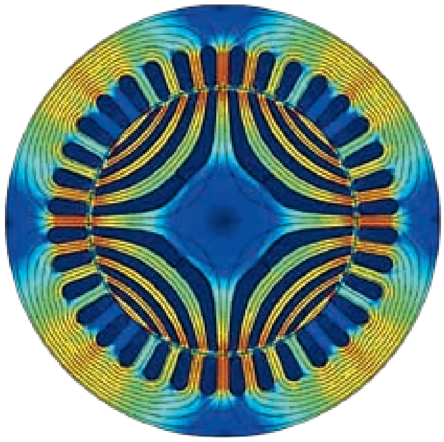
Driving force

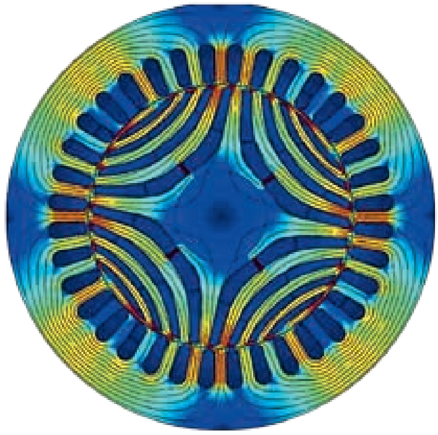
Rare-earth-free electric motors with ultrahigh efficiencies deliver sustainable and reliable solutions

FREDDY GYLLENSTEN, PETER ISBERG, ALESSANDRO CASTAGNINI, GIULIO SECONDO, JOUNI IKÄHEIMO, ARI TAMMI – Highly efficient electric motors in industrial applications often use permanent magnets containing rare earth elements (REEs) such as neodymium and dysprosium. These elements are subject to price variations due to changing market demands. Now, thanks to recent developments in variable-speed drive (VSD) motor technologies, there are alternative high-performance motors that are free of REEs. One is the synchronous reluctance motor (SynRM), characterized by being very energy efficient, reliable in operation and exceptionally easy to maintain. Another is the ferrite-assisted synchronous reluctance motor (SynRM^2), which is more energy-efficient and more powerful than the SynRM.

1 SynRM principle: The rotor will create torque whenever there is a magnetic field present in the air gap that is not aligned with the rotor.



1a The rotor is aligned with the magnetic field, so no torque is produced.



1b The rotor is not aligned with the magnetic field, and (counter-clockwise) torque is produced.

Although introduced over a century ago, electric motors continue to experience bursts of innovation and recent years have seen remarkable progress in electric motor efficiency improvements.

Since electric motors are involved in a significant fraction of energy conversion – 28 to 30 percent of all electrical energy is converted to mechanical energy in electric motors – special attention is devoted to their efficiency and all industrialized regions have minimum efficiency performance standards (MEPS) for them. In order to further reduce industry's energy consumption and CO_2 emissions, regional legislation sometimes sets a higher minimum level. Soon, all industrial regions will adopt the so-called IE3 classification level as the minimum requirement for almost the full power range of direct-online (DOL) low-voltage electric motors (0.12 to 1,000 kW, 50 to 1,000 V). Similar requirements for VSD motors are undefined today, but are expected in the near future.

Title picture
ABB's new SynRM and SynRM[2] represent a major step forward in sustainable electric motor technology in terms of efficiency and power density. Shown is SynRM's unique rotor.

Induction motors

The induction motor (IM) is by far the most common in industry. This powerful and efficient motor does not have a commutator or brushes, which makes it reliable and relatively maintenance-free. It is continuously under development to make it more efficient.

Despite universal use, IMs have some inherent drawbacks caused by their asynchronous speed, which results in conductor losses in the rotor that negatively affect efficiency, generate more heat and result in warmer bearings with a consequently shorter lifetime.

