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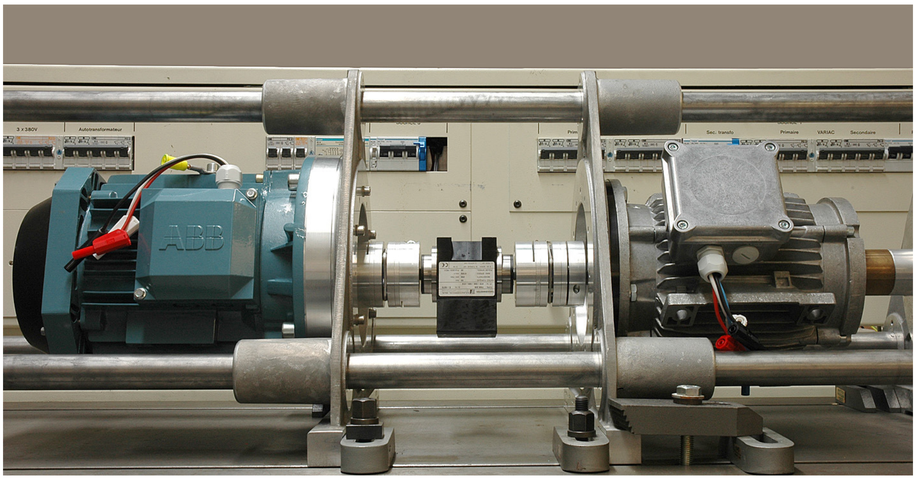
Economic viability, applications and limits of efficient permanent magnet motors

Summary and Update



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Postal address: CH 3003 Bern
www.bfe.admin.ch

Report prepared by:
CIRCLE MOTOR AG
Tannackerstrasse 25
CH-3073 Gümligen
info@circlemotor.ch   www.circlemotor.ch

Authors:
Markus Lindegger, electrical engineer, CIRCLE MOTOR AG
Prof. Hans-Peter Biner, University of Applied Sciences Western
Blaise Evéquoz, electrical engineer, University of Applied Sciences Western
Prof. Dr. Dominique Salathé, Lucerne University of Applied Sciences and Arts

SFOE sector head: Dr. Michael Moser
SFOE programme head: Roland Brüniger
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1. INTRODUCTION

Strong magnetic fields can be generated in electrical machines with the aid of permanent magnets comprising rare-earth elements, above all neodynium-iron-boron. One of the main advantages here is that, unlike induction motors, no external source of electrical energy is required for the production of the magnetic field. In the last decade, the quality of rare earth magnets has been improved considerably. The (BH)max product could be increased by a factor 2 and more. The temperature as well as the chemical stability and coatings were improved in the same manner. Since the price of the magnets went down by a factor of ten, the permanent magnet motor shows high potential to displace the induction motor.

This results in the possibility to design economical energy-saving drives, which are able to replace IEC standard motors with less or same life cycle cost due to higher energy efficiency.

2. OBJECTIVES OF THE STUDY

In the study **on the economic viability, applications and limits of efficient permanent magnet motors [1]**, the permanent magnet motor was compared with asynchronous motors. The latter are used in very large quantities as IEC standard motors, and in view of this, IEC standard motors were used as the reference for comparison purposes. The objectives of this study is to update and summarise from [1] the identified advantages and limits of permanent magnet motors and draw the attention to the market segments, where they can be advantageous used.

The project, was supported by the *Swiss Federal Office of Energy (SFOE)*, involved the following three partners:

- **Circle Motor AG** Project management and market-related studies
- **Lucerne University of Applied Sciences and Arts** Theoretical studies
- **University of Applied Sciences Western, HES-SO VALAIS** Laboratory tests

3. METHODOLOGY

In the **theoretical study** the effects of the increasing size of permanent magnet motors in terms of efficiency, weight, volume and performance is examined. At the time the study was carried out, only a very limited quantity of data concerning permanent magnet motors - which could compete against variable speed IEC standard motors - was available from major manufacturers. In view of this, the *University of Lucerne* calculated the required data for permanent magnet motors with the aid of the *Maxwell 3D* program. Data concerning standard motors were taken from available catalogues. For comparison purposes, output levels 5.5, 15, 55 and 90 kW, were used.

In the **laboratory tests**, the efficiency of six motors and various electronic drive methods were tested by the *University of Valais*. Here, three standard motors with different efficiency classifications were compared with three permanent magnet motors in the 3 kilowatt output range.

Circle Motor AG then **summarised the findings from the point of view of relevance to the market**, based on the following questions:

1. Is there a general limit for permanent magnet motors where the use becomes beneficial in terms of efficiency?
2. Which application areas are especially attractive in terms of electrical energy savings?

3. Where is the break even point of operating times, performance levels, weight categories, volume categories and engine speeds to switch to permanent magnet motors?
4. Where are the practical limits for the economic production of permanent magnet motors?
5. For which applications are permanent magnet motors best suited and in which areas are they less usable?
6. Do the control mechanisms of permanent magnet motors offer any advantages in terms of efficiency?

4. FINDINGS

4.1. THEORETICAL STUDIES

MAXWELL 3D SIMULATION PROGRAM, RMXPRT TOOL

MAXWELL® 3D
3D Electromagnetic-Field Simulation for High-Performance Electromechanical Design

Maxwell 3D was developed for simulating electromagnetic fields. It can be used for simulating the behaviour of various electromechanical and electromagnetic components in a virtual environment. This tool enables the user to save the costs associated with the production of prototypes, and to reduce the time for new developments.
Simulations are based on *finite element calculation*, in which the magnetic fields are calculated with the aid of a mesh placed over the component concerned. *Maxwell 3D* can be used in combination with a range of other tools such as *ePhysics*, *Simplorer* or *RMxprt*, which was of particular interest for this study.

RMXPRT™
Analytical Design Software for Electric Machines

RMxprt is the tool for designing and measuring electric machines. Its main advantage is that it can be used for quickly and simply defining the shape and size of a motor. The input of the parameters is very simple, and the motor can be depicted directly in 2D. Its templates can be used for quickly modifying existing motor types in order to construct a different one (Fig. 1).

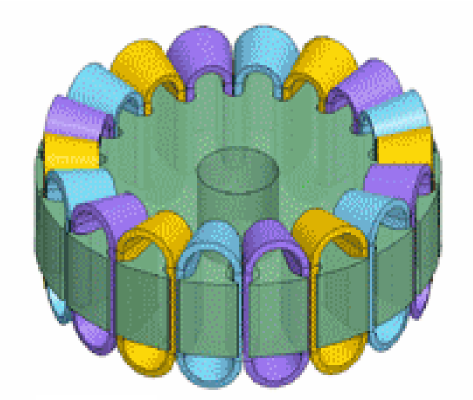

Fig. 1

The finished motor can then be defined by entering certain criteria such as output, voltage or speed, and the results are subsequently summarised on a data sheet.
Another advantage that should be noted here is that it is very easy to export a motor defined in *RMxprt* to *Maxwell 3D*. After it has been transferred to *Maxwell 3D*, the motor is depicted in the form of 3-dimensional (see next page).

3-DIMENSIONAL VIEWS IN MAXWELL

As we can see from Fig. 2 below, the various aspects of a 6-pole permanent magnet motor are depicted very clearly, including the double-layer winding. Views can also be removed from the display so that only parts of interest are shown on screen. In this example, the magnet poles are indicated through the use of yellow and blue colouring.

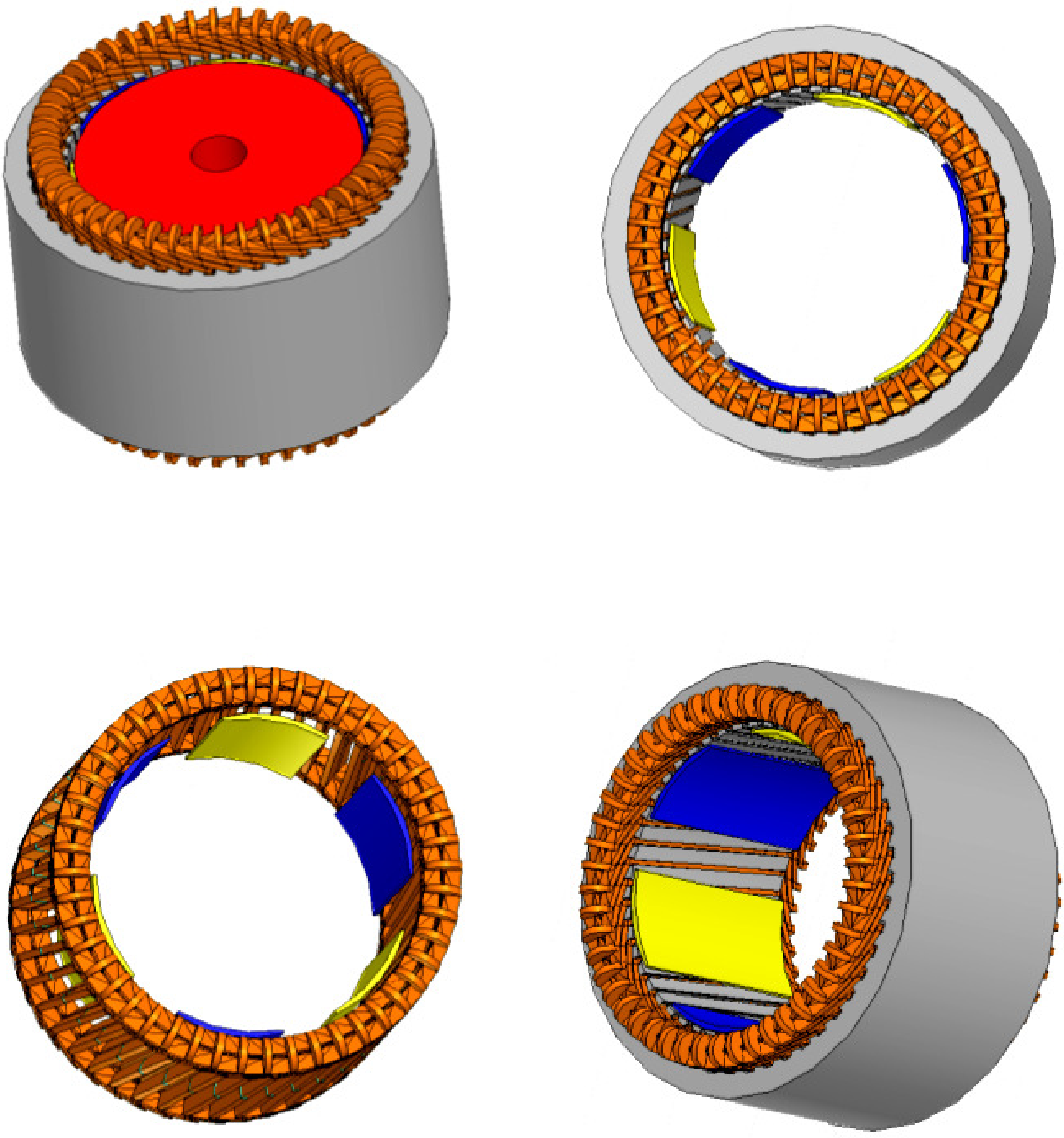

Fig. 2

CRITERIA FOR THE INPUT OF PARAMETERS IN RMXPRT

At the time the study [1] was carried out, the previously existing IEC standard was still in use, which divided 2-pole and 4-pole 50 Hz squirrel cage motors with output ranging from 1.1 to 90 kilowatts into three efficiency categories: EFF1 for high efficiency, EFF2 for improved efficiency and EFF3 for standard motors. The efficiency calculation was not carried out on the basis of direct measurement of mechanical shaft output divided by electrical input level. With the old standard, efficiency was determined by means of an indirect process, based on the recorded electrical input and the measured losses. Any additional losses were taken into account by 0.5% of the electrical input.
For the standard IEC motors the following four motor sizes were selected for simulation purposes:

