



DEMec - Dep. of Mechanical Engineering
SAIC- Automation, Instrumentation and Control Section
Master in Mechanical Engineering

Electromechanical Systems

1st Year- 2nd Semester
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Support documents to TP classes

High-Performance AC Motors

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2026 Edition

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High-Performance AC Motors

Paulo Abreu

March 2025

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High performance AC motors: Learning Outcomes

- Understand the limits of induction motor efficiency and thermal behavior
- Understand Synchronous Motor Topologies
- Describe the operating principles of LSPM, PMSM, SynRM, IPMSynRM, and AFM
- Compare synchronous motor topologies and torque mechanisms
- Apply VFD control techniques (FOC, sensorless)
- Interpret torque-speed curves, nameplates, and IE classifications
- Evaluate commercial solutions from major motor suppliers
- Assess LCC, sustainability, and rare-earth material implications
- Explain future trends in high-performance AC drives and axial-flux technology

High-performance AC Motors

Three-phase AC motors designed for high-performance operation and high-efficiency:

- **Operate directly from AC line voltage or with a VFD**
 - Line Start Permanent Magnet Motor (LSPM)
- **Operated from a VFD**
 - Permanent Magnet Synchronous Motor (PMSM)
 - Synchronous Reluctance Motor (SynRM)
 - Interior Permanent Magnet Synchronous Reluctance Motor (IPMSynRM)
 - Axial Flux Motors (AFM)

The Efficiency Limit of Induction Motors

- **Physics Limitation of Asynchronous Operation**
 - Standard squirrel-cage induction motors depend on asynchronous operation to create torque. This requires slip, which introduces unavoidable electrical and thermal losses. Because of this, pushing efficiency beyond IE3 (Premium Efficiency) becomes economically impractical
- **Why Higher IE Levels Become Unrealistic**
 - Even replacing aluminum with high-conductivity copper rotors only reduces losses, it cannot remove them
 - To reach IE4 or IE5, the required reductions in slip and losses are beyond what the induction topology can deliver without high cost, unmanageable mechanical complexity, and thermal limitations
- **Conclusion: The induction motor cannot escape slip**
 - Because slip always produces rotor I^2R losses, IE3 is the highest achievable efficiency in practice for standard IM designs. Moving beyond this requires alternative motor technologies (e.g., synchronous operation, with reluctance motors and permanent-magnet motors)

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The Efficiency Limit of Induction Motors

Thermal Dynamics & Mechanical Impact

- **Heat Transfer**
 - In an induction motor (IM), rotor-generated heat must dissipate either across the air gap - where thermal resistance is high - to the stator, or conduct through the shaft toward the bearings
- **Bearing Degradation**
 - Elevated rotor temperatures accelerate grease oxidation within the bearings. Based on the Arrhenius relationship, every 10 °C increase in operating temperature can reduce lubricant life by roughly 50%
- **Thermal Expansion**
 - Excessive rotor heating leads to shaft elongation, which may disturb the alignment of precision couplings or connected gearboxes
 - The thermal expansion of the rotor in an IM can lead to decreased air-gap clearance

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The Efficiency Limit of Induction Motors

Comparative Loss Analysis: Induction Motor vs. Synchronous Motor

- **Efficiency Progression (IE4-IE5)**
 - Achieving ultra-premium efficiency requires eliminating the largest variable loss in an induction motor - the rotor copper loss
- **Synchronous Motor Topologies (LSPM, PMSM, SynRM, IPMSynRM, AFM)**
 - By synchronizing the rotor with the stator's rotating magnetic field (slip $s=0$), rotor current either drops to zero (as in SynRM) or is replaced by a permanent magnetic flux source in PMSM and LSPM designs
- **The "Cold Rotor" Advantage**
 - In SynRM, the rotor operates near ambient or stator temperature, enabling:
 - Reduced cooling requirements (smaller fans and lower windage losses)
 - Higher power density, delivering greater torque for a given frame size

The Efficiency Limit of Induction Motors

Challenges of Achieving IE4 Efficiency with Induction Motors

- **Material-Heavy Approach**
 - Reaching IE4 efficiency with an induction motor essentially requires adding more active material to reduce losses
- **Increased Copper Volume**
 - Larger cross-sections in both stator windings and rotor bars are needed to decrease electrical resistance and cut copper losses
- **Higher-Grade Steel Laminations**
 - Thinner, premium magnetic steel must be used to reduce hysteresis and eddy-current losses in the core
- **The Mechanical Consequence**
 - Upgrading an induction motor from IE3 to IE4 often requires a larger frame size. For mechanical design, this introduces major drawbacks: increased mass, oversized geometry incompatible with standard mounting, and higher rotor inertia - each contributing to poorer dynamic performance