Permanent magnet motors

Although long known, permanent magnet (PM) AC motors really only became competitors to IMs in the 1980s with the creation of a new generation of permanent magnets based on materials such as neodymium iron boron (NdFeB), which was developed independently by General Motors and Sumitomo Special Metals in 1982. A prerequisite for the introduction of these new magnets into motors was the parallel advancement of the AC drives that were needed to control and operate the motors.

> Twenty-eight to 30 percent of all electrical energy is converted to mechanical energy in electric motors.

PM motors have magnets mounted on the surface of, or embedded into, the rotor. Further, unlike the asynchronous induction motor, where the rotor "slips" – ie, has a lower rotational frequency than the magnetic field driving it – the PM motor is synchronous, meaning the rotor rotates in synchronism with the magnetic field. This offers more precise speed control, higher efficiency and lower rotor/bearing temperature. PM motors eliminate rotor conductor losses, have lower conductor losses or Joule losses in the stator (mainly due to lower current), and exhibit a flatter efficiency curve. They also run cooler than IMs, resulting in longer insulation and bearing lifetimes. Also, PM motors give more torque for the same size of package, or the same torque in a smaller package.

However, the use of rare-earth elements (REEs), such as neodymium and dysprosium, has certain drawbacks. REEs are costly and can be subject to price variations. In addition, their strong magnetic rotor field can make servicing – a key feature of a mainstream industrial motor – more difficult.

2 IEC 60034-30-1

The IEC 60034-30-1 standard defines minimum limits for different efficiency classes for line-operated motors – ie, induction motors and motors with line-starting capabilities, like line-starting PMs (that have cages like the IM for allowing starting) [2]. The complication when trying to define the efficiency of SynRMs and other pure VSD-operated concepts is that no efficiency standards currently exist for these motors. But standardization work is ongoing and a future IEC 60034-30-2 will include these types of motors. The efficiency class definition of the ABB SynRMs has, therefore, used the limit values from IEC 60034-30-1, even though the SynRMs have been operated with a VSD during classification testing. Operating with a VSD will always give rise to higher motor losses for the same working point, compared with sinusoidal operation as is the case for line operation, since the VSD induces high harmonic voltages to the motor caused by pulse-width modulation (PWM) switching, with associated higher losses in the motor. The efficiencies claimed for SynRM are, therefore, conservative.

3 ABB's SynRMs won the Automation Award at the 2011 SPS Fair in Germany. Pictured is synchronous reluctance motor and ACS880 drive package.

The lower operating temperature of a SynRM has multiple benefits – including longer insulation life, and longer bearing greasing intervals or lifetime.

Applications and customers that currently favor PM motors may look for alternatives in the future, depending on price and market developments.

REE-free motors

A future economically and ecologically sustainable solution may lie in REE-free motors. ABB has now introduced two such motors, which are aimed at providing very high efficiency, high power density and freedom from the complications surrounding REE materials. These motors are the synchronous reluctance motor (SynRM) and the permanent-magnet-assisted synchronous reluctance motor (SynRM^2), which uses ferrite magnets.

Synchronous reluctance motors for VSD applications

SynRMs work on a very elegant principle that has been known for a long time, but only since the recent rise of sophisticated VSD control electronics did it become possible to fully exploit these super-efficient electrical machines. In SynRMs, the rotor is designed to produce the smallest possible magnetic reluctance (the resistance to the flow of a magnetic field) in one direction and the highest in the direction perpendicular → 1. The rotor turns at the same frequency as the stator field (as in the PM motor). Introduced at the Hanover Fair in 2011 (incidentally, the SynRM won the Automation Award at the SPS Fair in Germany the same year) ABB's first SynRMs were designed exclusively for variable-speed operation.

SynRMs perform better than conventional IMs. They can be designed for high-efficiency performance or to provide a higher power density for a smaller footprint than an equivalent IM. They need less maintenance, have a reduced inertia and are extremely reliable.

Without magnets and without a cage, the rotor construction is simpler than either IMs or PM motors.

