Trondheim

SWITCHED RELUCTANCE MOTOR WITH 16 STATOR POLES AND 12 ROTOR TEETH

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Abstract: The Elektrotechnisches Institut of the University Karlsruhe has developed, optimized and manufactured a Switched Reluctance Drive with power converter and control engineering according to the latest scientific findings. The motor was constructed for the rated output of about 25 kW and for industrial applications.
The nominal speed of the test Switched Reluctance Motors is 1500 revolutions per minute. The drive works in all for quadrants and was designed for applications with highest demands for dynamics, constant torque, low noise and highest power output.

Keywords: Switched Reluctance Drive, Switched Reluctance Motor

INTRODUCTION

The Switched Reluctance Motor has already been propagated in many publications of English literature. However, these general publications do not scientifically solve the use of this motor type as variable-speed drive. Most publications treat parts of the problems only. Less attention was paid to the examination and optimization of the overall system - composed of motor, converter and control. Uncertainties regarding utilization, torque undulation, noise generation and selection of converter circuits lead to today's shadowy exixtence of this motor. Since the simple construction of the Switched Reluctance Motor promises production at low cost, the industry launched occasional enquiries and examinations regarding the Switched Reluctance Drive. Nevertheless the drive could not yet find its wide acceptance, probably due to single, technically unsolved problems.
The motivation to realize this project at the Elektrotechnisches Institut of the University of Karlsruhe is based on the unsolved technical problems, the robust construction and the favourably-priced motor.
The paper will describe important findings regarding the Switched Reluctance Drive as a whole. As an example we selected a motor with an output of 25 kW at 1500 revolutions per minute.
Different types of variable-speed electromotors, such as a.c. and d.c. motors, are widely spread with the selected technical major parameters. The Switched Reluctance Drive can therefore quickly and easily be compared with these drive types.

MOTOR DESIGN

The Elektrotechnisches Institut selected the new Switched Reluctance Motor with 16 stator poles and 12 rotor teeth. It is a 4-pase-winding machine, the 4 stator poles that are shifted by 90° to each other form one phase-winding (Figure 1).

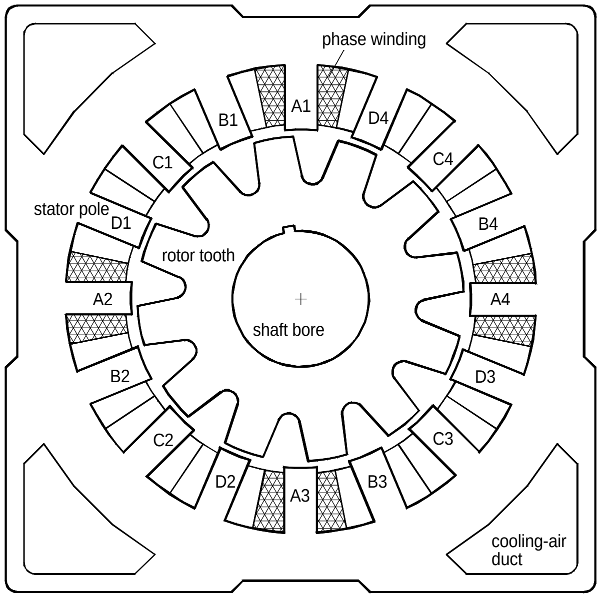

Figure 1: Schematic cross-section of the Switched Reluctance Motor

This design was proposed by author. Compared with the 3-phase Reluctance Motor, the 4-phase machine requires the same or even lower number of power semiconductors.
The four phase-winding poles split the forces up more evenly around the motor perimeter which reduces the noise. If only two opposite poles belong to one phase-winding as for example in the 4-phase-winding 8/6 reluctance motor, the forces do apply on two positions only. The 4-phase-winding 16/12 reluctance motor splits the forces up to four poles. Therefore, these are approximately only half as big as the forces of the 8/6 motor. Also, the 16/12 motor generates less noise than the 8/6 motor. These findings are proved true by comparative measurements done with a 15 kW 8/6 motor of the Oulton company.