The Efficiency Limit of Induction Motors

Magnetization and Efficiency: Induction vs. Synchronous Motors

- **Reactive Magnetizing Power**
 - An IM must draw magnetizing current from the stator supply to establish its magnetic field. This reactive power produces no mechanical work yet increases resistive losses in both stator windings and supply cables
- **Self-Generated or Optimized Flux in Synchronous Motors**
 - Synchronous machines either generate their own magnetic field (via permanent magnets) or guide the flux efficiently through designed reluctance paths. This eliminates the need for the grid to “magnetize” the rotor
- **Efficiency and Size Advantage**
 - By removing the requirement for external magnetization, synchronous technologies achieve higher efficiency and maintain a smaller physical footprint
- **Breaking the IE3 Barrier**
 - Think of IE3 as a combined thermal and volume ceiling for induction motors. Synchronous technologies - LSPM, SynRM, PMSM, IPMSynRM, AFM - surpass this ceiling not by adding mass, but by fundamentally changing rotor physics to eliminate slip and its associated heat generation

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Line Start Permanent Magnet Motor (LSPM)

The “Hybrid” solution for Direct-On-Line (DOL) starting or VFD

- **Hybrid Rotor Design**
 - The rotor combines a traditional squirrel-cage structure (used for induction starting) with interior permanent magnets (responsible for synchronous operation once up to speed)
- **Operating Principle**
 - **Start-up:** behaves like a standard induction motor, accelerating via cage currents
 - **Running:** once pull-in torque is sufficient and load inertia is within limits, the rotor synchronizes. The motor can run at a constant speed regardless of the load, synchronous to the operating frequency without slip
 - **Failure to Synchronize:** high-inertia loads may prevent locking unless a VFD provides controlled acceleration. A key mechanical constraint is: $J_{load} < J_{max}$ - if the connected load inertia is too high, the rotor may fail to pull into synchronism, leading to oscillation (“hunting”) or overheating

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Line Start Permanent Magnet Motor (LSPM)

■ Advantages

- High starting torque
- Improved efficiency and compact design
- Operates with Direct-On-Line (DOL) or Variable Frequency Drive (VFD)

■ Typical Applications

- Conveyor belts, textile machinery, fans, compressors, and high-speed pumps

Examples of LSPMs from SEW

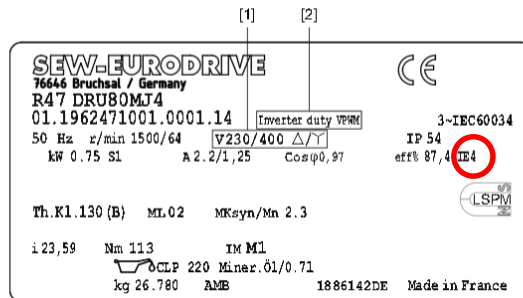
SEW LSPM Motors

- Compact design, higher efficiency
- DOL and VFD operation modes
- Early SEW DRE Series motors, with a power of 1.1 kW in size 90M meet the requirements of the energy efficiency class IE2. An equivalent is the SEW DRE.. J Series motors (LSPM technology), with a frame size 80S (smaller)
- Today LSPM motors from SEW are up to IE4 (DRU..J motors)

SEW LSPM motors

Examples of LSPM Motors from SEW

Motor nameplate for line-powered (DOL) or frequency-inverter operation (VFD)



12843412107

[1] Nominal voltage

[2] Line and inverter operation are permitted

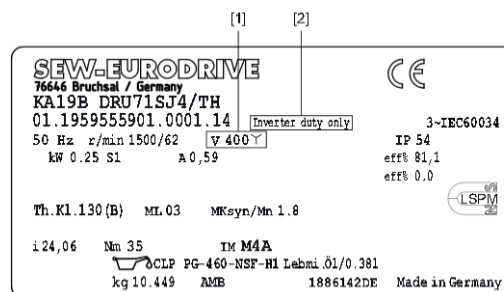
<https://download.sew-eurodrive.com/download/pdf/21281793.pdf>

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Examples of LSPM Motors from SEW

Motor nameplate, for 50 Hz frequency inverter operation (VFD) only



12842757259

[1] Nominal voltage 400 V Δ 230/400 V motor in 50 Hz, only in star connection

[2] Inverter operation only

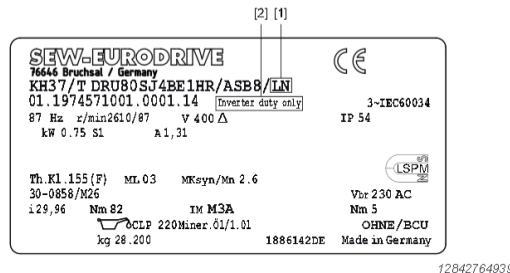
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Examples of LSPM Motors from SEW

Motor nameplate, for 87 Hz frequency inverter operation

In the 87 Hz variant, the power rating is one step higher than for the 50 Hz variant of the same frame size



