Motoring ahead

Synchronous motors controlled by variable-speed drives are bringing higher efficiencies to industrial applications

HEINZ LENDENMANN, REZA R. MOGHADDAM, ARI TAMMI, LARS-ERIK THAND – Electric motors in industrial applications account for approximately 60 – 65 percent of consumed industrial electricity. Using energy effectively by increasing motor efficiency is at the center of continued motor optimization. Major energy savings are also gained through the use of variable speed drive systems and today this technology is adopted in as many as 30 – 40 percent of all newly installed motors. Sustainable use and investment also demands increased reliability and lifetime of a motor. The streamlined rotor structure of ABB's synchronous reluctance motors eliminates rotor cage losses therefore increasing efficiency and compactness. The possibility of achieving standard power and torque levels at merely a low class-A temperature rise (60 K) improves the lifetime of the motor insulation, and lengthens the bearing lifetime or greasing intervals.

The possibility of high speed operation helps to eliminate mechanical power transmission elements such as gearboxes.

Electric motors are used in a wide range of industrial applications. What most applications have in common is the need for their motor to be as efficient as possible and to have the longest possible lifetime while simultaneously not increasing maintenance demands or failures. ABB's synchronous reluctance motors are physically smaller in size, helping machine builders to design smaller, lighter, and more efficient equipment. Additionally, the possibility of high speed operation helps to eliminate mechanical power transmission elements such as gearboxes. This eventually enables the integration of the motor and the load equipment which is an increasingly common request.

To answer the need for a motor that is more efficient, smaller, with a long lifetime and low maintenance needs with a new motor type, which would also be perfectly adapted to variable speed drive (VSD) operation, ABB radically rethought all technology options. Starting a VSD motor is very different compared to the direct line connection start. This, and other changes in boundary conditions, highlighted potential opportunities to simplify the motor design and improve efficiency. One well known approach is the utilization of synchronous motors (SM). SMs with a 4-pole rotor operated at 50 Hz rotate in synchronism with the supply at exactly 1500 rpm. The corresponding induction motor (IM) however, has slip losses and rotates only at 1475 rpm for a chosen 30 kW example. In modern IMs with a short circuit rotor cage, the losses associated with the rotor amount to 20 – 35 percent of the total motor losses. Synchronous rotation eliminates most of these associated losses.

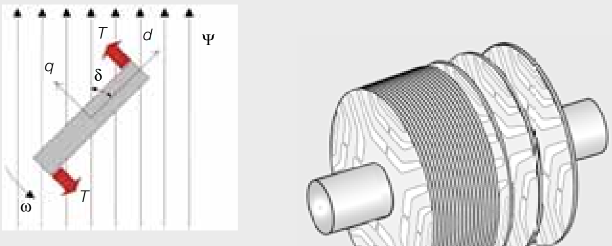
The elimination of these slip losses leads to an efficiency increase of about ~0.6 percent (220 kW motor) to 8 percent (3 kW), as well as a 20 – 40 percent increase in power and torque density for the same insulation temperature class.

Synchronous motors come in different variants: as field wound with brushless exciters; as permanent magnet (PM) motors; or as motors based on the principle of magnetic reluctance (often called a synchronous reluctance motor or SynRM). A SynRM rotor has neither a conducting short circuit cage as with the IM, nor permanent magnets, nor a field excitation winding. Instead, the magnetic principle of reluctance is utilized.

The synchronous reluctance motor

Magnetic reluctance is the magnetic equivalent of the resistance in electrical circuits. The rotor consists of one direction of least possible magnetic resistance (d) and a perpendicular direction (q) with a high magnetic reluctance or good magnetic "insulation" → 1. Torque is produced, as the rotor attempts to align the

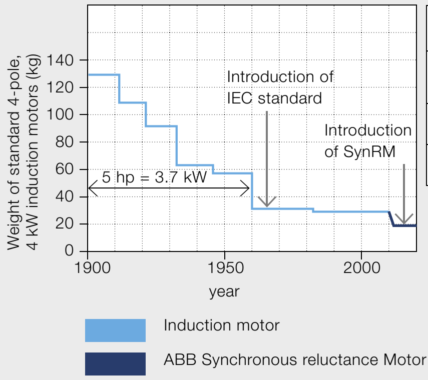
1 Synchronous reluctance rotor and torque principle



$$T = \frac{3}{2} P_p \left(\frac{1}{L_q} - \frac{1}{L_d}\right) \Psi^2 \sin(2\delta)$$