The authors of the paper [1] compared a 6/4 motor with a 12/8 motor and showed that the utilization of the high-pole machine is better for higher torques which is due to the flux linkage and the narrow winding coils. The first causes a higher torque, the latter a lower thermal resistance from the winding to the iron. However, with a bigger number of pole/teeth the magnetic reversal frequency and iron losses increase. According to [1], a lower flux density should compensate this effect, so that iron losses of both motors range in the same size. However, the latter context does not seem to be proved true by our Switched Reluctance Motor. The iron losses increase noticeably with higher torque.

TEST DRIVE

The main components of the test drive are the Switched Reluctance Motor and the power converter. The voltage-source converter consists of mains and motor converter. The common supply for the three-phase-self-commutated mains converter is 400V/50Hz. The control electronic - including the measurement and control techniques - is superior to the power electronic. Motor and converter can be used for the four-quadrant-drive. The basic structure is shown in Figure 2.

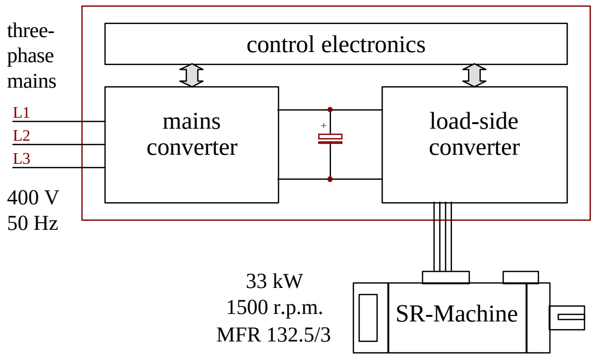

Figure 2: Basic structure of the Switched Reluctance Drive

MAINS FRIENDLINESS OF THE SWITCHED RELUCTANCE DRIVE

The mains converter is a three-phase-self-commutated IGBT-Converter. The control of the mains current has been optimized in a way that the drive, in stationary running with a power factor of about one, receives energy from or feeds energy into the 3-phase current mains. This results in a sinusoidal mains current and in conformity of the phase position between current and voltage - at long last the mains friendliness of the drive.
The mains current converter operates in all four quadrants and allows to implement highly dynamic drive solutions. For example, if the converter is used for the main drive of a group of drives, it may additionally be employed for compensating the reactive power of the auxillary drives. Figure 3 shows the current and voltage values for motor operation with 20 kW and reactive power compensation at the same time.
For reluctance drives less demanding in terms of dynamics and mains compatibility, diode bridges with smoothing and commutating reactors are used as mains current converters. The reluctance drive can also be operated with it, in most cases however, as motor only.

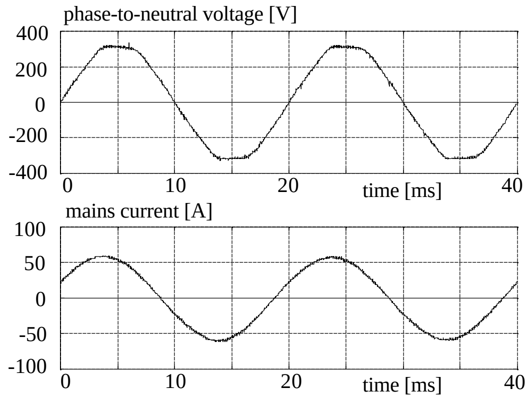

Figure 3: P_{mains} = 24,4 kW, Q_{mains} = -10 kVAr, $\cos\varphi$ = 0,925$_{cap}$, P_{motor} = 20 kW, (measurement)

LOAD-SIDE CONVERTER

For the Switched Reluctance machine the output current of the converter can be limited to one direction per phase due to the unipole excitation. The rotor moves into the magnetic field when the motor is in operation. This does not depend on the direction of the magnetic flux density.
With the generator in operation, the rotor moves out of the field.
Three criteria must be complied with when selecting the converter circuit:

1. low number and low cost of power semiconductors
2. less current measurements
3. many options for influencing the phase-winding current

Criteria 3 contradicts 1 and 2. Less requirements for power electronic and measurements restrict the options for current control. When defining the converter topology, you must compromise to fulfill these demands.