- 5.5 kW (IEC size: 132)
- 15 kW (IEC size: 160)
- 55 kW (IEC size: 250)
- 90 kW (IEC size: 280)

For the permanent magnet motors the same stator laminations were used as for the standard motors. The data source was the catalogue of *Kienle & Spiess [2]*, a well-known manufacturer of components for standard motors. Thus the simulated permanent magnet motors could be compared directly with equivalent standard motors with the same IEC size classification.
Rotors in permanent magnet motors are not exposed to a magnetic alternating field, and can therefore be manufactured mechanically from a solid steel component. This means that for our simulations the air gap was freely selectable.

Generally an electric drive has iron, copper, ventilation, friction and switching losses. But since we only studied the machines themselves, we did not include switching losses in our calculations. Ventilation and friction losses were ignored as well, since the significance of these parameters varies according to the output and application of the machine.

The following criteria always applied to these simulations:

$$\eta = \frac{P_{Welle}}{P_{Welle} + P_{Fe} + P_{Cu}}$$

For the simulation of motors in the power categories above, a number of variants were tried out. Stator laminations of 4 to 8 pole motors were studied. For the permanent magnet motors, a shaft speed of 3,000 rpm was defined, and the direct current in the intermediate circuit of the drive electronics was specified at 400 VDC. The permanent magnets were mounted on the surface of the rotor. With a remanence of 1.23 T a standard magnet was chosen.

SIMULATION METHODOLOGY

Initial simulation test results revealed that the arrangement of the air gap has a significant influence on the degree of efficiency. If the width of the air gap is increased, the flow density (B) is reduced and results in lower iron losses. Because the output at the shaft should be constant, when the air gap width is increased, more stator current is required in order to generate the same torque. This increase in current causes additional copper losses. If we now represent iron and copper losses in relation to the air gap width, the result is a situation as depicted in Fig. 3 (for IEC size 132 permanent magnet motors with 4 poles and 36 slots).

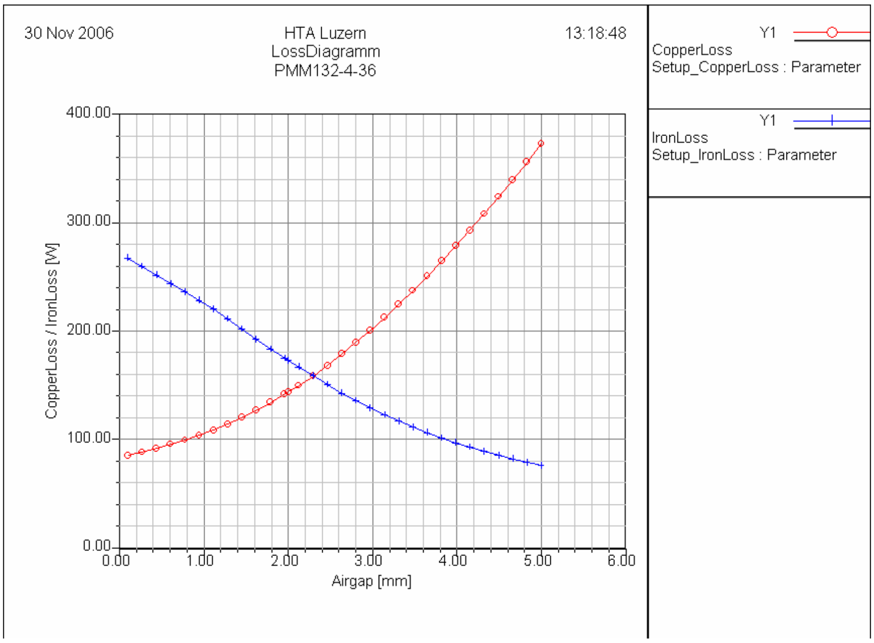

Fig 3

As we can see, the losses are equal and minimal at a certain air gap width (here, approx. 2.3 mm). At this point, iron and copper losses each account for 50 percent of the overall losses. The aim of the simulation was to determine the degree of efficiency, whereby the nominal output, nominal speed (3,000 rpm) and equal levels of copper and iron losses were specified in advance. Using a derived formula and iterative procedure it was possible to meet the above requirements in the simulation. The first iterative step was defined at an air gap of 1 mm.

Another point to be considered was the shape of the magnets to get an optimal air gap field. The pole surface can be flattened and the magnet length can be selected as shorter than pole pitch. In this way the iron losses are reduced and the efficiency of the permanent magnet motor is again increased. These are the additional parameters for varying the iron losses. To determine the highest degree of efficiency, we combined the iterative procedure with the shape of the magnets. The described iterative procedure combined with the RMxprt program permitted the calculation of the highest degree of efficiency at the four specified output levels, and the number of poles was also included. Please refer to the original study for a more comprehensive description of the formulae, calculations, diagrams and data relating to each permanent magnet motor.

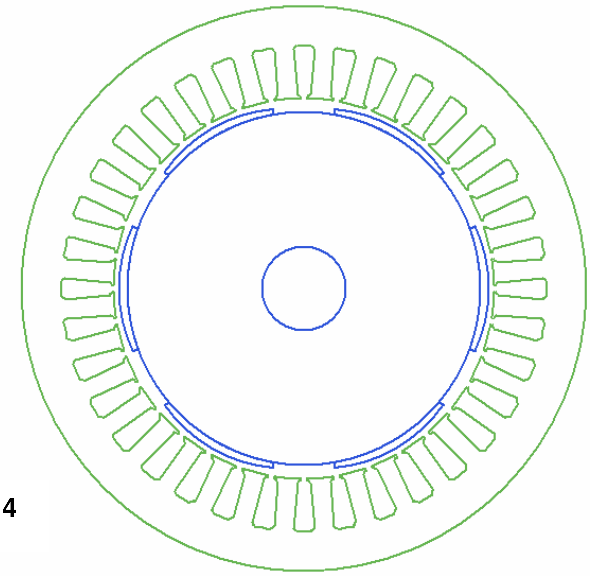

Fig. 4

Fig. 4 shows a cross-section of a permanent magnet motor according to the input in *RMxprt* with the stator lamination, the rotor with surface-mounted magnets with bended pole shape and width shorter than pole pitch.

The original study contains a detailed appendix dealing with magnetic material technology. Below is a summary of the most important points in the appendix.

The analysis shows that better magnetic properties have a positive influence on the machine and its degree of efficiency. Here we can refer to the "energy product" of the magnet. The greater the $(BH)_{max}$ product, the more compactly the magnet can be produced with the same properties. This results in a significant volume reduction of the magnet systems used in permanent magnet motors. Here are the volume relations for the same energy product:

Hard ferrite	**=**	**volume 6 cm^3**
AlNiCo	**=**	**volume 4 cm^3**
SmCo	**=**	**volume 1 cm^3**
NdFeB	**=**	**volume 0.5 cm^3**

This means that an NdFeB permanent magnet motors is always smaller in size than an equivalent asynchronous motor. And he will have always the higher efficiency.

Hence rare earth magnets offer a variety of advantages when it comes to motor construction. These magnets are also extremely resistant to opposing fields, i.e. they have a high degree of magnetic stability. They also offer the advantage of thermal stability, which is particularly important in the area of motor construction. One disadvantage that should be noted here is that NdFeB magnets in particular, which belong to the category of rare earth magnets, do not have a high level of chemical stability, i.e. they tend to oxidise and corrode fairly quickly, which results in losses. However, recent progress in this technology indicates that this problem has now been largely resolved by providing the magnets with a suitable protective coating.

In our simulations we used NdFeB35 as the magnetic material on the rotor.

FINDINGS

Table 5 shows the degree of efficiency and corresponding torque for each type of motor. The simulated permanent magnet motors have very high efficiency levels: on average, these are around 2 percent higher than those of asynchronous motors in the same power category. With increasing output, the difference in efficiency level versus an equivalent asynchronous motor becomes smaller but remains up to the highest power.
The asynchronous and permanent magnet motors listed in the table below have roughly the same torque levels, and this permits a more precise comparison between these two motor types.

	Permanent magnet motor			
	IEC 132	IEC 160	IEC 250	IEC 280
Efficiency	91%	94%	96.5%	97%
Torque	18 Nm	50 Nm	180 Nm	290 Nm
	Standard (asynchronous) motor			
	IEC 132	IEC 160	IEC 250	IEC 280
Efficiency	88.6%	91.3%	94.2%	95.1%
Torque	18 Nm	49 Nm	177 Nm	289 Nm

Table 5

COMPARISON OF EFFICIENCY LEVELS

Fig. 6 displays the energy efficiency of the produced and measured permanent magnet motors as blue dots. For comparison purposes, the efficiency thresholds are now in accordance with the new IEC standard 60034-30. The new standard classifies efficiency into IE categories: the higher the figure, the greater the efficiency. IE1 = standard efficiency and corresponds to the former category EFF2. IE2 = high efficiency (equivalent to the former EFF1), while IE3 is the new premium category.