[1] Low-noise fan guard (LN), for 87 Hz standard variant

[2] Nominal voltage 400 V Δ 230/400 V motor in 87 Hz, only in delta connection

- Connect the motor in Δ
- Feed it with a 400 V inverter output
- Raise the frequency proportionally until the voltage reaches 400 V at 87 Hz
 - This preserves the V/f ratio:

$$\frac{400V}{87Hz} \approx \frac{230V}{50Hz}$$
- Flux stays constant up to 87 Hz
- Full rated torque available up to 87 Hz (field-weakening starts only after 87 Hz)

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Examples of LSPM Motors from WEG



WEG W22 Quattro

- Power range: 0.37 - 7.5 kW
- Poles 4 or 6
- Synchronous speed: 1500/1000 rpm (50 Hz)
- Frame sizes: 80 to 132M/L
- Some models IE4
- Rotor: squirrel cage with permanent magnets
- DOL start, as an induction motor
- Synchronous speed (operation)
- Suitable for variable speed applications with scalar control and no need for encoder/resolver (open loop control)

[Link1](#), [link2](#) to catalogues

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Definition and Operating Principle

■ Fundamental Operating Principle

A synchronous motor operates through the interaction between two magnetic fields:

- The rotating magnetic field produced by the stator when supplied with AC power
- The constant magnetic field generated by permanent magnets embedded in the rotor

■ Creation of the Rotating Magnetic Field

- When AC power flows through the stator windings, it produces a rotating magnetic field
- The frequency of the alternating current (and the number of magnetic poles) determines the speed at which this magnetic field rotates

■ Rotor with Permanent Magnets

- Permanent magnets on the rotor “lock onto” the stator’s rotating magnetic field. As soon as the rotor reaches the vicinity of synchronous speed, the magnetic fields align, and the rotor becomes synchronized with the stator field
- The rotor then spins exactly at synchronous speed. No slip occurs. This provides precise, constant-speed operation independent of load variations (within torque limits)

■ Startup and Control Requirement

- Because a PM rotor cannot start asynchronously, the motor requires a Variable Frequency Drive (VFD) to:
 - Provide controlled startup
 - Regulate torque and speed, and
 - Ensure smooth synchronization with the stator’s rotating field

Permanent Magnet Synchronous Motor (PMSM)

Characteristics

■ Torque Generation

- The interaction between the stator's rotating magnetic field and the rotor's magnetic field generates torque, which causes the rotor to turn. The direction of the supplied AC current determines the direction of the rotor's rotation

■ Constant Speed Operation

- The motor speed remains constant under steady-state operating conditions, as long as the load on the motor does not exceed its capacity. The speed of the motor is determined by the frequency of the AC supply and the number of poles in the motor, according to the formula:
Speed (RPM) = (120 x Frequency) / Number of Poles per phase

PMSM motors are highly efficient and capable of precise speed control, making them suitable for applications where constant speed is required, regardless of load variations

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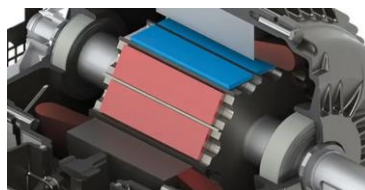
Examples of PMSMs from WEG

WEG W22 WMagnet

- Ultra-premium efficiency (IE5)
- Uses the inverter CFW11 for open-loop velocity control
- Dynamic behavior lower than a Servomotor



PM from WEG



- Frame: **132S**
- Output: **3 kW**
- Frequency: **50 Hz**
- Poles: **6**
- Full load speed: **1000**
- Slip: **0.00 %**
- Voltage: **400 V**
- Rated current: **5.20 A**

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Examples of PMSMs from WEG

W22 IR5 Ultra Premium Motors

- Efficiency IR5* Super Premium
- Power: 15 kW up to 315 kW
- Frame: 132S up to 315S/M
- Speed: 1000, 1500, and 3000 rpm (50Hz)
- Self-ventilated
- Started by frequency converter CFW-11
- Thermal protection: PTC (Positive Temperature Coefficient) thermistors embedded in motor windings



Réduction du volume



Moteur W22 Magnet
Puissance : 30kW
Vitesse : 3000 rpm
Carcasse : 132M/L
Masse : 76 kg
Volume : 24 dm³

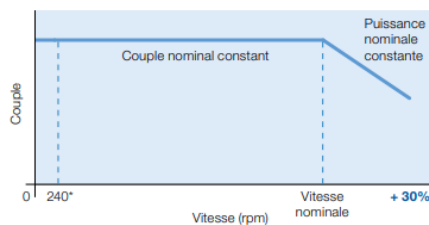
Moteur asynchrone
Puissance : 30 kW
Vitesse : 3000 rpm
Carcasse : 200L
Masse : 265 kg
Volume : 72 dm³

Link to [catalogue](#)

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Examples of PMSMs from WEG

Motors WEG W22 Magnet, operated with variable frequency drive



*Sur demande pour un fonctionnement continu à des vitesses inférieures à 240 rpm

**Les moteurs de 3600 rpm, jusqu'à la hauteur d'axe 200L, peuvent fonctionner jusqu'à 20% au-dessus de leur vitesse nominale. Pour les carcasses de 225S/M et plus, à la même vitesse, contactez WEG.