P_p = Pole pairs of the motor

2 Innovation timeline in LV motors



size	Induction motor	SynRM	Out-put
100	3.3kW η=83%	4.3kW η=90%	+30-45%
160	22kW	29kW	+32%
280	90kW	110kW	+22%

Technology comparison measured ratings

magnetically conducting direction to the stator field. The strength of the produced torque is directly related to the saliency ratio, ie the inductance ratio between the two magnetic directions of the rotor.

The invention of the synchronous reluctance motor concept dates back to 1923. However, the motor type was not industrially adapted primarily due to the lack of a direct online starting capability. Now, with the use of variable speed controllers, this obstacle has been removed → 2.

In 1982 NdFeB based permanent magnet materials were discovered. The resulting new permanent magnet (PM) motor technology was adapted for servomotors and is now emerging in many industrial specialty applications, such as gearless low-speed torque motors [1]. Again, less attention was paid to the unpretentious SynRM.

In addition, not all earlier published work on SynRM succeeded in demonstrating superior torque performance or reaching higher efficiency than the IM, as was expected from the calculations: a fact cited by experts and academics as to why the SynRM is not used more often today. Presumably these early results were due to less optimized converter control. Indeed some publications show very promising results, and have addressed the electromagnetic design aspects in great depth [2], [3]. It is important to note the contrast of the SynRM to the switched reluctance, or stepper motor, with an entirely different stator, winding concept, and non-sinusoidal current waves; a motor often considered unsuitable for industrial use, due to high noise. A cited disadvantage of the SynRM is a higher current need for the same torque compared to the PM motor, since the rotor must be magnetized through the stator. However, the power factor as seen from the network is determined by the power converter and is near unity in all operating modes, even for the SynRM.

The industrial motor for VSD systems

In ABB's SynRM rotor designs and drive control, the motor current, proportional to the inverse of power factor and efficiency, ($\propto 1/(\eta^*\cos(\rho))$) is actually lower than for a small size induction machine at the same torque and speed. This is primarily due to the significant gain in efficiency. Only for large motors is the converter current higher than with an IM at the same torque. In general, the ABB SynRM operates with the same frame size for the drive (e.g. ACS850) as the IM at the same power and torque level, albeit at the increased power density and higher efficiency than the IM. The motor efficiency increase translates to a nearly identical energy saving at the drive system level.

One other key advantage of ABB's SynRM is the plain rotor structure. Without magnets and without cage, the rotor construction is more robust than either IM or PM machines. In addition, no risk of permanent loss of performance exists due to potential demagnetization in case of failure or overheating situations. The motor is inherently safe in operation since, without magnets, no back-EMF voltage is induced, and over-voltage protection of the converter becomes superfluous. Finally, rare earth materials for permanent magnets are relatively expensive and may be in limited supply for some markets, due to geographic concentration of the common raw materials suppliers.

Elimination of most of the rotor losses, and the streamlined rotor structure, results in a number of benefits for this motor and its connected load equipment → 3. A motor with this technology can be operated at the IEC standardized power level for the given frame size. In this case, the VSD efficiency gain ranges from more than 5 percent units for single kW machines to about 0.5 percent for the largest motors (frame 315). Consequently, where an IM would have run at class-F temperature rise (105 K), the ABB SynRM operates merely at class-A temperature rise (60 K) → 4. In comparison for a specific compressor at 4500 rpm, the associated ABB SynRM features still lower bearing temperatures when run at true class-H rise (125 K), than the larger IM run at class-F rise (105 K). The motor was thus also called a "CoolMotor" → 5. This low temperature operation improves the lifetime of the motor insulation, and lengthens the bearing lifetime or greasing intervals. Motor bearings in particular require regular servicing and according to some