If a two-quadrant chopper circuit is used for each phase and if each phase current is measured separately, many options can be used. The complete d.c link voltage U_d can be used for switching the phase-winding current on/off. The current can - for all phase-windings and at any time - be adjusted to a predefined desired value. A free-wheeling of the phase-winding current is possible.

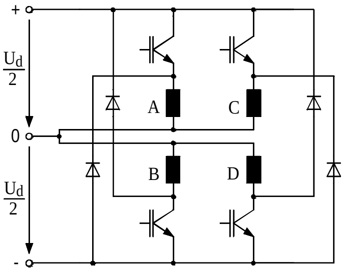

Figure 4: H-Circuit

The so-called H-Circuit [2] with connected neutral point (Figure 4) allows to control the single currents separately. This circuit only requires one power switch and one diode per phase thus operating with the lowest number of semiconductors. To profit from these benefits you must accept that there is no free-wheeling current and that only half the d.c. voltage is used. The current can only be in- or decreased with $U_d/2$. Like this, motor winding and current carrying capacity of the power semiconductors must be dimensioned for $U_d/2$. With regard to the two-quadrant chopper circuit per phase - provided that the nominal speed of the motor is the same - the number of turns per phase must be halved and the cross-section of the wire must be doubled. Additionally, power modules with doubled current carrying capacity must be selected. Two or four measurements are required to measure the phase currents. Usually, the neutral point is generated by means of a serial circuit of capacitors at the d.c. voltage source. The capacitors of both partial voltage sources must be loaded in a symmetric way. Like this, the H-Circuit can be used for all Switched Reluctance Motors with an even number of phases. It can be used for machines with two and also with four phases.
This project aims at finding a circuit which has less restrictions regarding the current control and which uses the complete d.c. link voltage with a number of power semiconductors as low as possible. We suggest the following circuit (Figure 5).

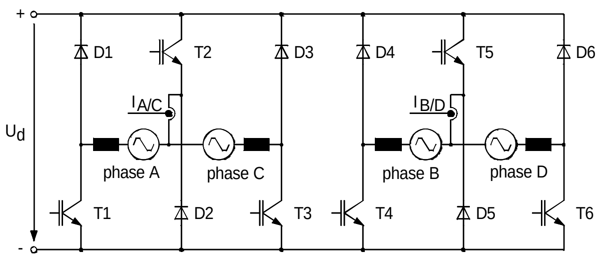

Figure 5: Circuit of the load-side converter for the 16/12 Switched Reluctance Motor

The transistors T2 and T5 supply two non-adjoining phase-windings each. When the machine turns right as motor, the phases are switched D-A-B-C-D-A. When turning right, they are switched A-D-C-B-A-D. When switching from one phase to another, current may flow in the adjoining phases. The phases A and C respectively B and D should not conduct current at the same time, since for example A generates a motoric and C a generator torque. Both torques are subtracted from each other, a not desirable status. Like this, the phases A and C respectively B and D can be supplyed with one common transistor each without further restrictions regarding the current control. The currents can be determined by one common measurement.
Only with very high output powers, the inactive phase conducts a small amount of residual current. The measurement errors resulting for the active phase are corrected in the control.
In comparison with the three-phase induction motor, the amplitudes of the phase currents are approximately 15% higher. Therefore, the power semiconductors can be selected with the size of the modules usually used in power converters of asynchronous motors.
Compared with the H-Circuit, the cost for power semiconductors from average to higher output powers are lower. The free-wheeling current can be used to lower the pulse frequency rate respectively the current ripple. Since there is no voltage neutral point this circuit can also be used for very small speeds and for standstill torques.