Link to [catalogue](#)

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Examples of PMSMs from SEW

SEW DR2C.. synchronous motors

- Two-speed classes: 2000 and 3000 rpm
- Six sizes up to 17 kW
- High efficiency over the entire speed range
- Highest normative efficiency class IE5
- System solution with control cabinet technology:
central MOVITRAC® advanced, MOVIDRIVE® and
decentralized MOVIMOT® inverters (only for inverter operation)
 - Encoderless with ELSM control method
 - With an encoder in the current flux control (CFC) method by SEW



Sew DR2C

Synchronous Reluctance Motor (SynRM)

The Magnet-Free High-Efficiency Alternative

Operating Principle

- **Creation of the Rotating Magnetic Field**
 - The AC power flows through the stator windings, producing a rotating magnetic field
- **Rotor Structure**
 - The rotor contains no magnets and no windings - only carefully engineered flux barriers that guide the magnetic field and create saliency
- **Reluctance Torque Generation**
 - Torque is produced by the reluctance force (not Lorenz force, as in IM)
 - Torque is produced by the difference between the motor's d-axis and q-axis magnetic reluctance ($L_d > L_q$)
- **Synchronous Operation**
 - The rotor aligns with the stator's rotating field and runs synchronously, without slip

Synchronous Reluctance Motor (SynRM)

Advantages of the “Cold Rotor”

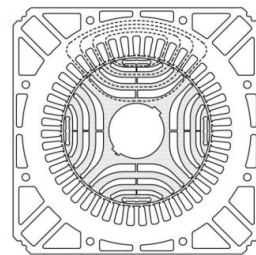
- **No Rotor Currents**
 - With no induced currents in the rotor (unlike induction motors) and no magnets to heat up, the rotor remains significantly cooler during operation
- **Lower Bearing Temperatures**
 - Cooler rotor \Rightarrow cooler shaft \Rightarrow cooler bearings \Rightarrow extended grease life, and improved reliability
- **No Magnet Materials**
 - Eliminates reliance on rare-earth materials such as neodymium or dysprosium, removing cost volatility and supply-chain risks
- **Possible to achieve high efficiency (IE5 and beyond)**

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Synchronous Reluctance Motor (SynRM)

- The operation of the synchronous reluctance motors takes advantage of the **magnetic reluctance force**
- It involves aligning the rotor with the stator poles to reduce magnetic reluctance, allowing magnetic flux to flow through the motor. This concentrates the magnetic flux and increases the motor's torque output, causing the rotor to rotate in synchrony with the rotating magnetic field that is created in the stator coils
- The motor is controlled by a VFD, using FOC control, to adjust the speed and torque



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Synchronous Reluctance Motors (SynRM) from ABB

Synchronous reluctance motor

- Rotor without permanent magnets or brushes. The rotor has a special shape that creates reluctance, or resistance, to magnetic flux
- When the driver generates a rotating magnetic field in the stator, the rotor automatically aligns with the stator flux, which generates torque and propels the motor
- Need for a variable frequency drive (VFD) to operate a SynRM
- Do not require a rotor position sensor, although it can be used



video <https://youtu.be/3g9IDqkCP3g>
video <https://youtu.be/vvw6k4ppUZU>

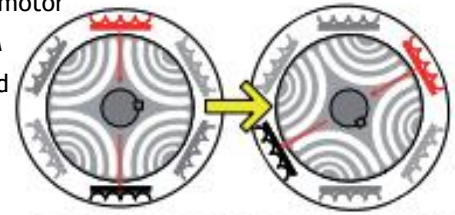


Figure 9: The regions of high magnetic permeability in the SynRM's rotor follow the stator's magnetic field.

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Synchronous Reluctance Motors (SynRM) from ABB

- High efficiency motors IE5 (since 2020)
- Small motor footprint for the same power when compared to an induction motor
- Possible to replace induction motors due to standard frames/dimensions
- IE5 SynRM Liquid-Cooled Motors (since 2024)



Ref video



ABB Product range:

- Motor type: M3AL/M3BL
- Output: 5.5-315 kW
- Frame sizes: IEC 132-315
- Voltage 230-690 V

- Inverter ABB ACS 880

Link to [ABB catalog](#)

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Synchronous Reluctance Motors (SynRM) from ABB

Torque-speed curve

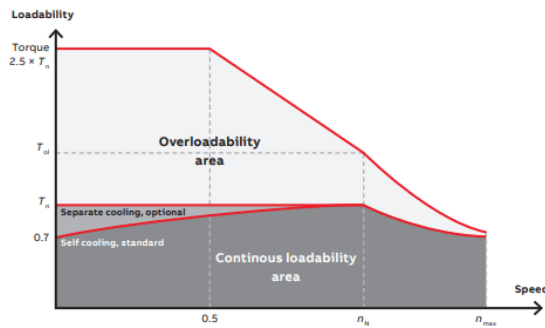


ABB Catalog 2

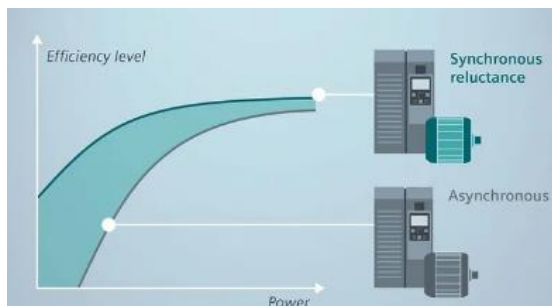
Motor type
 M3BL ...