The lower operating temperature of a SynRM has multiple benefits – including longer insulation life, and longer bearing greasing intervals or lifetime (bearing failure is a major cause of motor outage).

ABB's SynRM hardware is identical to that of ABB's equivalent IMs. Only the rotor is different. This simplifies spare-part provision and maintenance. It also means that replacing an existing IM with a SynRM is easy.

Recent advances in the efficiency of ABB SynRMs has been so rapid that existing IE efficiency classifications have been

4 IE5 SynRM² concept motor and rotors pictured with an ACS880 drive.

SynRM motors work on a long-known and very elegant principle – but only since the recent rise of sophisticated VSD control electronics have these super-efficient electrical machines been fully exploited.

outstripped → 2. While the EU requires IE3 as a minimum, ABB already has a catalog of IE4 SynRMs. The potential of SynRMs has not been fully explored and higher efficiency levels are quite feasible.

It is important to note that only DOL motors have been classified as to their efficiency; VSD motors have not. So, when ABB VSD motors now undergo "classification," they do so in the frame of reference used for DOL motors, which does not properly reflect VSD operation – for instance, the excellent performance of VSD systems at partial load and the harmonic losses that are significantly lower than those of IMs under VSD operation.

Two SynRM ranges are available: IE4 SynRM (5.5 to 315 kW) and compact high output SynRM (1.1 to 350 kW). These currently come in several motor/drive packages → 3–4:

– IE4 SynRM and ACS880 for industrial users and end users
– IE4/HO SynRM and ACS850 for machine builders and original equipment manufacturers (OEMs)
– IE4 SynRM and ACQ810 for the water and wastewater segments
– IE4/HO SynRM and ACH580 for heating, ventilation and air-conditioning (HVAC) applications

An expansion to the SynRM product palette – SynRM² – was introduced in 2014 when the 15 kW model was displayed in Hanover as the first ABB demonstrator of an IE5-enabling technology.

As mentioned above, efficiency is becoming a critical issue for manufacturers of motors and motor systems: The trend in the EU, United States and Asia is in the direction of further legislation – not only for motors, but for the system in which they are embedded. This is why ABB is a step ahead – with SynRM² technology.

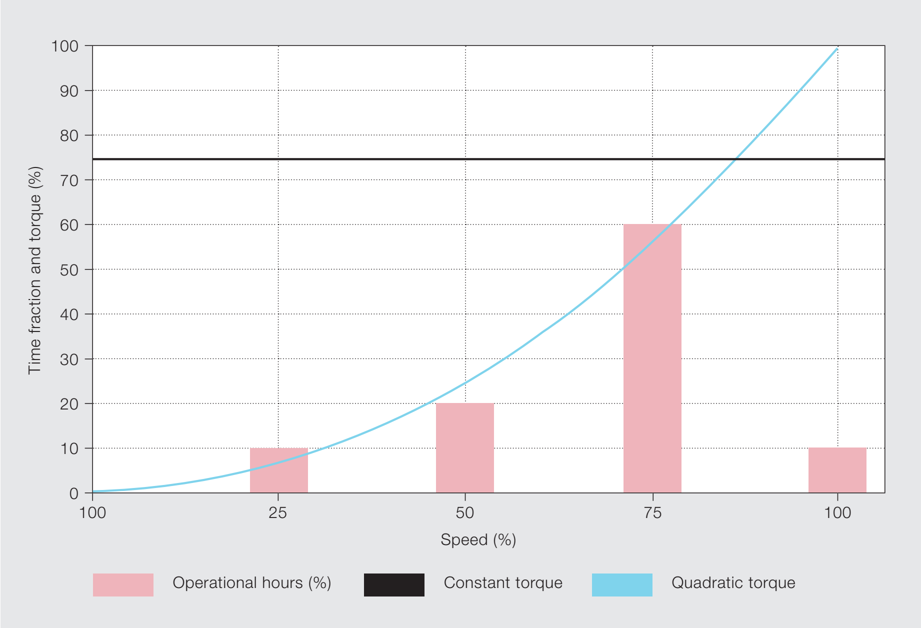
SynRMs can be designed for high-efficiency performance or to provide a higher power density for a smaller footprint than an equivalent IM motor.