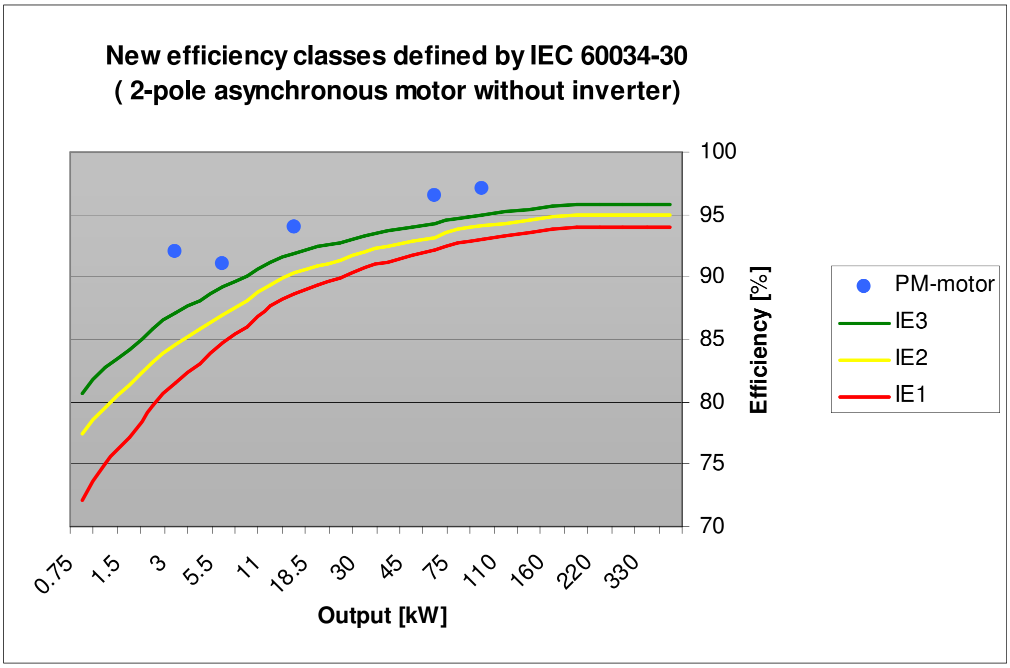

Fig. 6

In Fig. 6 the curves for the IEC standard for 2-pole asynchronous motors have been drawn in. The synchronous speed is around 3,000 rpm. The graph shows that the measured permanent magnet motors can be allocated to efficiency category IE3 (premium efficiency) and higher, which indicates that they have a great deal of potential for use as energy-efficient motors in the future.
In the text and illustrations below, the efficiency categories have been indicated in accordance with the new IEC standard 60034-30, i.e. with designations IE1 to IE3.

4.2. LABORATORY TESTS

The efficiency of the various motors was measured in a laboratory at the University of Valais. The output of the measured motors was in the 3 kW range. The measurements were carried out for the following purposes:

- To compare no-load losses with operation at constant grid or inverters.
- To determine the degree of efficiency at nominal speed and various loads.
- To measure operation of permanent magnet motors at constant grid, without drive electronics. This point has not been included in this summary. In view of the large market for variable-speed motors for turbo-machines, constant grid operation was no longer examined after this study.

INVOLVED MOTOR TYPES

For this project, the University of Valais had three different asynchronous motors, one permanent magnet synchronous motor with trapezoidal current (brushless DC motor) and two permanent magnet synchronous motors with sinusoidal current. Table 7 contains the details of the rating plates. The first three letters refer to the motor type: ASM = asynchronous motor; BLDC = permanent magnet synchronous motor with trapezoidal current; PMSM = permanent magnet synchronous motor with sinusoidal current.
The asynchronous motors differ in the way they are connected. Below, “Y” refers to Y or star connection, and “D” to delta or triangle connection.

- Motor “HB 100L” operates at 400 V, delta connected.
- Motor “ETR DN100” was wound according to the Dahlander principle, and operates at 400 V in double star connection.
- Motor “ABB M3AA” is intended for inverter operation, Y (star) connection, at 400 V.

In order to obtain comparable measurements, the asynchronous motors were measured at a nominal speed of 3,000 rpm. The measurements under load were made at 400 V. To measure the iron losses, the intermediate circuit voltage of the inverter was lowered in order to obtain an output voltage of 320 V. In this way it was possible to compare these motors with the synchronous machines.
In order to compare the asynchronous motors with motor **BLDC “EMB DM-SNP”**, the feed of the induced voltage of the permanent magnet motor was adjusted to 250 V for measurements under load.

RATING PLATES OF THE MOTORS / SPECIFICATIONS

Symbol	Unit	Description	ASM HB 100L	ASM ETR DN100	ASM ABB M3AA	BLDC DM-SNP	PMSM	PMSM HGA
Sup-plier	-	Manufacturer or supplier	Harry Bürgi GmbH	ETR SA	ABB Suisse SA	Elektromaschinen-bau GmbH	HEV's	Gebrü-der Meier
Type	-	As per supplier	HB 100L	ETR DN100 B2/4	M3AA 100 LB 2 3GAA101312-BSE	DM-SNP 63-6-1-77	Lange	HGA WGPM 280 S38
P_n	W	Output at shaft	3000	3300 YY / 2500 Y	3000	3008	2000	3250
U_n	V	Phase-to-phase voltage	380-415 D / 660 Y	400 YY / 400 Y	220-240 D / 380-420 Y	250 Y	230 Y	400 Y
I_n	A	Current	6.3 D / 3.7 Y	8.1 YY / 5.9 D	10.6 D / 6.1 Y	6.2 Y	5 Y	5 Y
f_e	Hz	Electrical frequency	50	50	50	150	100	19
n_n	min^{-1}	Mechanical speed	2880	2850 YY / 1430 D	2920	3000	1500	60
cos φ	-	Power factor	0.87	-	0.86 D / 0.86 Y	-	-	0.95
m	kg	Machine weight	32	21.9	25.2	12.7		600
Prot. IP	-	Protection category	55	55	55	-	-	54
Is. Cl.	-	Insulation category	F	F	F	F -	-	F
Serv.	-	Function		S1		-	-	
eff	-	Efficiency category	Eff2	Eff3	Eff1	-	-	-
Norm	-	Standards	VDE0530 / IEC341	-	IEC60034-1	-	-	IEC431
Ser. No.	-	Serial no.	617304	A044775 6	60510P0 971 /5	-	-	A39451 / 308 270
Date		Date of manufacture	2005.06	-	-	-	-	2004.09

Fig. 7: Rating plates of the measured motors

ASYNCHRONOUS MOTORS: PARAMETERS AND ALTERNATE CIRCUIT

Instead of the usual T alternate circuit, a modified circuit was used as depicted in Fig. 8. This made it possible to specify all parameters through measurements inclusive stator iron losses.

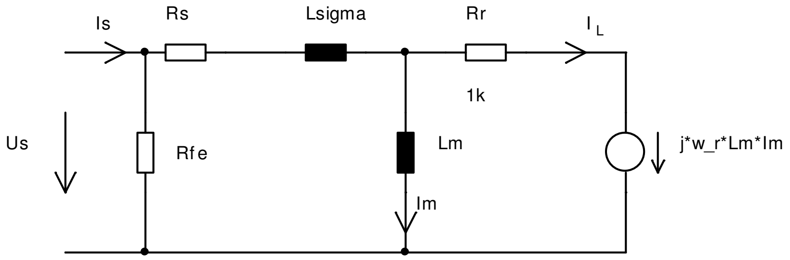

Fig. 8: Alternate circuit of the asynchronous motors

Measured parameters of the asynchronous motors

Table 9 shows the measured data for the three asynchronous motors:

Symbol	Unit	Measurement conditions	Description	ASM HB 100L	ASM ETR DN100	ASM ABB M3AA
R_s	Ω	$I = I_n$	Stator resistance	1.45	2.31	1.27
L_σ	H	$I = I_n$ $f_e = 50$ Hz	Leakage inductance (stator side)	17.4E-3	13.5E-3	12.3E-3
L_m	H	$U = U_n$ / $f_e = 50$ Hz $n \approx 2950$ min^{-1}/ $I_L \approx 0$ A	Magnetisation inductivity	290E-3	164E-3	220E-3
R_r	Ω	$I = I_n$ $f_e = 50$ Hz	Rotor resistance	1.4	1.99	1.22

Table 10 shows the no-load losses measured at different voltages:

Symbol	Unit	Measurement conditions	Description	ASM HB 100L	ASM ETR DN100	ASM ABB M3AA
Pcu	W	$n \approx 2950$ min^{-1} $f_e = 50$ Hz / $U = 400$ V	Copper losses without load	36	29	12
Pmec.	W	$n \approx 2950$ min^{-1}	Mechanical losses without load	133	130	114
Pfer	W	$n \approx 2950$ min^{-1} $f_e = 50$ Hz / $U = 400$ V	Iron losses without load	126	330	140
Ptot	W	$n \approx 2950$ min^{-1} $f_e = 50$ Hz / $U = 400$ V	Total losses without load	295	489	266
J	kgm^2	-	Moment of inertia	-	-	0.005

SYNCHRONOUS MOTORS: PARAMETERS AND ALTERNATE CIRCUIT

Fig. 11 shows the equivalent circuit of the permanent magnet synchronous motors which can be applied to machines with sinusoidal or trapezoidal current supply.

