16.7 Hz, this network no longer runs synchronously to the public three-phase network[10]. Feeding via converter stations with a six-pole synchronous motor and a two-pole synchronous generator no longer operates this way; a double-fed three-phase motor must be used. However, this technique is also on the brink of extinction, because while self-generation is on the decline for DB Energie and feeding from the three-phase network is very much on the rise, today this is increasingly done with static electronic inverters that replace the converter stations in the so-called traction substations (cf. Section 1.2). We therefore need not pay any particular attention to the technique of the double-fed drive from our present perspective.

PERMANENT MAGNET SYNCHRONOUS MOTORS

Conversely, synchronous motors with permanent magnet rotors represent a growing, albeit often over-stated and in no way new market. These motors do not start up by themselves and therefore require a frequency inverter, which must also have a high switching frequency (normally 4 kHz and above). A rotor encoder is also required—unless an encoder-free control algorithm of the inverter is used. This is possible but at an appropriate extra cost. It must also be ensured that ‘a cow cannot be milked and slaughtered’ simultaneously. Time and again the trade press has extolled the benefits of the permanent magnet motor as having:

- Better efficiency
- Greater torque, which means a gear can often be omitted
- Smaller size and weight, therefore attractive as a vehicle drive

What is generally not mentioned is that if no speed adjustment is required, an asynchronous motor without an inverter would possibly have to be replaced by a synchronous motor with an inverter but—as with losses—at a price. Furthermore, statements such as ‘greater torque’ will always prompt the question of what the comparison is aimed at:

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[10] Stefan Fassbinder: *Energieeffizienz im Schienenverkehr – Teil 1: Besonderheiten der Energieerzeugung und physikalische Grundlagen*. Elektropraktiker 1/2011, p. 48

- If size is meant—greater torque than an equally large/equally powerful asynchronous motor, then the two statements are identical and merge into one.
- If the comparison is related to rated power, the speed in the relevant synchronous motor is lower in the same proportion as the torque is greater than the asynchronous geared motor being replaced. Otherwise the rated power would not be the same.

However, in the situations described, the reference has never been mentioned. Such comparisons are therefore worthless. Doing away with gears thanks to a high torque certainly means that the motor will run very slowly in the application in question. Much more slowly in fact than it could, based on its design. Therefore the motor only gives off a fraction of the power that could physically be expected, given its size. The motor is also far from being fully utilized, and will therefore tend to be bigger and heavier than a fast-running asynchronous motor with gears. To be able to make full use of the advantage of mass and volume—around 30% is generally quoted—the motor must run quickly and the gears must remain. Both advantages are not available in a double pack.

The operating conditions also have to be considered. Permanent magnet motors achieve particularly high efficiencies at part-load—but what is part-load? Depending on the application, a load factor of, for example, 20% can mean that the motor only has to offer 20% of the rated torque at rated speed or full torque at only 20% of rated speed. These operating conditions are in no way comparable, and must be considered separately. This becomes particularly difficult with the electric vehicles that are so often mentioned in this connection. In this application, a high torque at low speeds is required for a relatively short time followed by a low torque at high speed over a longer operating period, including many sizeable and rapid fluctuations. Less magnetic force is required for a smaller torque, and in this case the asynchronous motor employs a so-called natural load sequence method: if little torque is demanded of it, the speed increases slightly. Slippage drops significantly—and with it the driving force to excite the rotor field. Only so much magnetic field strength/flux density is ever generated by itself as is used. Conversely, in the case of the permanent magnet motor, the excitation is not variable. If it is running quickly with a low torque, it is over-excited by several multiples. The motor then becomes capacitive. When idling, it behaves like a capacitor in the network.

MOTORS FOR THE ELECTRIC CAR?

Yet with reactive power, this is not enough. Unfortunately, the magnetic losses (hysteresis and eddy currents in the iron of the stator) also increase proportionally to the excitation and as a square of the frequency. Frequency is proportional to speed—and the efficiency advantage of the permanent magnet motor becomes an efficiency disadvantage for the operating area relevant to the electric car. Depending on the extent to which the magnetic material is conductive, harmonics and high-frequency super-positions induce eddy currents in it, and the synchronous motor then displays eddy current losses in the rotor, even though it does not need any excitation power.

The often described but as yet unbuilt gearless hub motor largely avoids this problem because without gears it only runs comparatively slowly. Precisely because of this, however, the advantage of volume and weight is lost, as described above. It is pointless to meditate on the possible *disadvantages* of such motors—availability of rare earths, sensitivity of the magnets to shocks, weakening of the magnets due to age or the opposing field should the motor occasionally fall out of step—as long as the assumed *advantages* do not even exist.