CURRENT AND TORQUE CONTROL

For the test drive, the torque control was optimized in switching mode for high utilization and low torque ripple with the parameters turn-on angle, current flow angle and current desired value [3].
The respective angles result from the rotor position. The turn-on angle determines the beginning of the current increase. The difference between beginning current decrease and beginning current increase is called current flow angle. The current desired value forms the amplitude of the current impulse.
Switching mode means that the power is brought to the final value after the turn-on angle and without interim pulses.
A two-step controller ist used to keep the phase-winding current on the final desired value until the current flow angle has been reached, afterwards it is switched off again without interim pulses. This method of controlling the torque can be realized easily, even without using a digital processor.
The optimal parameters of the torque control were determined off-line and were afterwards implemented in the system.
When the output power increases, the current turn-on angle is continuously pre-drawn while the turn-off angle changes insignificantly only. The current amplitude increases linearily to the torque starting at 20 Nm.
This procedure yielded a torque ripple of less than 4% in the nominal point whithout effects at the speed.

SPEED CONTROL

The control has been optimized to minimize speed variations. The speed controller is a PI-controller.

The control parameters were adjusted according to the symmetric optimum [4]. Torque and current control are united in the speed control to a delay part of first order with a small time constant. The actual speed is determined by a position encoder located at the machine. For this purpose the encoded position is differenciated and afterwards transmitted to the setpoint/actual-value comparison via a smoothing filter. Rapid changes of the desired speed must not be intruded directly into the setpoint/actual-value comparison. This requires a ramp-function generator. It transforms the jump of the desired value into a suitable ramp for the speed control. The output of the ramp-function generators increases slowly, reaches the ramp profile after a short time and drives to the end value smoothly afterwards.
This function is intruded into the setpoint/actual-value comparison as desired value. It is remarkable that the measurement value reaches the final value earlier than the output of the ramp-function generator does.

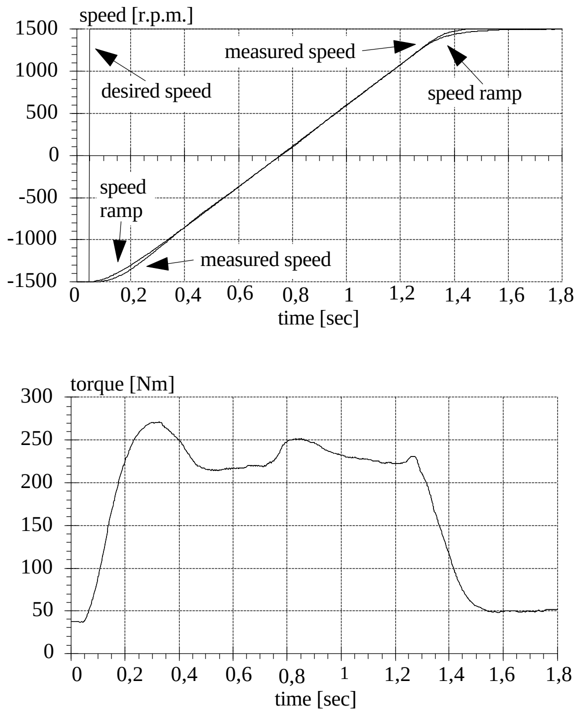

Figure 6: Speed control (measurement)
$M_{load} \cong 50$ Nm, $J_{all} = 0,54$ kgm^2

Figure 6 shows the reversing process from negative to positive nominal speed with a load torque of approx. 50 Nm and an accellerating torque of approx. 200 Nm. After the zero crossing of the torque, it rises a little bit, the brush friction of the d.c. machine that is coupled as working machine must be overcome.
After this desired value jump of the speed, the measured speed does not swing over.

POSITION CONTROL

Likewise, the position control of, for example, workpieces, tools, conveyor baskets etc. belongs to the applications of electric motors. The measuring result in Figure 7 proves that Switched Reluctance Motors with 16 stator poles and 12 rotor teeth are suitable position drives. After a desired value jump of 1000°, the motor performs about 2,8 turns and reaches the desired value without over-swing in one second.
An optimized position controller determines this transient response. It is superposed on the speed control circuit and has a proportional character. It can be dimensioned according to the usual adjustment regulations of other drives. The cascade structure was selected for the complete control circuit which is composed of current, torque and position control.