5 Comparison of IM, SynRM and SynRM² of different IE classes

Efficiency class[2]	IE2	IE3	IE4	IE5[3]
Motor data[1] (from tests in frequency converter operation)				
ABB product	M3BP (160)	M3BP (160)	M3BL (160)	N.A. (160)
Type	IM	IM	SynRM	SynRM²
Output power (kW)	15	15	15	15
Speed (r/min)	1,500	1,500	1,500	1,500
Voltage (V)	380	380	380	380
Current (A)[4]	29.9	29.5	31.5	25.2
Power factor (–)	0.845	0.838	0.763	0.949
Efficiency (%)	90.6	92.2	94.7	95.2
Converter data (network voltage 400 V)				
ABB converter product in tests	ACS850-035A	ACS850-035A	ACS850-035A	ACS880-087A
Suggested ABB converter for end users	ACS880-032A	ACS880-032A	ACS880-032A	ACS880-032A
Control type	DTC	DTC	DTC	DTC
Comparison cases with IE2 motor and drive system as reference				
Constant torque (75 %) duty (with 8,585 hours of annual operation in duty cycle according to graph)				
Annually consumed electricity (kWh)	74,846	73,536	71,924	70,745
Annual electricity savings (kWh)[5]	0	1,310	2,922	4,100
Annual electricity cost savings ($)	0	210	470	658
Average output power (kW)	7.6	7.6	7.6	7.6
Average system efficiency (%)	87.1	88.7	90.6	92.2
Payback time (months)	–	< 10	< 10	< 11
Quadratic torque duty (with 8,585 hours of annual operation in duty cycle according to graph)				
Annually consumed electricity (kWh)	56,386	55,335	54,089	53,275
Annual electricity savings (kWh)	0	1,050	2,296	3,110
Annual electricity cost savings ($)[5]	0	168	368	500
Average output power (kW)	5.7	5.7	5.7	5.7
Average system efficiency (%)	86.7	88.4	90.4	91.8
Payback time (months)	–	< 12	< 13	< 15

1 Motor data from tests at nominal working point.
2 Minimum efficiency limits according to IEC 60034-30-1.
3 An IE5 efficiency class is not yet defined, but is calculated to have 20 percent lower losses than the IE4.
4 The currents are scaled from measured values for harmonizing to an equal voltage of 380 V, for simple comparison.
5 The comparisons are done with Germany as an example with an industry electricity price of $0.16/kWh.

5a Summary of test data



5b Basis of the energy calculations

SynRM²

An expansion to the SynRM product palette – SynRM² – was introduced in 2014 when a 15 kW model with an IEC shaft height of 160 mm ("SH160") was displayed in Hanover as the first public ABB demonstrator of an "IE5"-enabling technology. IE5, at the moment undefined by IEC 60034-30-1, is envisaged to have 20 percent lower losses than the IE4 class. (This cut in losses is typical between IE classes.)

After 10 years of operation, the initial purchase price corresponds to only around 2 to 3 percent of the electricity cost, for all VSD systems compared.

A unique feature of this motor is that it uses ferrite (iron oxide, Fe_2O_3) magnets, which are generally more cost-effective and more easily available than rare-earth permanent magnets. Their use results in a more economical and ecologically sustainable product.

Ferrites have been used before in low-power applications, but in industry a ferrite-based motor alone could not compete against an IM. A motor has to have a dominant reluctance, assisted by ferrite magnets, to be strong enough. With the rapid development and increasing intelligence of VSD drives, full control and utilization of these motors is now possible – as in the case of SynRMs.