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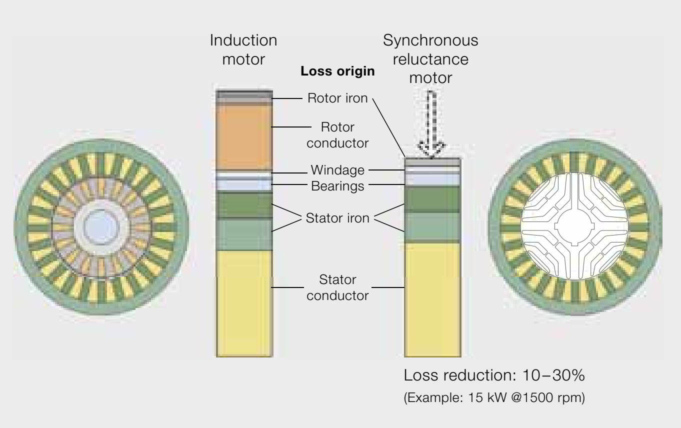
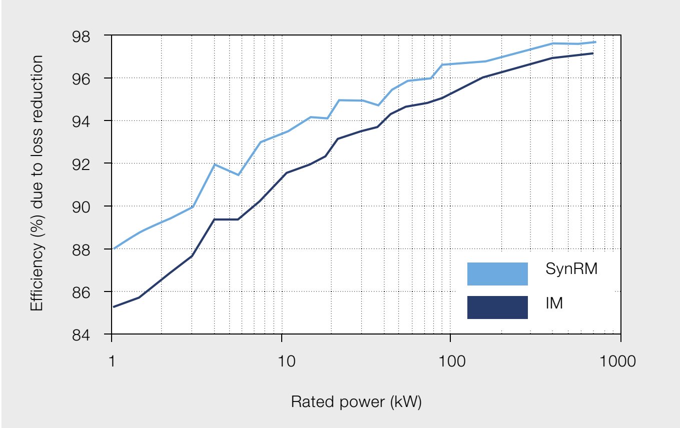




studies bearing failure is the root cause of approximately 70 percent of all unplanned motor outages. The lower bearing temperature directly translates into longer greasing intervals, reduced maintenance and higher reliability. Even if a bearing eventually needs replacing, having no magnetic forces, unlike a PM motor, the bearing change is as easy as for an IM.

The technology enables good torque utilization at higher speeds. In another utilization of this technology, the operation is maintained at the conventional temperature often B- or F-class. Since losses on the rotor are arduous to cool, compared to stator losses, its near elimination has a particularly high impact on the torque performance. For small motors at 3 or 4kW level, as much as 60 percent more power can be obtained for the same temperature rise. For a 60 kW motor the gain is in the 40 percent range and for a 220 kW motor in the 20 percent range compared to an IM. In most cases, the same power can be obtained from a motor by one, or sometimes two, frame sizes smaller than an IM. The reduction of the footprint is appreciable for all applications that can utilize lower frame heights and smaller motors. An additional gain is the reduced heat load on nearby parts, particularly in closed cabinets. Even at this vastly increased power density, a further important advantage results from the removal of the losses on the rotor side: since much of the heat conduction through the shaft is eliminated, the bearing temperature, particularly on the drive-end, is reduced. Comparing an ABB SynRM with an IM at 6 kW, this can be as much as a 30 K reduction, with an approximately 15 to 20 K reduction typical over the entire range. This effect is particularly pronounced at higher speeds, as well as for operation at higher temperature classes. The generally high efficiency is maintained even at this high output. Furthermore, the ABB SynRM has the excellent partial load efficiency curve which is typical of synchronous machines, ie the efficiency remains high even at partial load, a feature particularly appreciated in VSD drives for fans and pumps.

Finally, these rotors feature about 30 – 50 % percent reduced inertia due to the lack of cage and magnets. In highly dynamic applications such as cranes, this reduction implies further benefits in energy efficiency as well as faster lift cycles due to higher speed ramp rates.

Rotor construction and reliability

Most technical aspects of drive systems with ABB's SynRMs are directly based on existing technology. The housing, connection box, stator, winding design and technology, and bearing options are identical to IMs. As the 3-phase currents are sinusoidal, the same drive products can control this motor type, provided the firmware is optimized and includes this motor type. Only the rotor is different.