ACS880
 Variable
 frequency
 driver

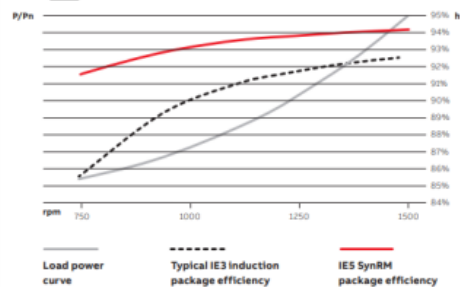


Synchronous Reluctance Motors (SynRM) from ABB

Motor efficiency comparison: IE5 SynRM + Drive vs. IE3 induction motor + Drive



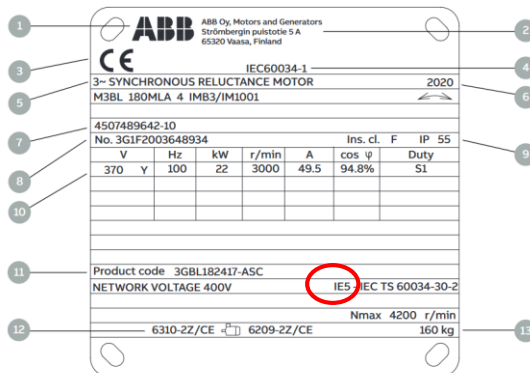
110 kW,
 1500 rpm drive system
 in pump/fan duty



Example: For a 110 kW
 1500 rpm drive system in
 pump/fan duty, with an IE3
 induction motor the package
 efficiency is 92.5%, while for
 an IE5 SynRM motor the
 package efficiency is 94.2%.

Synchronous Reluctance Motors (SynRM) from ABB

Motor plate



1. ABB logo
2. Manufacturing place
3. CE mark on Eco-design approved motors
UKCA mark on UK-approved motors
4. Manufacturing standard
5. Product Description
6. Manufacturing year
7. Factory order reference number
8. Serial number
9. Insulation class, IP protection class
10. Voltage, Frequency, output, speed,
current, power factory, duty
11. Product code
12. Bearing type
13. Weight

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AC Synchronous Reluctance Motors (SynRM) from ABB

Data for motors/inverter (partial data)



		Performance at nominal speed										
Output kW	Type designation	Product code	IE class acc. to IEC TS 60034- 30-2	Motor ef- ficiency with VSD supply $T_w=100\%$, $n_w=100\%$	Typical IE3 induction motor ef- ficiency with VSD supply***	Current		Torque		Inertia J kgm ²	Weight kg	Suggested ACS880 SynRM package frequency convert- er for light duty (**no overload)
						I_n /A	T_n /Nm	T_{c0}/T_n	Nm			
3000 r/min (100 Hz)												
400 V network												
5.5	M3AL 132SMA 4	3GAL132217--SC	IE5	92.8	87.8	12.1	17.51	1.5	0.0174	41	ACS880-01-14A3-3	
7.5	M3AL 132SMB 4	3GAL132227--SC	IE5	93.1	88.8	16.5	23.87	1.5	0.0174	41	ACS880-01-17A7-3	
11	M3AL 132SMC 4	3GAL132237--SC	IE5	94.0	90.0	24.5	35.01	1.5	0.0211	47	ACS880-01-25A5-3	
15	M3AL 132SMD 4	3GAL132247--SC	IE5	94.1	90.8	32.9	47.75	1.5	0.0211	47	ACS880-01-035A-3	
11	M3BL 160MLA 4	3GBL162417--SC	IE5	93.7	90.0	25.6	35.0	1.5	0.0579	133	ACS880-01-25A5-3	
15	M3BL 160MLB 4	3GBL162427--SC	IE5	95.1	90.8	34.6	48.0	1.5	0.0579	133	ACS880-01-035A-3	

See catalogue ABB IE5 SynRM 32 packages

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Synchronous Reluctance Motors (SynRM) from ABB

- **ABB is first to reach anticipated IE6 hyper-efficiency with magnet-free motors** (release date [Jun. 2024](#)) [new feb.2026 news](#)
- Well-proven synchronous reluctance motor (SynRM) technology is first magnet-free design to reach IE6 hyper-efficiency - an anticipated efficiency level ABB defines as achieving a **20 percent reduction in energy losses against comparable IE5 motors**
- Magnet-free SynRM motors are part of a wide-ranging technology portfolio that also includes permanent magnet (PM) and magnet-assisted SynRM (IPMSynRM) motors covering a wide range of application needs