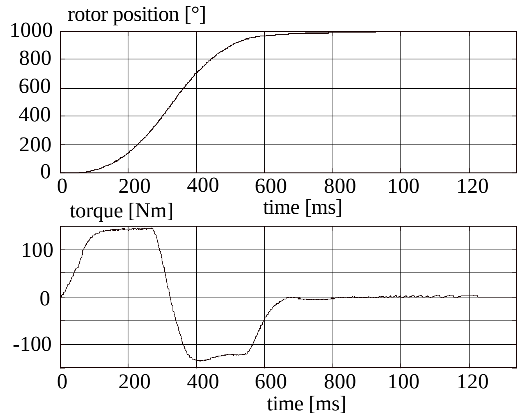

Figure 7: Position control (measurement)
$J_{all} = 0,54$ kgm^2

UTILIZATION

Altogehter three Switched Reluctance Motors were measured. Size and measures of these SR Motors are identical with each other. Only the quality of the used electric sheet steel and cooling method vary. Used sheet steel types include a 0,5 mm slightly alloyed respectively a 0,35 mm and highly alloyed magnetic sheet steel.
Two motors were built for continuous running duty. Cooling is obtained using an external blower, which blows air over the machine (cooling method IC416). The degree of protection is IP54. The third motor was built for continuous running duty with cooling method IC06 and protection degree of IP23. The cooling air for this motor is additionally blown through the tooth spaces of the rotor. This allows a better dissipation of the winding and rotor heat - thus increasing the maximum admissible continuous power.
The iron losses of switched reluctance motors, unlike those of asynchronous motors, make up a considerable portion of the total losses. However, the iron losses drop heavily as the speed is reduced . This effect is made use of to increase the rms currents in the pole