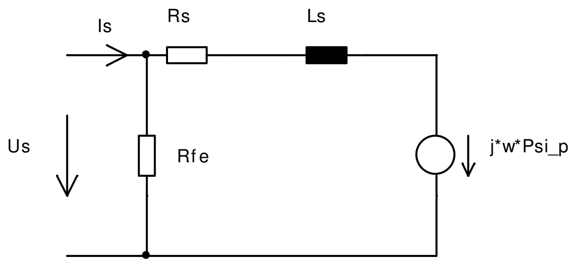

Fig. 11: Alternate circuit of the synchronous motors

Measured parameters of the synchronous motors

Table 12 shows the measured data for the three permanent magnet synchronous motors:

Symbol	Unit	Measurement conditions	Description	BLDC DM-SNP	PMSM Lange	PMSM HGA
R_s	Ω	$I = I_n$	Stator resistance	1.05	0.594	2.29
L_d	H	$I = I_n$ / $f_e = f_n$	Stator inductivity in rotor d axle	-	15.8E-3	46E-3
L_q	H	$I = I_n$ / $f_e = f_n$	Stator inductivity in rotor q axle	-	20.1E-3	57.3E-3
ψ_p	Vs		Influence of permanent magnet	0.1582	0.231	1.875

Table 13 shows the no-load losses measured at different voltages:

Symbol	Unit	Measurement conditions	Description	BLDC DM-SNP	PMSM Lange	PMSM HGA
Pcu	W	$n = n_n$ / $f_e = f_n$ / $U = U_n$	Copper losses without load	3	-	-
Pmec.	W	$n = n_n$	Mechanical losses without load	40	88	-
Pfer	W	$n = n_n$ / $f_e = f_n$ / $U = U_n$	Iron losses without load	69	89	-
Ptot	W	$n = n_n$ / $f_e = f_n$ / $U = U_n$	Total losses without load	112	177	102
J	kgm^2	-	Moment of inertia	0.003	0.029	1.6

SPEED CONTROL OF SYNCHRONOUS MOTORS

The frequency-voltage method is the simplest to control the speed. However, this method is not recommended because it is difficult to ensure a stable operation of the machine without knowledge of the exact position of the rotor. Measuring with a rotor position indicator permits reliable operation of the drive system.

Sine wave modulation

Fig. 14 shows the principle of sine wave modulation without torque adjustment and appropriate current control. An additional low-pass filter can be used for removing HF components from the machine current.

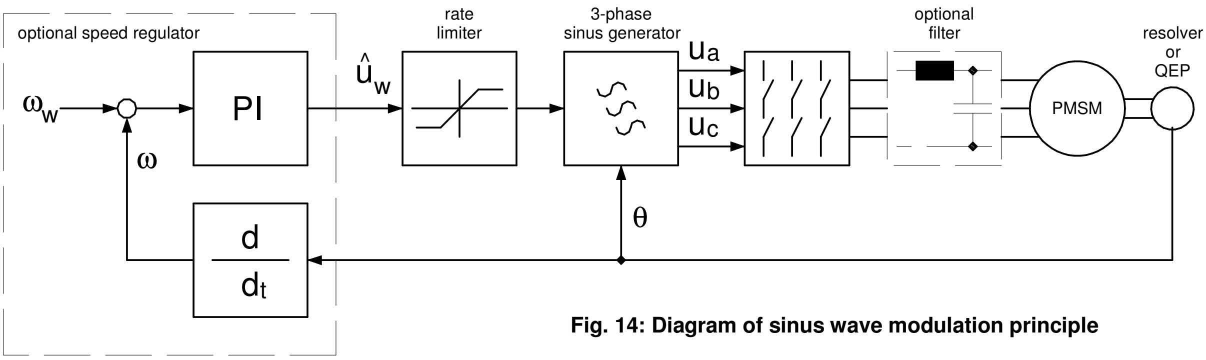

Fig. 14: Diagram of sinus wave modulation principle

"PMSM Lange" and **"PMSM HGA"** were both tested at no load using this type of modulation. It was found that only "PMSM Lange" could be operated faultlessly in this basic mode. "PMSM HGA" did not function optimally. With a speed of 60 rpm, "PMSM HGA" has to be allocated to the category of special machines [3], and is no longer considered within this study.

Block modulation

Fig. 15 depicts the principle of block modulation without torque adjustment. An actuator may be also be used if required.

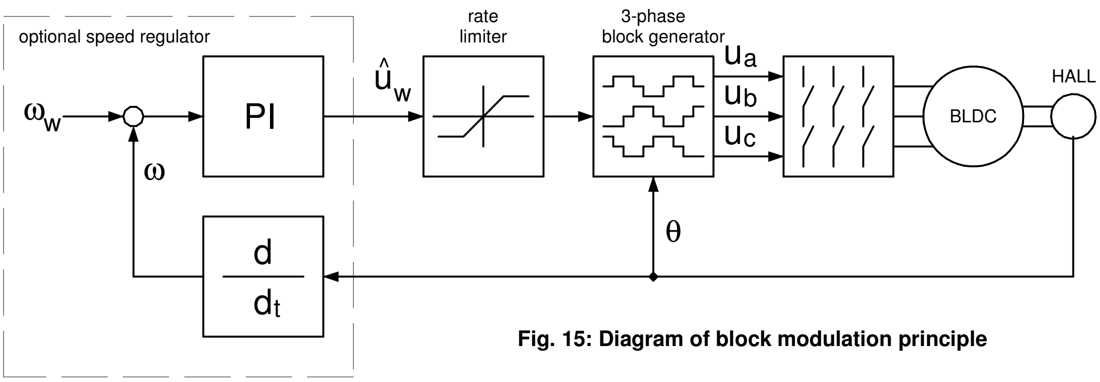

Fig. 15: Diagram of block modulation principle

The **"BLDC DM-SNP"** motor was tested with this type of modulation. The system functioned faultlessly at speeds above 100 rpm.

4.2.1 NO-LOAD MEASUREMENTS

LOSSES RELATING TO VOLTAGE

With the three asynchronous motors, tests were carried out at practically constant speed and variable voltage at no-load operation. A similar measurement was carried out on the **"BLDC DM-SNP"**, In order to compare the results, the asynchronous machines voltage was set with a Variac, while the synchronous machines were tested with the aid of a current inverter with variable sinusoidal voltages. The high-frequency components of the inverter current were filtered out.

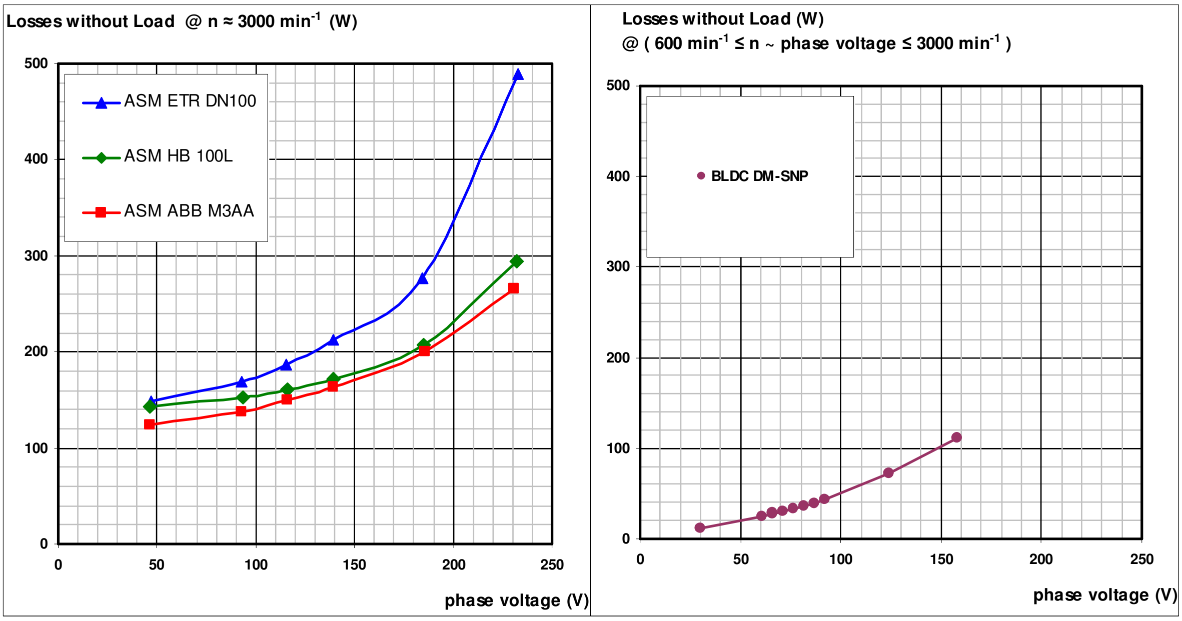

Fig. 16: Losses relating to phase voltage

The graph on the left shows the total no-load losses of the asynchronous motors relating to phase voltage. The quality of the machine (especially the lamination) influences the losses above 185 V. These measurements were used for determining the copper, mechanical and iron losses.
The graph on the right shows the total no-load losses of the synchronous motor relating to nominal voltage, and thus also to the speed. At nominal speed, the total no-load losses are negligible: 112 W versus 166 W, 295 W and 489 W with asynchronous machines. Based on these measurements, the losses were divided into copper losses (determined from the current measurements), mechanical losses proportional to the speed, and iron losses increasing with increasing stator voltage.
The mechanical losses of the "BLDC DM-SNP" were estimated at 40 W, i.e. approximately one-third of the losses of the asynchronous machines.

At 3 W, the copper losses of the **"BLDC DM-SNP"** were very low**.**

The iron losses of the **"BLDC DM-SNP"** were estimated at 69 W, i.e. slightly more than half the losses of the two more efficient ASM machines.

4.2.2 LOAD MEASUREMENTS

The load measurements were carried out up to a mechanical power of 2.25 kW. It was not possible to carry out the tests at 3 kW because the **"BLDC DM-SNP"** permanent magnet motor supplied by the manufacturer (EMB) did not attain the required and calculated emf.

MEASUREMENT PRINCIPLE

The same measurement principle was applied to all the machines. Each asynchronous machine was connected to the "**BLDC DM-SNP**" permanent magnet motor. A torsion meter was placed between the two machines in order to determine the shaft output. The asynchronous machine was then either connected directly to the 400 V power supply or controlled using an inverter, the intermediate circuit voltage of which was supplied from the rectified mains (560 V DC). The torque of the asynchronous machine was regulated by an inverter.
In order to obtain comparable measurements, the intermediate circuit voltage of the synchronous motor inverter was set at 520 V DC. The voltage is determined from the projection of the too low induced voltage of 270 V of the "**BLDC DM-SNP**". The existing inverter does not compensate idle time and can only be used with a maximum modulation level of 90 percent. This means that the intermediate circuit voltage has to be higher than the theoretically required level of 380 V DC.
The speed of the asynchronous machines was not controlled. Only the 50 Hz rotating field is specified for the supply to the inverter. This permits a comparison with mains operation, and thus the speed changes under load. By contrast, the speed of the synchronous machine is always set at 3,000 rpm, which corresponds to mains operation.
The electrical measurements are carried out with the aid of voltage probes (Aaron connection). They were connected with a broadband sampling oscilloscope.