The rotor is less complex than in both IM and PM. Laminated electrical steel sheets are fitted to the shaft. Instead, the complexity, is in the design. Extensive finite element simulations (FEM) were used to design the cross-section carefully, in terms of electrical and mechanical properties. Important design choices are the number of magnetic segments and the exact shape of the air barriers. This determines the torque production and the magnetization current of the motor. Minimizing this reactive current was

The low temperature operation improves the lifetime of the motor insulation, and extends the bearing lifetime or greasing intervals.

crucial to maintain a favorable drive rating. The exact placement of the segments along the periphery is essential to create smooth torque during rotation, keeping the motor noise as low as in conventional motors. One result of this complex optimization using FEM, analytical and genetic algorithms, was that a 4-pole configuration is most suitable for the entire speed range up to 6000 rpm.

To verify the reliability of this new rotor, extensive motor and drive system testing was conducted throughout development (see title picture, pages 56–57). Drive conditions of pumps, fans, compressors, and mining and crane applications were emulated using methods for highly accelerated stress testing (HAST). HAST cycles were developed specifically for this motor to ensure robust lifetime performance. For example, one successful experiment conducted at high repetition rate motor starts and stops into speeds above catalog permitted values. The cycle count and overload conditions were dimensioned to correspond to more than a 20 year lifetime of rated operation.

Drive converter and control

Conventional ABB drive technology used for IM and PM motors, with standard direct torque control (DTC), was adapted to include the SynRM as a new motor type. Despite sharing many similarities with the PM motor, except for zero rotor flux, strong development focus was given to optimizing the torque production through maximum torque per Ampere (MTPA) control. This ensures that the drive current is kept minimal in each operating point. The control also includes capabilities for the field weakening range, ie the speed range above the nominal rated speed. A maximal rated speed of as much as 1.5x nominal can be reached for much of the motor range. This drive control is a particularly important ABB result which enables this SynRM to reach appreciably higher torque densities than IMs.

The installation and operation of the power electronic drive for this motor is indistinguishable from driving VSDs with IM or PM motors. Standard features include automatic parameter identification based on name plate values and sensorless operation. The motor does not need any speed sensors but nevertheless can maintain perfect speed

4 Temperature classes

Ambient temperature is the temperature of the air surrounding the motor. This is the threshold point or temperature the motor assumes when shut off and completely cool.

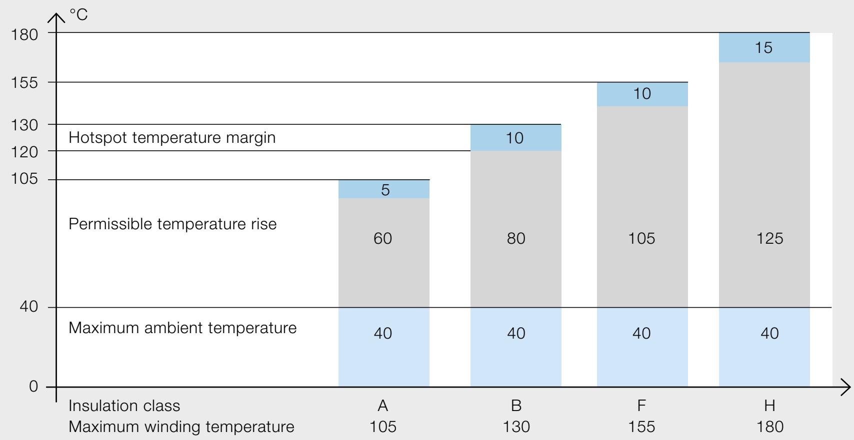
Temperature rise is the change within a motor when operating at full load. The difference between the motor's starting temperature and its final elevated temperature is the motor's temperature rise.

The standard method of measuring temperature rise involves taking the difference between the cold and hot ohmic resistance of the winding. This averages the temperature change of the whole winding, including the motor leads, end turns, and wire deep inside the stator slots. Since some of these spots are hotter than others, an allowance factor uses the average temperature to indicate what the temperature probably is at the hottest spot. This is known as the "hot spot" allowance.