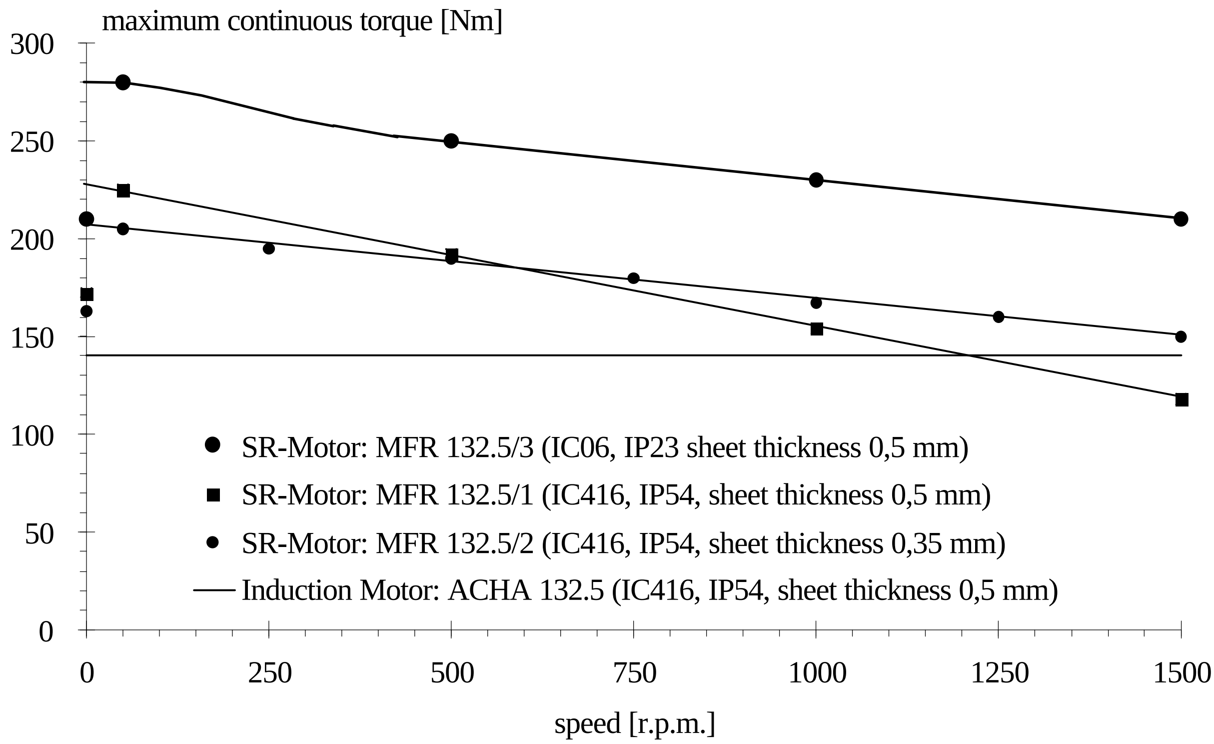

Figure 8: Maximum permissible continuous torque in the speed range from standstill to nominal speed (thermal/isolation class F, continuous running duty)

windings and obtain a high permissible continuous torque in the lower speed range. Moreover, operating the machine at low speeds results in low rotor iron losses - consequently, the rotor temperature rise remains low. In asynchronous motors, the stator and rotor winding losses make up the largest portion of total losses which remain almost constant from standstill to rated speed if the torque is assumed to be constant. This explains why asynchronous motors, when operated in continuous duty, must not be subjected to a torque higher than the nominal torque until the rated speed ist reached. Field weakening operation begins for all motor types when the rated speed is exceeded.

In Figure 8, the maximum permissible continuous torque is shown in the speed range from 0 to 1500 r.p.m. for the use of thermal and isolation class F.

For the used measurement methods with integrated temperature sensor, the temperature difference between winding and coolant temperature must not exceed 110 Kelvin.

The measurements were spot-checked with the resistance method. The measured temperatures ranged between 1 and 2 Kelvin below the maximum permissible value.

In continuous duty, the maximum permissible holding torque of the SR-Motor MFR 132.5/1 amounts to 145% of the rated torque when the motor is at rest. As soon as the rotor starts to rotate, however, all pole windings are subjected to the same thermal loads, and the continuous torque may be 190% of the rated torque at low speeds. For dynamic transient processes in the base speed range, the motors may be subjected to two to three times the rated torque.

Furthermore Figure 8 shows that using a thinner and highly alloyed magnetic sheet metal, is not always useful. Only for higher speeds the reduction of the eddy-current losses is decisive.

Below 600 r.p.m. the thicker sheet metal offers advantages: better magnetizability, higher thermal conductivity, better lamination factor and less punching works.

At nominal working point, the efficiency of the switched reluctance motor is that common for a three-phase induction motor of this performance class. In lower speed range, however, the efficiency of the reluctance motor drops insignificantly. With the motor at nominal torque, the efficiency raises to above 80% as from 400 r.p.m., and gradually increases further to approx. 90% until rated speed is reached (Figure 9).

Switched Reluctance Motors basically have a very efficient operation at partial stress.

The overall power efficiency of the test power converter is 91 % in the nominal working point.

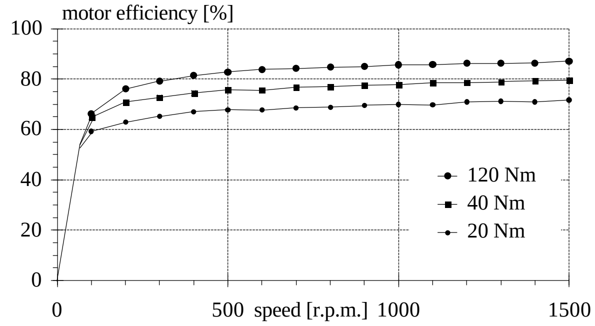

Figure 9: Efficiency of the Switched Reluctance Motor MFR 132.5/1

Table 1 compares constructive data of the Switched Reluctance Motor MFR132.5/1 and of the three-phase induction motor ACHA 132.5. Construction and function of both motors with these air gaps is not a problem. The production costs are the same.