ELECTROMECHANICAL CONNECTION OF THE MOTORS

The motors were placed on standard laboratory bench and tested in no-load operation with blocked rotor and with a load motor.
For the load measurements, each asynchronous machine was connected to the **BLDC** machine. A torque transducer was inserted between the shafts with the aid of aluminium helical couplings, each of which permitted a degree of freedom in order to compensate any errors in orientation. Fig. 17 shows the test bench and connection of an ASM motor to the **"BLDC DM SNP"**.

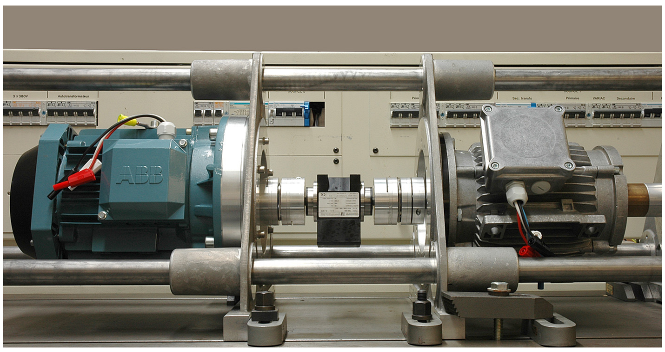

Fig. 17: Mechanical connection of ASM ⇔ BLDC motors

4.2.3 EFFICIENCY

EFFICIENCY IN MAINS OPERATION

The asynchronous machines were connected directly to the mains. Since the permanent magnet asynchronous **"BLDC DM-SNP"** cannot be operated directly from the mains, a sine wave inverter was used with a 20 kHz switching frequency and an output filter. Fig. 18 shows the degree of efficiency of each machine.

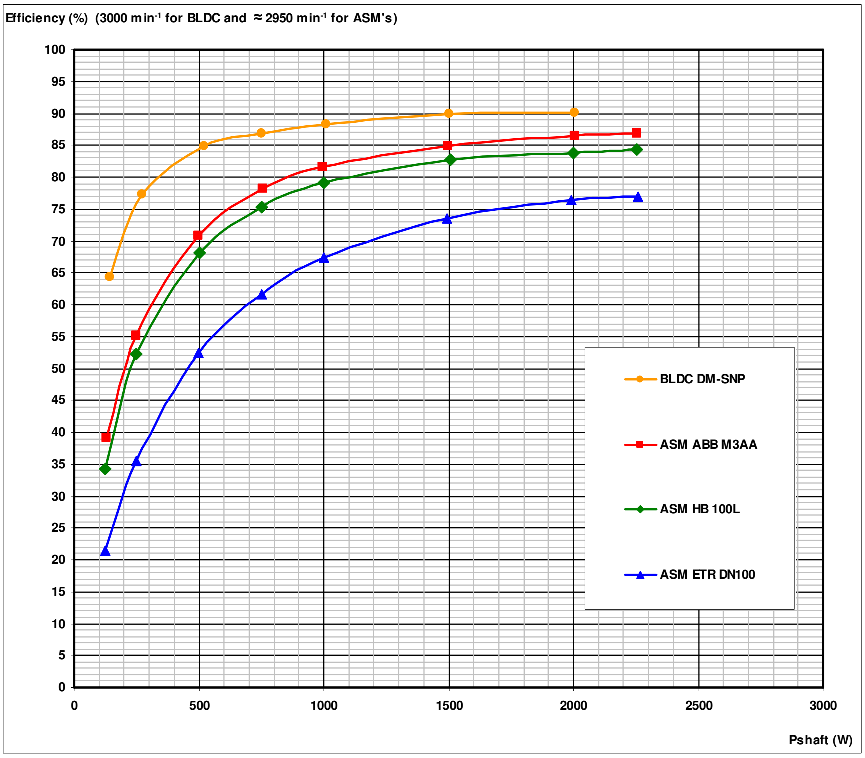

Fig. 18: Efficiency comparison without an inverter, between BLDC- and ASM-motors

From Fig. 18 we can clearly see that the efficiency of the **"BLDC DM-SNP"** permanent magnet motor is higher. This is additionally enhanced through the type of regulation, especially under partial load. In an asynchronous machine the copper losses are approximately 5 times higher than in a synchronous motor.
The only slight difference in efficiency between the highly efficient **"ASM ABBM3AA"** and the less expensive **"ASM HB100L"** was a positive surprise.
The high stator resistance and the quality of the lamination used in the **"ASM ETR DN100"** (Dahlander connection) result in a low degree of efficiency.

INFLUENCE OF THE SWITCHING FREQUENCY ON THE DEGREE OF EFFICIENCY

The option of speed control calls for an inverter for both asynchronous and permanent magnet motors. The inverter controls the motor voltage with a higher switching frequency than the stator voltage. The higher switching frequency results in additional losses.

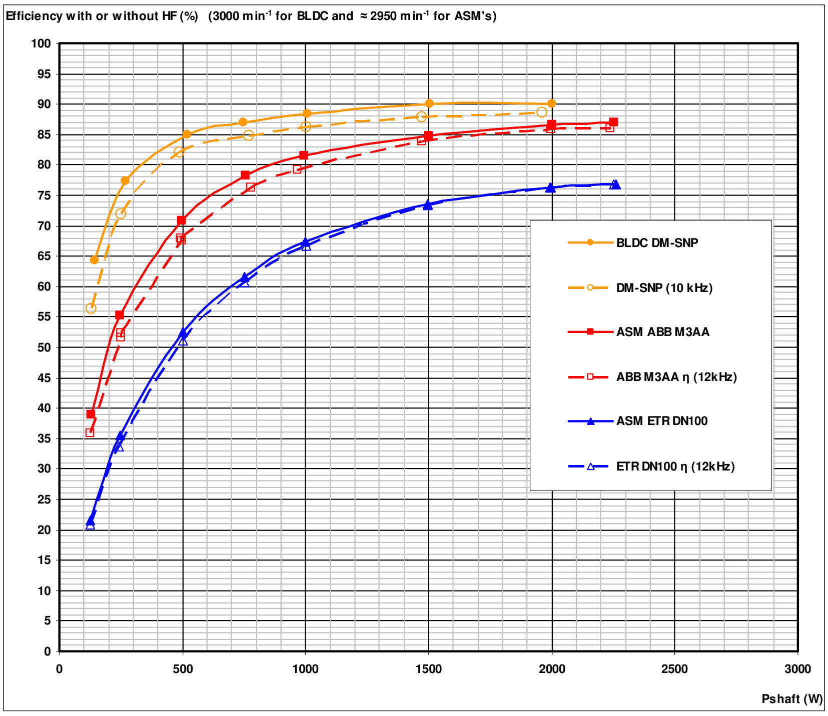

Fig. 19: Efficiency comparison

solid lines ⇔ motor without an inverter dotted lines ⇔ motor with an inverter

These additional losses influence the degree of efficiency especially at partial load, when the pulse factor of the switches is 50 percent and the current ripple factor is at its highest value. At nominal load, these losses become negligible because the pulse factor climbs close to 100 percent and the ripple factor gets small.

INFLUENCE OF SINUSOIDAL VERSUS BLOCK COMMUTATION TYPE

With a brushless DC motor the induced voltage is trapezoid and the modulation of the inverter is block type. With a permanent magnet synchronous motor the induced voltage is sinusoidal, as is the modulation of the inverter.

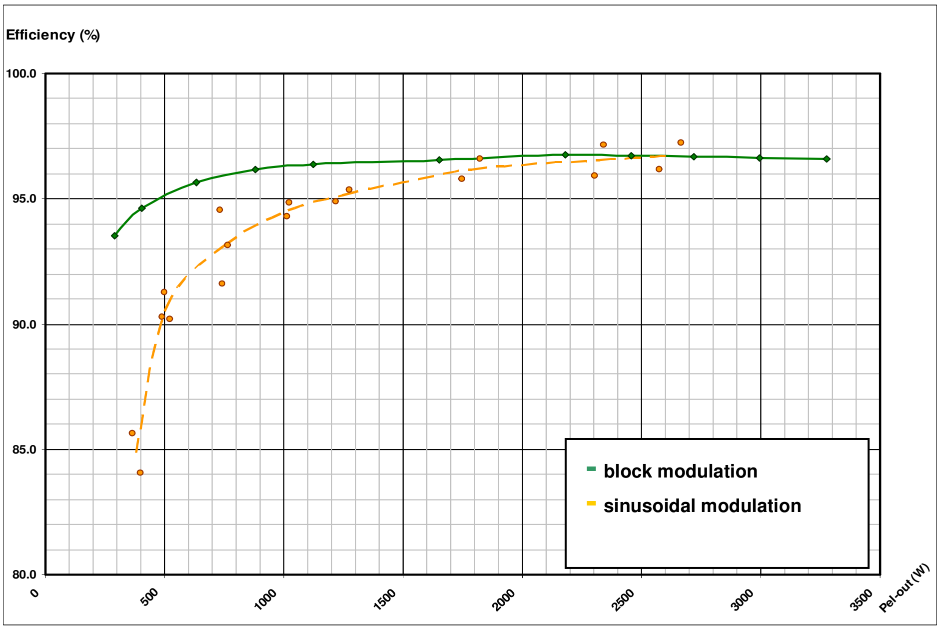

Fig. 20 shows the efficiency of the inverters at sinusoidal- or block modulation (measured between grid and motor connector)

Fig. 20 shows that a high degree of efficiency is attained with block modulation. **In view of the greater efficiency of the inverter and the simpler control procedure we decided to study brushless DC technology in permanent magnet motors as well as in inverters.** On the other hand it should be noted that the level of noise associated with block modulation is considerably higher (and thus less desirable) than with sinusoidal modulation.

FINDINGS

With three standard 3kW 3,000rpm asynchronous motors, one low-cost Asian machine (HB 100 L), one Italian machine with Dahlander winding (ETR DN100) and one high-efficiency ABB machine (ABB M3AA), the no-load losses and efficiency under load were measured at constant grid operation and with inverter supply. The results were compared with those obtained from the same tests with a permanent magnet motor that was ordered as a synchronous machine but supplied as a brushless DC machine, i.e. with trapezoidal voltage (BLDC DM-SNP).

The measurements under **no load indicated a clear superiority of the permanent magnet machine**, in terms of mechanical losses (approximately one-third of the ASM readings) as well as copper (no idle current) and iron (approximately half the ASM readings) losses. Similarly, the measurements of the machines under no load with unfiltered inverter operation indicated that the losses were lower with the permanent magnet machine. The switching frequency of the measured motors was between 5 and 20 kHz.