In addition, two asynchronous motors could in this case manage with one shared inverter. At best, driving through a broad curve would reduce the load unevenly on the drive wheel on the inside of the curve. In tight curves, the motor on the outside of the curve would enter generator mode—which should be acceptable at corners and roundabouts. The highly praised synchronous motors, however, would each require their own inverter, which would make the operation disproportionately expensive, but otherwise the car would drive like a single-engine vehicle without the differential—which would actually make the single-wheel drive unnecessary.

Whether or not the electric car will ever come about can be questioned[11]. However, when we consider the future and the possible designs of the electric car, we ought to reflect on the compact form of the established drive, the asynchronous motor with a squirrel cage cast in copper instead of aluminium and use this motor (Section 2.4)—or two of them—to render the differential unnecessary following the clutch and the manual gearbox.

It is possible when reading the aforementioned specialist publications to get the impression that three-phase synchronous motors excited by permanent magnets are a recent invention. The fact is that they have been used as so-called multiphase motors for decades, typically in robots and co-generic machines, since they provide almost ideal conditions for these applications. Being synchronous machines, they always perform a precisely definable number of rotations in a defined number of three-phase periods, repeatable millions of times, relatively unaffected by age and wear—as long as they do not fall out of step through over-use. This would mean, however, that they were chosen too weak, incorrectly controlled, or the machine being driven is faulty and blocked. It is then time to switch off and report the problem.

But it has always been like this. If all the talk is now about permanent magnet motors, it is because better, stronger magnetic materials are available. The hope is therefore, that these motors can also be used in other drive segments. However the meaningfulness of doing so should first be examined.

RELUCTANCE MOTORS

In a synchronous reluctance motor, a rotor made from magnetically soft materials has a preferred direction of magnetization. The rotor can also be fitted with a shading coil and then runs automatically like an asynchronous motor. After start-up, it lapses into synchronous mode because of the preferred direction of magnetization. These motors therefore do not necessarily need a frequency inverter to operate. However, they are an option only for special applications, for which they must be specifically sized and where automatic start-up together with synchronous operation is required, e.g. flow rate meters based on the Coriolis force.

In a switched reluctance motor, the respective teeth of the teethed stator winding are switched on by an electronic circuit whenever one of the salient poles of the soft magnetic rotor approaches, and switched off again as soon as the rotor pole reaches the tooth. This follows more or less the principle of the brushless DC motor.

HYBRID MOTORS

Another type of synchronous motor contains both permanent magnets and a squirrel cage and can therefore be used for direct start-up. These motors also do not necessarily need a frequency inverter. However, their start-up behaviour is poor, and they cannot be used as machines for general applications because of torque fluctuations, the noise generated, significant limitations in terms of the permissible counter-torque, and the moment of inertia to be accelerated.

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[11] Andreas Stöcklhuber: *Alles fährt elektrisch?* Editorial in »de« 23-24/2009, p. 4; see also: http://leonardo-web.org/de/strom/autostrom

REACTIVE POWER

Depending on the quantity of magnetic material used, it is sometimes argued that a motor excited by permanent magnets can have higher power factor than an asynchronous motor, as a result of which the distribution network, and also the frequency inverter, is relieved of reactive power. However, the benefit is rather minor when you consider that the grid losses in Germany overall, from power stations to meter panels, are only 4.6%, of which approximately one-fifth is due to reactive power, if there were no compensation. However, there is compensation, and the reactive power needed to excite an asynchronous motor can also be provided very easily using compensation capacitors. These capacities are sometimes fitted directly to the motor or in its immediate vicinity and connected parallel to this. If the motor is switched off, the capacity is also separated from the grid, which could otherwise lead to over-compensation and therefore to the opposite, that is, an additional load on the grid instead of taking a strain off the grid. But even without this, the compensation only becomes fully effective—and this cannot be repeated often enough—if it is in the immediate vicinity of the generation of the reactive power to be compensated. Then, however, the argument of the low reactive power with a synchronous motor no longer exists, since the extra cost of the magnets is significantly greater than the price of three capacitors.

When operating with an inverter, this works simultaneously as a phase shifter and supplies the motor with active and reactive power according to its individual needs. On the input side, the difference between inductive and capacitive (over-excited) motors does not appear. The argument for the low reactive power of the synchronous motor does not therefore exist, since it can only be operated with an inverter. Without doubt, however, the inverter has to be sized somewhat larger if it has to feed the motor with both effective and reactive power. However, the reverse also applies if the synchronous motor excited by permanent magnets is running at high speed and low load, in which case it generates large amounts of capacitive reactive power that must be absorbed and processed by the inverter.