Reference [ABB](#)

Note that **currently**, there is no official standard for IE6 efficiency in electrical motors! IE5 is, presently, the highest official standard defined by the IEC

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Synchronous Reluctance Motors (SynRM) from ABB

- ABB with a complete range of **IE5 SynRM Liquid-cooled motors** from 75 kW to 710 kW
- The addition of liquid cooling results in high power density without an increase in size
- Liquid-cooled motors' main benefits are the fact that they do not need fans or ventilation for cooling purposes, and therefore do not disturb the surrounding air
- Their torque characteristics - with a wide speed range for constant torque applications and 100% torque down to zero speed - make these motors very suitable for driving extruders

[ABB video](#)



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Synchronous Reluctance Motors (SynRM) from Siemens

Data for motors/inverter (partial data)

Selection data, synchronous-reluctance drive system with SINAMICS G120 for 50 Hz and 400 V line voltag



Document Siemens.
“Small step, big impact: a new dimension in efficiency”
Document ID number:
PDL-D-B10002-03-7600

SIMOTICS reluctance motor VSD4000							SINAMICS G120 frequency converter				
Rated power (kW)	Frame size	Torque (Nm)	Rated current (A)	Rated speed (rpm)	Max. speed SIMOTICS GP/ SIMOTICS SD (rpm)	Motor code	Motor Article No.	Frame size	Power Module Article No.		
0.55	80M	3.5	1.6	1,500	3,200/3,200	60017	1FP1	■ 14-0DB22-1 ...	A	6SL3210-1PE11-8	■ L1
		4.8	2.2	1,500	3,200/3,200	60018	1FP1	■ 14-0DB32-1 ...	A	6SL3210-1PE12-3	■ L1
0.75	80M	2.4	2.1	3,000	- / 6,000	60019	1FP1	■ 14-0DF22-1 ...	A	6SL3210-1PE13-2	■ L1
		7.0	2.8	1,500	3,200/3,200	60021	1FP1	■ 14-0EB02-1 ...	A	6SL3210-1PE13-2	■ L1
1.1	80M	3.5	3.0	3,000	- / 6,000	60020	1FP1	■ 14-0DF32-1 ...	A	6SL3210-1PE14-3	■ L1
		9.5	3.8	1,500	3,200/3,200	60022	1FP1	■ 14-0EB42-1 ...	A	6SL3210-1PE14-3	■ L1
		9.5	4.0	3,000	- / 6,000	60023	1FP1	■ 14-0EF02-1 ...	A	6SL3210-1PE14-3	■ L1

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Internal Permanent Magnet Synchronous Reluctance Motor (IPMSynRM)

Definition and Hybrid Operation

- Combination of SynRM and PMSM
- Dual torque mechanism for improved performance: **Reluctance Torque** and **Magnetic Torque**
 - The rotor is made of laminated steel sheets with air-gap barriers (as in SynRM), and small permanent magnets (typically ferrite or rare-earth, depending on design) are inserted inside the flux barriers. These magnets enhance the rotor’s ability to align with the stator’s magnetic field, reducing losses and increasing torque density, efficiency, and overall performance
- The stator is similar to PMSM, where a rotating magnetic field is created
- The rotor rotates in synchrony with the rotating magnetic field of the stator
- Startup and Control Requirement: use of a VFD

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Internal Permanent Magnet Synchronous Reluctance Motor (PMSyncRM)

■ Advantages

- The rotor has no windings, no slip rings, and no rotor copper losses
- This leads to high efficiency and low heating
- Motors can reach an efficiency rating IE5

■ Applications

- Compressors, pumps, fans, blowers, and conveyors, in HVAC systems and in traction motors in BEVs

Examples of PMSynRM from WEG

- WEG provides a motor, W23 Sync+, that combines synchronous reluctance with permanent magnets inside the rotor (**release date feb. 2024**)
 - Available in IE5 efficiency rating
 - Frame sizes IEC 80 to 450 (NEMA 140 to 7000)
 - Operating Speed from 750 up to 6000 rpm
 - Output power 0.75 - 1250 kW
 - Compatible with 220/380 V, 230/400 V, 240/415 V and 400/690 V power supply



Reference [WEG](#)

Examples of PMSynRM from Wolong

- Wolong (en.wolong.com.cn) provides motors, series WERM5, that combine synchronous reluctance with permanent magnets inside the rotor
 - Available in IE5 efficiency rating
 - Frame sizes IEC 80 to 160
 - Operating Speed: 1000, 1500, 3000 rpm
 - Output power 0.37 - 30 kW
 - Rated voltage 380 V/ 400 V



Axial Flux Motors (AFM)