The **load measurements** were carried out up to a shaft output of 2.25 kW. At constant grid operation, **the efficiency** of the **permanent magnet motor** at 500 W output exceeded 85 percent and reached a **maximum level of 90 percent** in comparison with the degree of efficiency of the asynchronous machines, which was between 52 and 72 percent at the same output, with maximum levels of between 77 and 87 percent.

With **the inverter** driven asynchronous machines, a maximum degree of efficiency of 96 percent was measured. Generally speaking it may be stated that by **inserting an inverter** for **asynchronous motors**, the **degree of efficiency** of the drive system **in the higher range is reduced by around 5 percent.**

With the **permanent magnet motor**, the highest **degree of efficiency** is attained if the modulation type of the **inverter** is adapted to the induced voltage of the permanent magnet motor. With the tested brushless DC motor, **the degree of efficiency was 1 to 2 percent higher with block modulation than with sinusoidal modulation.**

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5. FINDINGS FROM THE POINT OF VIEW OF RELEVANCE TO THE MARKET

INTRODUCTION

The largest group of asynchronous motors in the market at the power range of 1 to 100 kW concerns machines in accordance with the IEC standard. Leading manufacturers such as *Siemens*, *ABB* and *SEW* supply the market with large quantities of these motors. The squirrel cage induction machine is the primary type.

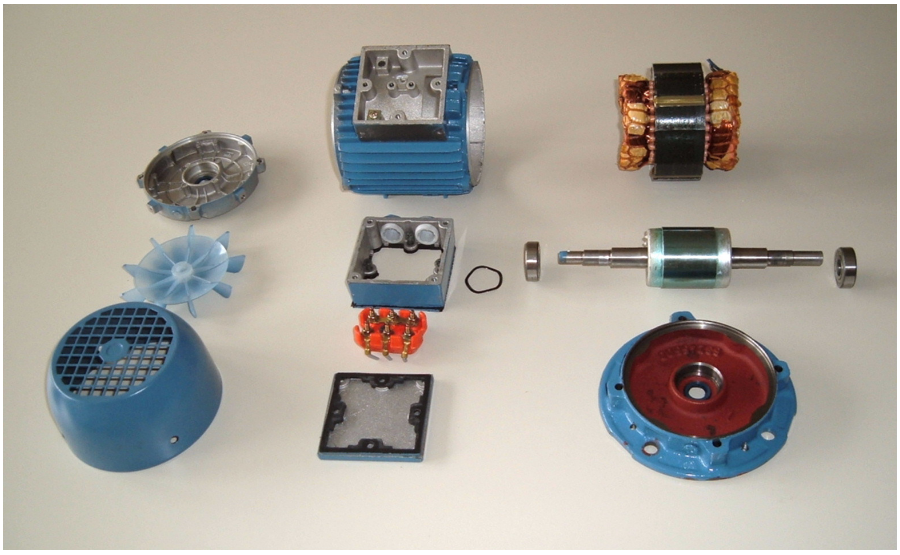


Fig. 21: The components of a standard motor.

The flanges and shafts are standardised in order to ensure trouble-free connection with the drive mechanism. The housing with foot attachments is used for attaching the motor to a base plate. The sizes of standard motors are indicated through the use of numbers, which indicate the distance between the base plate and the centre of the shaft. Thus with an IEC 80 motor the shaft height is 80 mm. The housings of smaller standard motors are made of aluminium, while those of larger models are made of cast steel.

This study compared asynchronous and permanent magnet motors from the point of view of efficiency. In terms of construction, what distinguishes a permanent magnet motor is its rotor, which is fitted with permanent magnets. It is this rotor that has a positive influence on the efficiency of the electric motor. Permanent magnet motors can be readily installed in standard IEC housings.

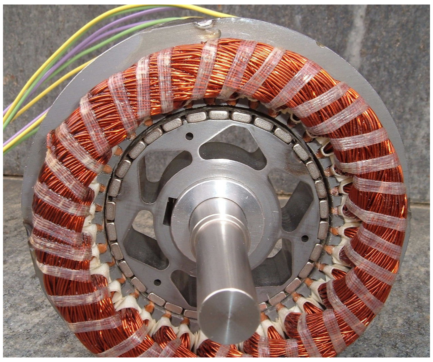


Fig. 22: Rotor / stator of a permanent magnet motor

CAUSES OF LOSSES

Losses in motors can be split into:

- Current losses in the stator winding
- Current losses induced in the rotor cage
- Hysteresis losses in the laminated iron
- Eddy current losses in the laminated iron
- Bearing friction losses
- Ventilation losses
- Harmonic voltage and current losses
- Losses of harmonic field waves

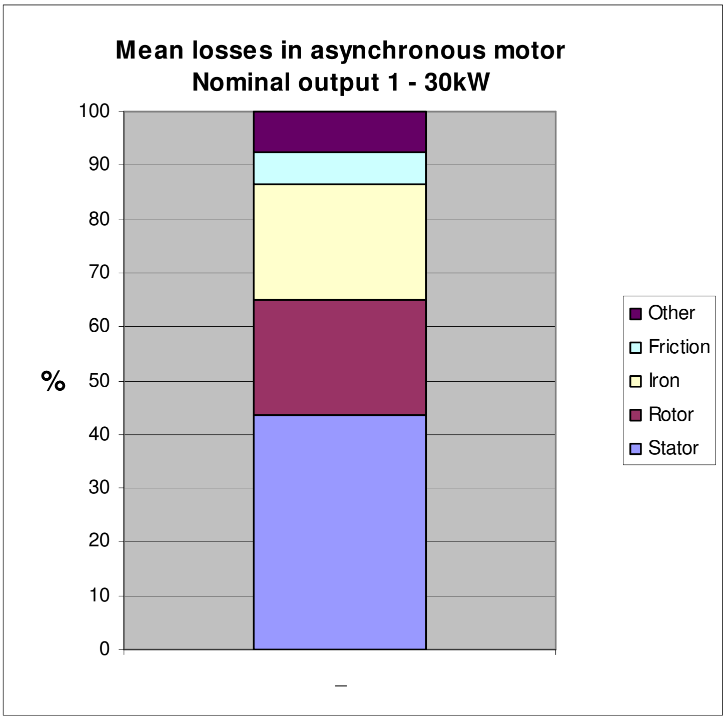


Fig. 23: Mean losses of asynchronous motors (in percent) in the 1 to 30 kW range

Significant factors for increasing the efficiency of asynchronous motors are:

- Use of more active material, i.e. increased cross-section of wires in the winding, of aluminium in the rotor and use of more iron in the rotor and stator.
- Changing the cage material from aluminium to copper. In this way, the rotor losses can be reduced by approximately 40 percent.
- Iron losses can be reduced by using better quality lamination. Higher quality also means higher production costs. Approximately 20 percent is an acceptable level of loss reduction by using better laminations.

An increase in active material inevitably means an increase in the dimensions of the motor and costs. And the use of copper cage results in heavier rotors. This is why IE2 standard motors are heavier than IE1 motors. Depending on the classification of IEC standards, it is possible that for an IE2 motor a shift up to the next IEC size category could be required.

Using a permanent magnet rotor instead of a squirrel cage rotor is an effective way of avoiding losses!!!

Fig. 24

A permanent magnet rotor generates the electro magnetic force without current losses in the rotor. The rotor no longer needs any electric wires. The rotor revolves synchronously with the stator field. The iron of the rotor is no longer exposed to an alternating magnetic field. Hysteresis and eddy current losses in the rotor are eliminated. Hence, losses in the motor are significantly reduced, since these losses are also linked to the stator current. Every reduction in losses in the motor results in a reduction of the electrical input circuit, and thus results in a reduction of heat loss (Joule effect) in the windings of the stator. For the same output power, permanent magnet motors can be more compactly constructed. Compactness offers two advantages in particular:

- Savings in terms of raw materials weight and costs.
- Less energy is required for starting the motor thanks to reduced rotor inertia.

5.1. SAVINGS IN TERMS OF RAW MATERIALS AND WEIGHT

High energy prices have a direct impact on the production costs. Since aluminium and copper are major components of standard motors, and the production of both of these materials is associated with rather high energy consumption.

High energy prices promote the acceptance of efficient permanent magnet motors on the market. Because IE2 and IE3 asynchronous motors, require more material in order to be more efficient. This can be considered for whole IEC power range.

- The measured BLDC DM-SNP permanent magnet motor with a shaft output of 3 kW, a speed of 3,600 rpm and an efficiency level of 90 percent weighs **12.7** kilograms (excluding the ventilator), and is classified in size category **IEC 90**.
- The measured ABB M2AA IE3 standard motor with a shaft output of 3 kW, a speed of 2,910 rpm and an efficiency level of 87.5 percent weighs **25.2** kilograms, and is classified in size category **IEC 100**.
- A permanent magnet motor listed in a catalogue with a shaft output of 290 kW, a speed of 750 rpm and an efficiency level of 96.1 percent weighs 1,605 kilograms, and is classified in size category IEC 315.
- A standard motor listed in a catalogue with a shaft output of 315 kW, a speed of 743 rpm and an efficiency level of 96.1 percent weighs 2,700 kilograms, and is classified in size category IEC 400.

The measured BLDC DM-SNP 3 kW permanent magnet motor was in size category IEC 90, while the 2-pole 3 kW standard motors have to be larger (size category IEC 100).

The levels of efficiency of both motor types get similar at higher power, but permanent magnet motors require significantly less material than standard motors for the same efficiency.

A calculation based on the prices of raw materials at the time the study was carried out indicated that ***the savings in costs of raw materials in heavier IE1 standard motors offset the additional costs of magnetic material required by lighter permanent magnet motors.***

5.2 LOWER STARTING ENERGY DUE TO REDUCED MASS INERTIA OF THE ROTOR

The mass inertia of permanent magnet motors is significantly lower. Starting a permanent magnet motor requires considerably less energy in comparison with an IE2 / IE3 standard motor.

Efficient permanent magnet motors should be used for operations involving frequent starts and stops.

Comparison of mass moment of inertia:

- Measured permanent magnet motor with 3 kW shaft output, 3,600 rpm, size category IEC 90 = 0.0019 kgm^2.
- IE3 standard motor (listed in catalogue) with 3 kW shaft output, 2,910 rpm, size category IEC 100 = 0.005 kgm2.

Here the most suitable applications are frequently used automatic doors and elevator systems, and operations requiring frequent speed adjustments, e.g. conveyor systems with pronounced changes in speed, automated and handling systems that do not place especially high demands on precision.