Insulation classes group insulations by their resistance to thermal aging and failure. The four common insulation classes are designated as A, B, F, or H. The temperature capability of each class is the maximum temperature at which the insulation can operate to give an average life of 20,000 hr.

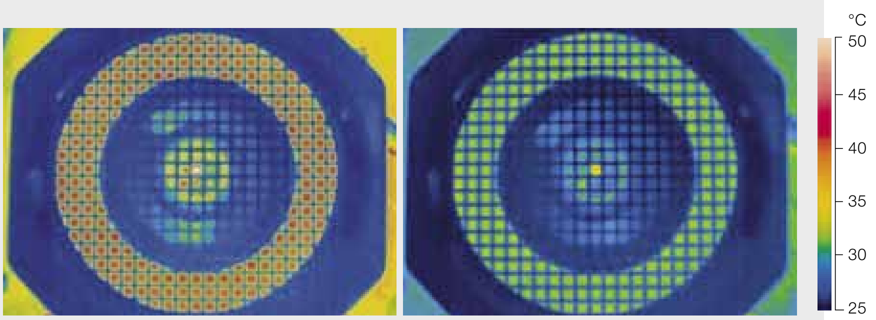
Operating a motor at a lower temperature rise than allowed by the insulation class can change the motor's thermal capacity, allowing it to handle higher than normal ambient temperatures. In doing so, the motor's life is extended.

The graph below shows the temperature ratings, temperature rise allowances and hot spot allowances for various enclosures of standard motors.



Drive conditions of pumps, fans, compressors, and mining and crane applications were emulated using methods for highly accelerated stress testing (HAST).

5 Temperature scans from a thermal imaging camera



Induction rotor

Synchronous reluctance rotor

6 Performance of motor drive system for piloting

The performances of the new motor drive system are given for three IEC motor frame sizes.

Motor, temperature rise class F								Drive, 400 V				
Size mm	PN kW	nN r/min	PN kW	nmax r/min	Eff %(1/1)	TN Nm	MM kg	Type code ACS-850-04	IN A	Noise dBA	Frame size	MD kg
100	4	1500	4	2250	84.3	25	22	010A-5	10.5	39	B	5
100	7.5	3000	7.5	4500	88.7	23	22	018A-5	18	39	B	5
100	13	4500	13	6000	90.5	27	22	030A-5	30	63	C	16
100	17.5	6000	17.5	6000	91.3	27	22	044A-5	44	71	C	16
160	26	1500	26	2250	91.7	165	180	061A-5	61	70	D	23
160	50	3000	50	4500	94.0	159	180	144A-5	144	65	E0	35
160	70	4500	70	5300	94.6	148	180	166A-5	166	65	E	67
280	110	1500	110	1800	96.0	700	640	260A-5	260	65	E	67
280	130	1800	130	2200	95.9	689	640	290A-5	290	65	E	67

For full specifications check ABB web pages at www.abb.com/motors&generators

accuracy, as well as a high torque dynamic. The drive can even be dimensioned for specially requested overload and cycle load capability.

An additional gain is the reduced heat load on nearby parts, particularly in closed cabinets.

Performance preview

Since this motor, like the PM motor, always requires a VSD drive, matched pairs of motor and ACS drives are given as the standard recommendation for a range of power and speed levels → 6.

As a response to the key market trends of higher output, higher efficiency, longer service intervals, and footprint reduction, a radical new motor uniquely suited for VSD systems is now available. Increased power density by 20 – 40 percent when compared to an IM, with a rotor construction without short circuit cage nor permanent magnets, featuring smaller motors, with less heat generation, and highest efficiency for VSD systems is being achieved. A standard IM fitted with a new rotor, combined with a standard drive with new software, results in a high output, high efficiency VSD system. The output and efficiency performance is comparable to a PM motor drive, but using technologies associated with the robust induction motor, bring the best of both worlds to users, and with additional benefits as a bonus.

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Title picture

The motor and drive system undergoing highly accelerated stress testing (HAST)