A TECHNOLOGICAL LEAP IN THE DIRECTION OF BETTER EFFICIENCIES: COPPER ROTORS

Three-phase asynchronous motors represent a tried-and-tested technology and employ the principle of very simple construction. Their mode of operation is difficult to describe, which is why the principle representation in figure 4 avoided an asynchronous model. However there is only room for improvement in the area of the individual components, particularly with the use of more conductive materials and better magnetic materials. The only improvement that represents a switch to a different technology is the copper rotor. This device the shading coils of which are cast in copper instead of aluminium, has been available for a long time. The technical superiority of the finished product was obvious from the outset and unchallenged; however, the road to industrial manufacture was long and stony[12]. Things have now advanced to the point where the world no longer relies on a single manufacturer in France. Siemens, for example, maintains a manufacturing site in the USA. It can be found in the Czech Republic and in China. A smaller German foundry[13] has produced the first series for VEM, the well-known motor manufacturer. A larger plant is preparing itself for the manufacture of an appropriate production line.[14]

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[12] Stefan Fassbinder: *Eine runde Sache: Kupferrotoren*. de 20/2004, p. 68

[13] www.metall-breuckmann.de

[14] www.wieland.de

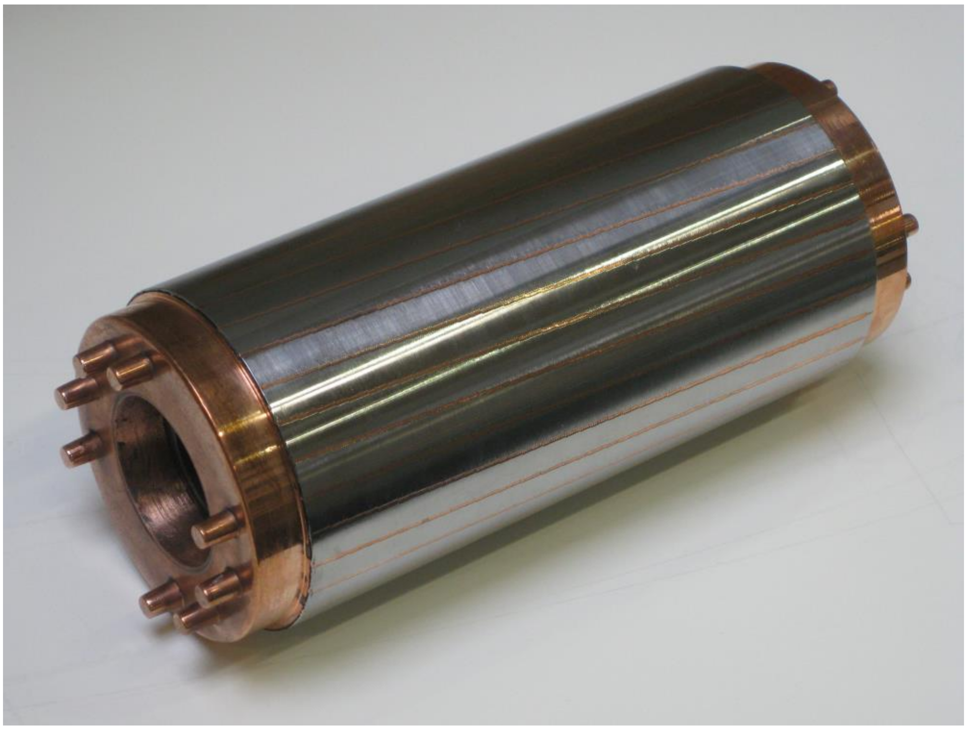

Figure 8—Copper rotors: A first delivery was made to VEM.

CONCLUSION

In the case of electrical energy, a particular obstacle to saving is the fact that it comes out of the socket. Economy measures are difficult to imagine. The cost of a more expensive motor is on a piece of paper and is therefore seen immediately—even before the purchase is made. The costs saved, on the other hand, are not. These seem to evaporate somewhere in the general electricity bill of the undertaking as a whole, which of course always remains subject to minor fluctuations. If a bad electric motor is 90% efficient, the 3%, 4%, or 5% saved by an even better motor are not readily apparent. Nevertheless, these costs are incurred, and at the end of the day have to be paid. It is and remains a fact that the additional cost of the better motor has paid for itself in less than a year when there is more than 3,000 to 4,000 operating hours per annum.

And if this situation was not already complicated enough, there is a further obstacle in the fact that in large undertakings the electricity bill is paid by a different cost centre than that of a new motor. While it is the task of any cost centre to keep costs as low as possible for the entire undertaking, all too often the available structures lead to the misunderstanding that costs should—where possible—be outsourced from one's own to other cost centres. Overcoming this mentality is the actual task of, for example, specialist journals. Conversely, the technical difficulties are almost modest.