Other suitable applications include dynamic servomotors for the operation of machine tools. However, for costs reasons they are only suitable for use for operations involving precise positioning.

5.3 HIGHER EFFICIENCY AT PARTIAL LOAD

The difference in efficiency between permanent magnet motors and standard motors increases with smaller motor size. A large market segment is the power range below to 22 kW.
Especially at partial load the difference in efficiency in favour of permanent magnet motors is very attractive. For this reason it would be beneficial to equip small-scale power plants with permanent magnet generators. This includes facilities that generate electricity from water, wind and biomass (highly efficient cogeneration). The production of electricity directly at the source also means that losses associated with the transport of electricity from large-scale power plant to end consumer can be eliminated. Electricity transport can result in losses of up to 10 percent (2 percent for transmission, 8 percent for distribution). [4]

Fig. 25

Fig. 26

Fig. 25 depicts a Pelton turbine for a small-scale hydropower plant, equipped with a permanent magnet generator. Fig. 26 shows a permanent magnet linear generator [9], which is in use in a free-piston Stirling system (cogeneration).

5.4 GEARED MOTORS / DIRECT DRIVES

Geared electric motors are used in very large numbers in applications in which low speeds and high torque are required. Here the mechanisms can take the form of spur, bevel, planetary or worm gears, or combinations thereof. Leading manufacturers use IEC standard (asynchronous) motors for drive purposes. High engine torque can also be attained with permanent magnet motors with a high pole number, and preferably with a large external diameter. These gearless direct drives are today strong competitors for geared motors.
The significant presence on the market can be attributed with a study of the efficiency of geared motors. The data source was the catalogue of a leading European manufacturer of these machines, the study was carried out on motors with output levels of 3, 5.5, 15 and 45 kW, and the output levels were measured at 10, 100 and 725 rpm.

The study showed that the overall degree of efficiency can be significantly increased through the use of efficient motors at high gear reduction, both with spur gears and worm gears. At low gear reduction and outputs of only **several kW it may be assumed that permanent magnet direct drives are superior to geared motors in terms of efficiency**.

Demand for motor vehicles that consume high levels of fossil fuel is rapidly declining, and the focus is gradually shifting towards electric vehicles. High-efficient permanent magnet motors are the preferred drive for electric vehicles, since increased efficiency of the motor goes hand in hand with a reduction of the weight of lithium-ion batteries for the same operation radius. Permanent magnet direct drives with very high torque are now being constructed as wheel hub motors. When wheel hub motors are used in road vehicles, attention has to be drawn to the aspect of the unsprung weight. Fig. 27 shows the integration of a permanent magnet motor into a wheel for driving a small electric vehicle.

Fig. 27

5.5 OPERATING PERFORMANCE

PERMANENT MAGNET MOTOR CONNECTED DIRECTLY TO THREE-PHASE SUPPLY

This point has not been included in this summary. In view of the large market for variable-speed motors for turbo-machines, this type of operation was no longer examined in this study.

OPERATION OF MOTORS WITH SPEED REGULATION

Studies (e.g. [5]) have shown that around 45 percent of electricity in Switzerland is used for drives and drive systems. Drives for turbo-machines alone account for approximately 30 percent of Switzerland's electricity consumption (pumps, ventilators, compressors). The operating hours of the required motors are extremely high, and many come very close to the maximum total of 8,760 hours (i.e., 24 hours a day, 365 days a year). Compared with inefficient throttle mechanisms, electric drive control systems, which precisely adapt the speed of turbo-machines to the effective output rate, save a significant amount of energy. The higher costs for inverters for speed control can already be fully amortised after only a few months. Please visit www.topmotors.ch for a list of sources for software tools for carrying out amortisation calculations.

In order to save energy, permanent magnet motors are therefore the most suitable drives for turbo-machines in the following circumstances:

- Where a genuine need exists for speed control.
- Where there is considerable potential for reducing electricity consumption through lengthy operating times of motors because of partial load operation.
- Where the saved energy quickly offsets the investments for speed regulation mechanisms.
- Where a standard motor also requires an inverter (and thus results in additional costs) for speed regulation.
- Where the degree of efficiency of a permanent magnet motor is higher than that of a standard IE1 / IE2 motor.

Considerable progress has been made with respect to permanent magnet motors in circulation pumps for heating purposes. Here the efficiency of variable-speed permanent magnet pumps has been increased by a factor of three to four versus circulation pumps with an asynchronous motor. [6]

5.6 COSTS

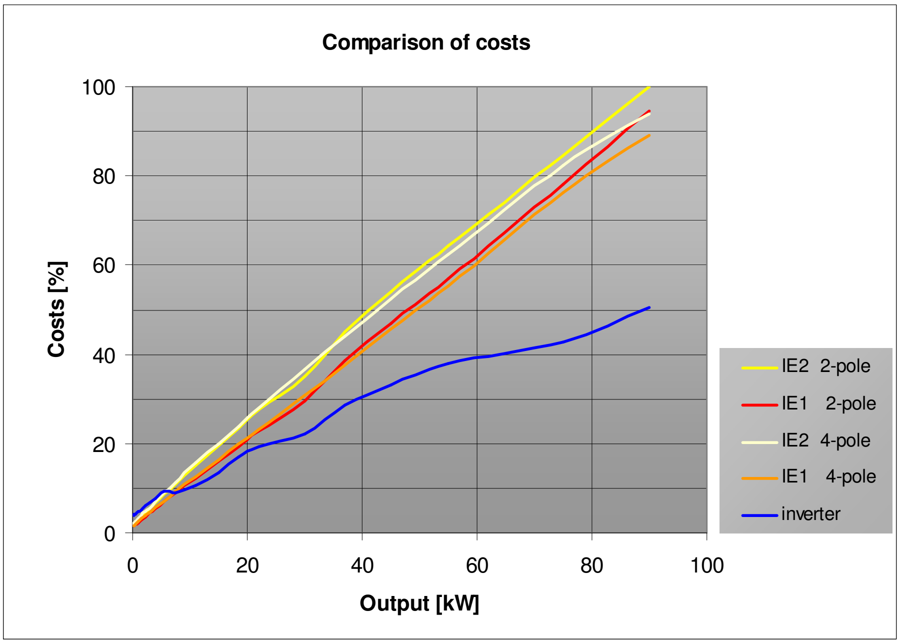


Fig. 28

The graph in Fig. 28 shows the costs of standard motors and inverters in relation to their output. As we can see, the costs of inverters decrease as the power of the motors increases.

The costs of the components of an inverter for a standard motor are similar to the costs of an inverter for a permanent magnet motor. The speed of both types of motor can be adjusted with the aid of an inverter. The cost calculation shows that the efficient permanent magnet motor can compete with the asynchronous motor if speed regulation is required. **The savings in costs of raw materials in heavier IE1 standard motors offset the additional costs of magnetic material required by lighter permanent magnet motors.**

5.7 SIZE LIMITS

No size limits were identifiable for efficient permanent magnet motors with an output of up MW.

5.8 SAVINGS POTENTIAL WITH EFFICIENT PERMANENT MAGNET MOTORS IN SWITZERLAND

In the study on the economic viability, applications and limits of efficient permanent magnet motors [1] it was estimated that it would be possible to achieve an average saving of around 5 percent in energy consumption if standard motors in existing systems in Switzerland were to be replaced with efficient permanent magnet motors.

Additional savings of around 20 percent [7] would be possible through speed control for optimised operating processes in systems driven by electric motors.

The savings potential with efficient, variable speed permanent magnet motors with optimised operating processes in Switzerland amounts to around 4 billion kWh, or a generator output of approximately 500 MW.

These estimates do not take account of the efficient drives using permanent magnet technology that are already in operation today. They are only based on turbo-machines, which account for around 30 percent of Switzerland's electricity consumption, whereas the figure for all electric motors in Switzerland is around 45 percent [5].

A dissertation at the University of Lucerne dealing with the ecology of electric motors [10] shows that it is essential to optimise systems for maximum efficiency if they are in operation for a very high number of hours a year. This requires the use of optimised operating processes, speed control and highly efficient electric motors. Compared with the burden on the environment caused by the production of electricity for the operation of a drive over its entire service life, the "grey energy" and the associated greenhouse gases that result from the production of an inverter and an electric motor are of little significance.

5.9 AREAS OF APPLICATION IN WHICH PERMANENT MAGNET MOTORS ARE UNSUITABLE

- Where short operating times apply and motor-driven appliances are used that only have a service life of a few hundred hours. For these applications, universal motors (collector motors for mains operation) or single-phase standard motors with auxiliary capacitors are more suitable in terms of cost. Typical examples include kitchen appliances, do-it-yourself appliances, vacuum cleaners, etc.
- According to the current status of technology, with direct mains connection and lengthy operating times (preferably at nominal load), IE2 and IE3 asynchronous motors are can be more suitable.

In the course of this study we did not identify any other applications for which permanent magnet motors would be less usable. Certain restrictions were found to apply as follows:

- When explosive materials are used, since neodynium reacts strongly with hydrogen.
- Asynchronous motors for applications without the need of process control. This means that the drive system can become more robust. But the process energy consumption and maintenance costs could be higher.
- In contrast to asynchronous motors, permanent magnet motors cannot take the form of pole changing motors.

6. FURTHER STUDIES

The action that could be implemented quickly and simply would be to replace standard motors with efficient permanent magnet motors **via a standardised shaft-flange connection**. This was the goal of a study entitled **"More efficient 3 kW IEC permanent magnet motors"** [8]. The chosen size was IEC 100. In this way it is possible to replace a 2-pole standard motor with a shaft power of 3 kW in a mechanically compatible system with an efficient permanent magnet motor. This applies both to new systems as well as to existing ones in which an older standard motor is replaced.

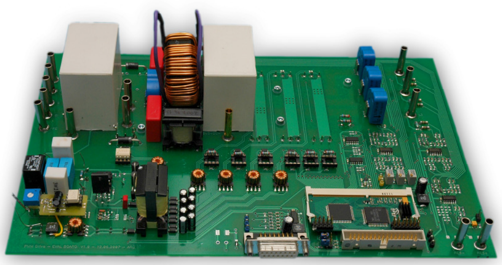


Fig. 29: PMM-drive inverter

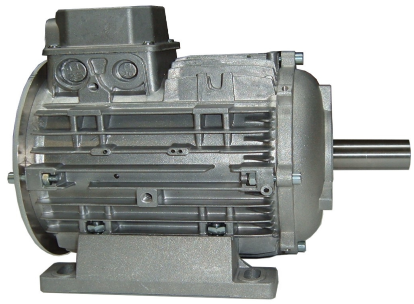


Fig. 30: BLDC CM IEC 3 kW motor

BLDC CM IEC 3 kW is the designation of an efficient brushless DC motor designed by Circle Motor AG. In order to determine the overall degree of efficiency, this motor was connected with a **PMM-drive inverter**, which was designed so that the speed of the **BLDC CM IEC 3 kW** motor is variable.