The IE5 SynRM² is designed for customers chasing ever-higher efficiency and power density levels. Moreover, with power factor levels equal to PM motors and excellent field-weakening properties, the IE5 SynRM² can enable new, more compact motor-plus-drive package solutions. ABB is working to develop a SynRM² range, from 0.55 to 15 kW, targeting, for example, the HVAC market. Moreover, based on the attractive properties of the motor technology, ABB is proposing this technology to large OEMs in other application fields for whom it would be of great interest and benefit.

Test comparisons for different motor types in VSD operation

The IE energy efficiency classes are defined for DOL motors in the IEC 60034-30-1 standard and classified at the nominal working point (ie, at full load and speed). Naturally, the relative efficiency performances of VSD motors and drives are

ABB is prepared to meet the requirements of DOL motors with the newest member of the SynRM family – DOLSynRM, a concept version of which was demonstrated at the 2015 Hanover Fair.

not given by this motor class definition alone, since partial load and speed working-point performances and harmonic losses in the motors caused by frequency converter operation, as well as the losses in the frequency converters, are not accounted for. Therefore, the system efficiencies using different motor types and efficiency classes have been characterized in tests ➔ 5a. Two different and typical industry load profiles – constant torque (eg, for a conveyor belt) and quadratic torque (eg, pumps and fans) – versus speed are used, according to the definition in ➔ 5b, including duty cycles.

The energy savings are also calculated with the IE2 induction motor and drive system as the reference for Germany, with an industry electricity price of $0.16/kWh. Since the electricity cost is such a dominating part of a life-cycle cost of electric motors for industry, the payback time for choosing a VSD system with higher efficiency is extraordinarily short. The payback times for the IE3 induction motor, the IE4 SynRM and the IE5 SynRM² using similar ACS880-032A converters from ABB, compared with the reference IE2 induction motor system, are less than 10 to 15 months, depending on motor type and duty cycle. After these relatively short payback times, the higher efficiency systems save on costs for the rest of their lifetimes. After 10 years of operation the initial purchase price corresponds to only around 2 to 3 percent of the electricity cost, for all VSD systems compared.

Field tests/implementation example

Installations run by water utilities are among the United Kingdom's most efficient users of electricity. South Staffordshire Water's Somerford Pumping Station is no exception – yet its annual electricity bill adds up to around $13 million, 90 percent of which is used for pumping water. The company's effort to increase energy efficiency led to the decision to replace a 20-year-old 115 kW IM – controlled by a more modern ABB ACS800 frequency converter – with a new 110 kW IE4 SynRM and ACS850 drive package. The drive system ran a borehole pump that extracted 2.5 million L of water per day. The customer expectations were that efficiency would be improved and maintenance costs lowered by deploying the latest motor drive technology. The results far exceeded customer expectations: 6 percent energy savings; 58 percent reduction in frame temperature hotspots; 28 percent reduction in drive end bearing temperature; and 75 percent reduction of audible noise, compared with the induction motor that was replaced.

Motoring into the future

In motors, ABB provides the right solution for any industrial need and as a response to market demands for higher output, higher efficiency, longer service intervals and footprint reduction, ABB has brought out new synchronous reluctance motors. The environmental credentials of SynRM and SynRM² go beyond energy saving, however, as they use standard production methods and commonly available materials with low environmental impact. ABB is also prepared to meet the requirements of DOL motors with the newest member of the SynRM family – DOLSynRM, a concept version of which was demonstrated at the 2015 Hanover Fair. This technology, which combines a special cage (similar to those in IMs) with a SynRM structure, is under development but has already demonstrated that IE4 – and even, with careful optimization, IE5 – levels can be achieved, without the use of REE magnets or other special materials. The state-of-the-art design of SynRM provides the base for sustainable efficiency technology of electric motors into the future.

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[2] *Rotating Electrical Machines – Part 30-1: Efficiency Classes of Line Operated AC Motors*, IEC Standard 60034-30-1:2014.