	Switched Reluctance Machine	**Three-phase Induction Machine**
manufacturer	Elbtalwerk Heidenau GmbH	
motor type	MFR 132.5/1	ACHA 132.5
rated output power	18,5 kW	22 kW
nominal torque	118 Nm	140 Nm
nominal speed	1500 r.p.m	1500 r.p.m.
output at 1000 r.p.m	16 kW	14,7 kW
output at 500 r.p.m	10 kW	7,3 kW
moment of inertia	0,0883 kgm^2	0,105 kgm^2
<u>lamination stack:</u>		
quality	V 470-50A	
losses at 50 Hz and 1,5 T	4,7 W per kg	
sheet thickness	0,5 mm	
length of lamination stack	235 mm	
outside width of stator	ÿ 260 mm	
inside diameter of stator	∅ 165 mm	
width of air gap	0,3 mm	0,55 mm
shaft bore diameter	∅ 65 mm	
weigth befor punching	118,7 kg	
weight of stator stack	54,0 kg	56,1 kg
weight of rotor stack	24,2 kg	21,9 kg
<u>windings:</u>		
weigth of stator windings	13,3 kg copper	14,2 kg copper
copper fill factor	55,4 %	56,8 %
length of winding overhang	2 x 22 mm	2 x 70 mm
weigth of rotor winding	without winding	4,8 kg aluminium
<u>utilization at nominal point:</u>		
power/volume ratio	981 W/dm^3	868 W/dm^3
power/weigth ratio	202 W/kg	227 W/kg
<u>compare conditions:</u>		
shaft heigh	132 mm	
duty type	continuous running duty (S1)	
thermal/isolation class	F	
protection degree	IP 54	
cooling method	IC416	
cooling fan power	65 W	

Table 1: Comparision of material and utilization

ADVANTAGES - APPLICATIONS

When comparing the data listed in table 1, some advantages but also disadvantages become evident. Advantages of the three-phase induction machine are the low noise level and an already widely spread technique with high availability. The reluctance drive offers a better accelleration and production costs are lower.

The Switched Reluctance Motor ist characterized by a high operating safety after the failure of one or several motor phases. When such a failure occurs, the motor continues to run under load, and it can be accelerated or braked. However, the torque and speed fluctuations occurring are of a measurable magnitute, and the start-up of the motor is no longer ensured. Despite this drawback, the driven machine, or process under way, can be set back into safe state in many applications.

For judging the ratio power per volume respectively power per mass, the following can be assessed for 1500 r.p.m.:

The active part of the Switched Reluctance Mortor is, compared with the three-phase induction motor with the same nominal power, about 10% smaller and 10% heavier.

If the thin magnetic sheet steel is used for the SR-Motor, production costs rise, the active part of the SR Motor becomes 30% smaller and 10% lighter. (For this assess the magnetic sheet steel and the windings were considered as active part.) For a speed range of about 1500 r.p.m. the Switched Reluctance Drive can offer advantages for certain applications.

Considering the speed range below 1000 r.p.m. or the MFR 132.5/3 machine with inner ventilation, the Switched Reluctance Drive is more suitable for many applacations compared with other drive types.

At 50 r.p.m the machine with the inner ventilation can be stressed with a permanent torque of 280 Nm. The rotor heating is very low, the temperature rise of the bearing does not exceed 35 K for the overall base speed of up to 1500 r.p.m.

At 500 r.p.m., the MFR 132.5/1 machine with surface ventilation has a continuous rating of 10 kW - 37% more than the comparable three-phase induction machine.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Lovatt, H.C.; Stephenson, J.M.: Influence of number of poles per phase in switched reluctance motors. Proc. IEE, 139, No. 4, 1992, p. 307-314

[2] Steiert, U.: Drehmomentsteuerung einer Reluktanzmaschine mit beidseitig ausgeprägten Polen und geringer Drehmomentwelligkeit. Dissertation Universität Karlsruhe, 1992

[3] Späth, H.; Wolff, J.: Der elektrische Antrieb der Zukunft? TECNICA, No. 19, 1996, p. 49-53

[4] Meyer, M.: Elektrische Antriebstechnik. Vol. 2 Springer, Berlin 1987