- **Definition and Unique Design**
 - Permanent magnet synchronous motors (PMSM) with an **axial flux** design
 - Magnetic flux flows parallel to the rotation axis (unlike traditional radial flux motors, where the flux flows perpendicular to the axis)
 - More compact and lightweight than radial flux motors
- **Advantages**
 - High power-to-weight ratio; High Torque density
 - Better cooling efficiency, which can enhance performance and longevity
 - High efficiency, reduced energy consumption and operational costs
 - Suitable for electric vehicles, HVAC, Aerospace and Drones, and renewable energy

What is an Axial Flux motor? [Video](#)

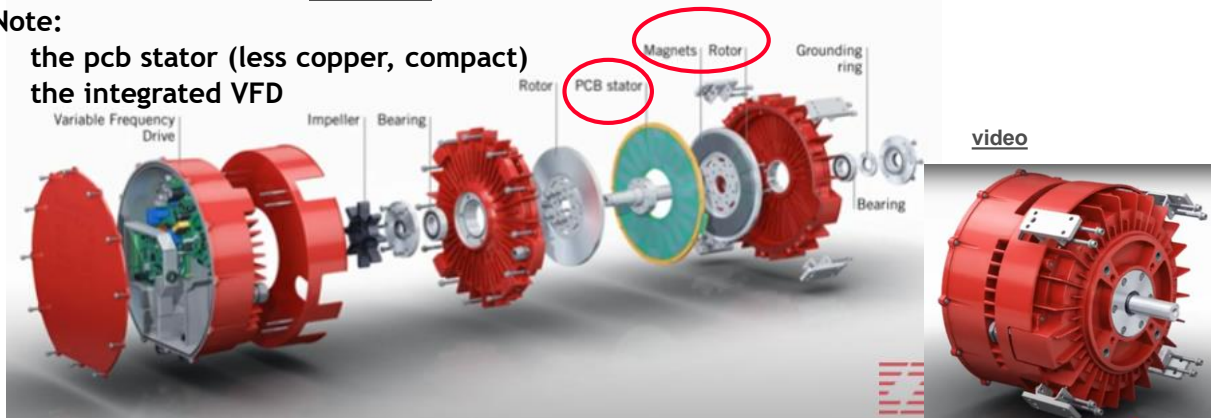
Axial Flux Motors Explained: [Video](#)

Examples of Axial Flux Motors (AFM) from Infinitum

Air core EC motor from Infinitum

Note:

- the pcb stator (less copper, compact)
- the integrated VFD

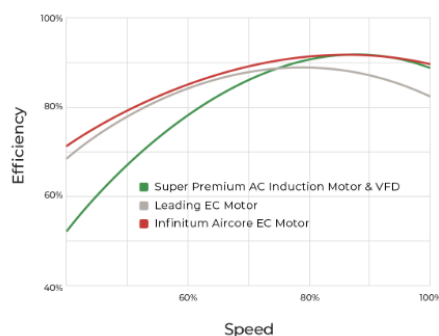


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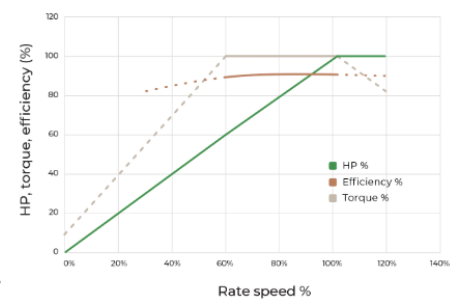
Examples of Axial Flux Motors (AFM) from Infinitum

Air core EC motor from infinitum

Aircore EC motor efficiency



Aircore EC motor operation range



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Axial Flux Motors (AFM) suppliers

Main suppliers of axial flux motors

- Infinitum - Air core EC motor, (<https://goinfinitum.com/>), suitable for HVAC
- Sierramotion ([Axial Flux Motors - Sierramotion](#)), suitable for machines
- Turntide ([Axial Flux Motors Deliver High Torque - Turntide](#)), suitable electric traction
- YASA (<https://yasa.com>), founded 2009, Main Products: YASA 750 and YASA P400, suitable for electric vehicles
- Magnax (www.magnax.com), founded 2015, suitable for electric vehicles
- Shanghai PANGOOD (www.pan-good.com), founded 2016, suitable for electric traction, HVAC
- Shenzhen SEMOTOR, <https://www.semotor.cn>, founded: 2016, suitable for robotics, traction
- BEYOND Motors, (<https://www.beyondmotors.io>), suitable for electric traction
- Phi-Power AG ([Home - Phi-Power AG](#)), founded: 2016, suitable from racing to heavy goods vehicles

Comparison of High-Performance AC Motors

Technology	Efficiency	Torque Density	Cost	Best Mechanical Use Case
Induction (IM)	IE3	Low	\$	Standard Pumps/Fans
LSPM	IE4	Medium	\$\$	Constant speed, no VFD
PMSM	IE5+	High	\$\$\$	Robotics / High Dynamics
SynRM	IE5	Medium-High	\$\$	Extruders / Compressors
IPMSynRM	IE5 +	High	\$\$	Traction /Compressors
Axial Flux (AFM)	IE5+	Ultra-High	\$	Traction /HVAC