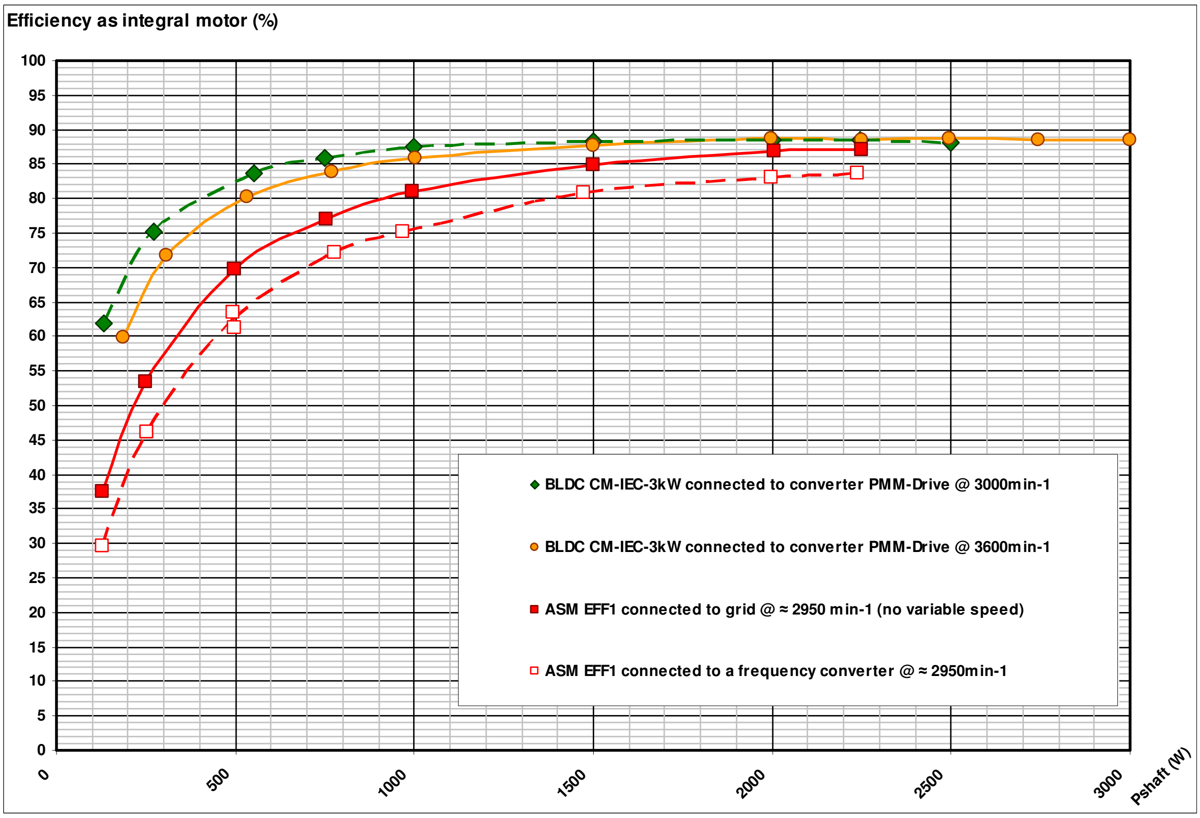


Fig. 31 shows the efficiency of the measured motors with an inverter (exception: red solid line ⇔ asynchronous motor connected direct to grid)

The maximum measured efficiency of the PMM drive inverter was 96.5 percent, while the figure for the BLDC CM IEC 3 kW motor was 92 percent.
With the advantage of variable speed operation, the **efficiency** of the **BLDC CM IEC 3 kW motor** with the **PMM drive inverter is always higher than that of the measured ASM ABB M3AA asynchronous motor**, operating at constant grid.

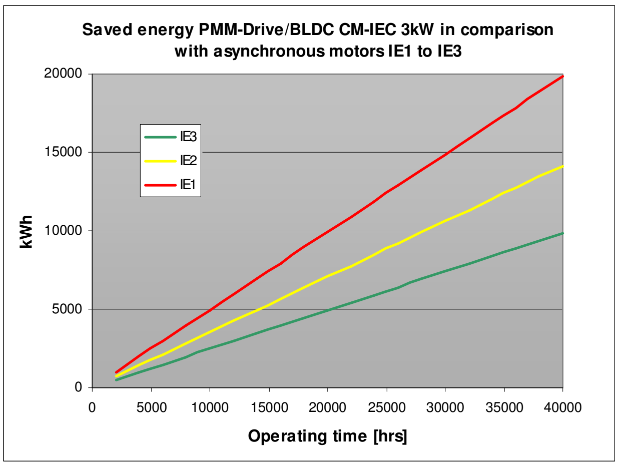
Table 32 shows the weights per component of the **BLDC CM IEC 3 kW** permanent magnet motor. For drawing up an ecological balance, the proportions of the main raw materials that were used have also been shown.

Weights table of 3 kW permanent magnet motor (excluding electronics)	
Component(s)	**Weight (in kilograms)**
Stator iron	4.3
Winding copper	1.7
NdFeB magnets	0.295
Rotor (Fe) excluding magnets	1.9
Shaft (excluding bearings)	1.17
Ball bearings A	0.21
Ball bearings B	0.11
Empty stator casing, incl. terminal box, flange (middle), end cap, excluding A flange, all parts aluminium	3.1
Aluminium A flange including sintered steel bush	0.82
Total weight of permanent magnet motor	**13.605**

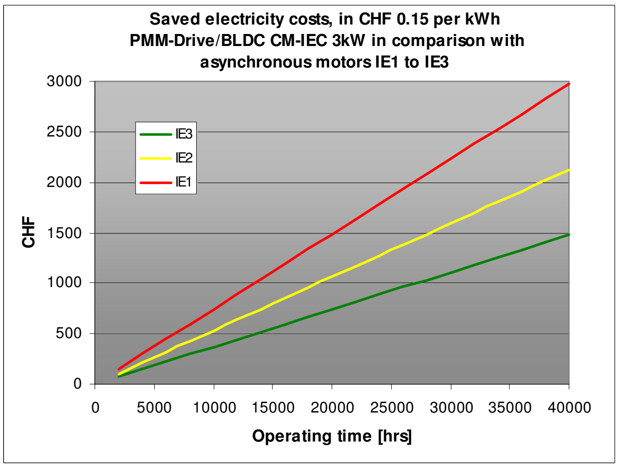
Raw materials	Weight (in kilograms)
FE	7.69
Cu	1.7
ALU	3.92
NdFeB	0.295

Table 32: Comparison of weights

The BLDC CM IEC 3 kW permanent magnet motor is approximately 10 kilograms lighter than the studied ASM ABB M3AA asynchronous motor.



Graph 33



Graph 34

Graphs 33 and 34 are based on a comparison of the PMM drive / BLDC CM IEC 3 kW with efficiency class IE1 to IE3 asynchronous motors connected to an inverter, and show the savings in terms of energy consumption and electricity costs (average electricity price, CHF 0.15 per kWh).
The cost calculation shows that the efficient IEC 3 kW permanent magnet motor can compete with the asynchronous motor if speed control is required. This is also where the greatest efficiency potential can be found for variable speed pumps, compressors and ventilators.

DEFINITIONS OF TERMS USED IN THIS REPORT

Asynchronous motor, induction motor and **standard motor** are synonymous. The rotor takes the form of a squirrel cage rotor.
The term **permanent magnet motor** refers to a motor, the rotor of which is fitted with permanent magnets.
In this report, the term **inverter** refers to an electronic device for controlling the speed of permanent magnet or asynchronous motors.
Brushless DC control mechanism refers to the control mechanism of a permanent magnet motor with the character of a DC motor, but in which the mechanical brushes have been replaced with electronic components. A permanent magnet motor that behaves like a DC motor when connected to a brushless DC control mechanism is referred to as a **brushless DC motor**.
HF stands for high frequency.
IEC stands for International Electrotechnical Commission.

REFERENCES

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[2] *Kienle + Spiess*/Katalog: Spitzentechnologie und Know-how für den Bau elektrischer Maschinen (Kienle + Spiess catalogue: Leading technology and know-how for the construction of electric motors).

[3] *Hocheffizienter, getriebeloser Antrieb* (High efficiency gearless drives): study carried out on behalf of the Swiss Federal Office of Energy in 2004 by Vivatec GmbH, Gebrüder Meier AG, University of Valais.

[4] *European Commission Green Paper on Energy Efficiency.* European Commission, 2005. DE 265, page 28.

[5] www.motorsummit.ch

[6] *Workshop* on efficient electric drives held at Swissmem on 20 January 2005: Spezialantriebe mit komplexen Rahmenbedingungen (Special drives with complex requirements). Biral AG, Wolfram Mayer, pages 2 and 5.

[7] www.topmotors.ch

[8] *Effizienter IEC Permanent-Magnet-Motor 3kW* (Efficient IEC 3 kW permanent magnet motors): study carried out on behalf of the Swiss Federal Office of Energy in April 2008 by Circle Motor AG, the University of Lucerne and the University of Valais. www.electricity-research.ch

[9] *Effizienter Lineargenerator / Linearmotor für Kolbenmaschine* (Efficient linear generators / linear motors for piston engines): study carried out on behalf of the Swiss Federal Office of Energy in June 2008 by Circle Motor AG. www.electricity-research.ch

[10] *Effizienz Normmotoren / Ökobilanz und Demonstration* (Efficient standard motors / ecological balance and demonstration): B.SC. dissertation by Thomas Gander, Norbert Büchel, University of Lucerne, July 2007.

SOURCES OF ILLUSTRATIONS

Lucerne University of Applied Sciences and Arts	Figs. 2 to 6
Maxwell 3D, RMxprt software	Fig. 1
University of Applied Sciences Western	Figs. 7 to 20, 29 and 31
Circle Motor AG	Figs. 21 to 28, 30, 32 to 34