The Role of the VFD and Control

- **Mandatory VFD**
 - Required for PMSM, SynRM, IPMSynRM, and AFM (no self-start capability)
- **Control Strategies with a VFD**
 - **Scalar (V/f):** Simple, low performance ; $V \propto f$ (constant V/f ratio)
 - Acceptable for induction motors (IM), but it is unsuitable for high performance for SynRM / IPMSynRM due to:
 - No control of rotor position; No torque-producing current alignment; High risk of loss of synchronism; No capability to fully utilize reluctance torque; Poor dynamic response
 - **Vector (FOC):** Independent control of torque and flux (essential for high-performance)
 - Essential control method for SynRM and IPMSynRM
 - Allows keeping the rotor and stator fields perfectly aligned for maximum torque (90° apart); Extract maximum reluctance torque; Maintain synchronism smoothly; Handle dynamic loads without pulling out of sync; Provide high efficiency

The Role of the VFD and Control

FOC always requires rotor position information. The drive can obtain it in two ways:

A. Sensorless Control (Estimator-Based)

- The drive infers rotor position using
 - Back-EMF
 - High-frequency signal injection (at low speeds)
- Implications
 - Lower cost. No mechanical components
 - Reduced accuracy at low speeds. Not ideal for precision or high-dynamic applications

B. Encoder / Resolver Feedback

- Using a physical position sensor: Incremental encoder or Resolver
- Implications
 - High precision. Superior low-speed control. Required for precise motion
 - Higher cost and complexity

Torque in Synchronous Motors

The electromagnetic torque (T_e) of a synchronous motor in the dq rotating reference frame, including PMSM and SynRM machines is given by

$$T_e = \frac{3}{2} p [\psi_m \cdot i_q + (L_d - L_q) i_d i_q] = \text{PM torque} + \text{Reluctance torque}$$

where

- $\frac{3}{2} p$ constant factor, with 3/2 comes from the transformation from 3-phase (abc) to 2-axis (dq) reference frame
- p is number of pole pairs
- $\psi_m \cdot i_q$ is the **Magnet Torque Component** (created by the permanent magnets on the rotor)
- i_q is the q-axis current (this is the torque-producing current)
- i_d is the d-axis current (this is the flux-producing current)
- $(L_d - L_q) i_d i_q$ is the **Reluctance Torque Component**
- L_d is the inductance along the d-axis
- L_q is the inductance along the q-axis

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Torque in Synchronous Motors

- **In a PMSM with surface-mounted magnets**
 - $L_d \approx L_q$, so reluctance torque ≈ 0 and $T_e = \frac{3}{2} p [\psi_m \cdot i_q]$
 - i_d mostly controls flux; usually set to 0 A (no field weakening needed at low speeds)
- **In an IPMSM with interior permanent magnets**
 - $L_d \neq L_q$, (high saliency)
 - i_d creates reluctance torque
 - The driver can often inject negative i_d at higher speeds for:
 - field weakening; extra reluctance torque; higher constant-power speed range
- **In SynRM (no magnets at all)**
 - All torque comes from the reluctance term, as $\psi_m = 0$. So $T_e = 3/2 p [(L_d - L_q) i_d i_q]$
- **In IPMSynRM**
 - Interior PMSynRM benefits from both PM torque and Reluctance torque, providing them with higher torque, wider constant-power speed range, and better efficiency

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Life Cycle Cost (LCC) and Sustainability

- **Purchase Price: only ~5-10% of Total Lifetime Cost**
 - Across a 10-20 year lifetime:
 - Electricity costs represent 90-95% of the total cost of ownership
 - Maintenance, downtime, and installation make up the remainder
 - This means that choosing a slightly cheaper, less efficient motor is almost always a false economy—energy consumption dominates the budget
 - **Energy Savings: IE5 motors often pay for themselves in < 2 years**
 - IE5 motors (Ultra-Premium Efficiency), including SynRM and IPMSynRM designs, have:
 - 15-25% lower losses than IE3 motors
 - 5-10% lower losses than IE4 motors
 - Significant reduction in heat, extending both motor and bearing life
 - Lower cooling and ventilation requirements
- This renders high-efficiency motors both sustainable and economically imperative**

Conclusions and Future Outlook

- Induction motors (IM) with fixed speed are legacy
- Transition to VFD with Synchronous motors is the future
- Sustainability: moving away from rare-earth magnets (SynRM/Ferrite)
 - IPMSynRM motors using low-cost ferrite offer high power factor and torque without reliance on neodymium or dysprosium
- Axial-Flux Growth
 - Axial-flux motors promise unmatched torque density, thinner form factors, and new opportunities for EVs, drones, aerospace, robotics, and compact automation
- Integration
 - Motor and inverter as a single unit
 - Motors are becoming part of the mechanical structure