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Modern Motor Control Applications and Trends

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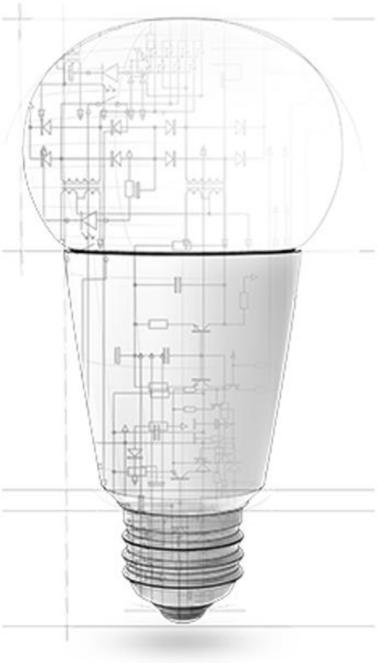
Content



- Introduction
- Electric Machines
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- Power Inverters and Semiconductor Requirements
- Trends in Electric Drives
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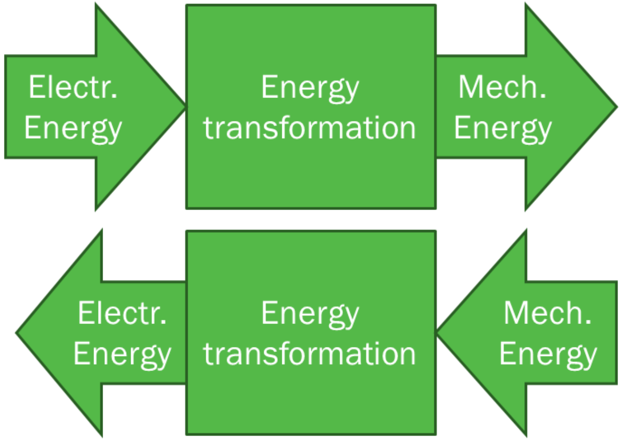
Introduction

Electric Drive (definition)

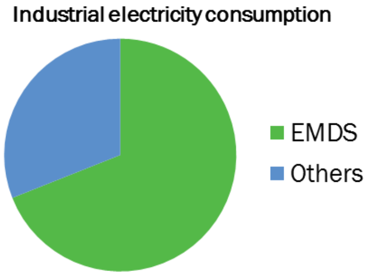
- Transforming electrical energy into mechanical energy.
- Consists out of electric motor and optional components, like a control unit, feedback measurements and rectifier, booster, inverter to convert the electrical energy.
- Electric motor can operate in 4 quadrants on the speed/torque plain, so mechanical energy can have positive or negative sign.



Electric motor driven system (EMDS)

- about 45% of all global electricity consumption and 69% of the industrial electricity consumption is EMDS*.
- Increasing and developing industry.
- Regulations established (e.g. ErP directive 0,75..375kW VSD).

*Source: www.iea.org (2011)



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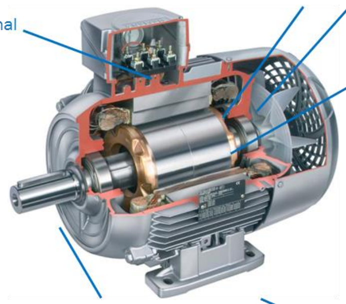
Electric Machines

Induction Machine / Asynchronous Motor

- Industry most widespread machine
- High reliability and efficiency
- Simple construction



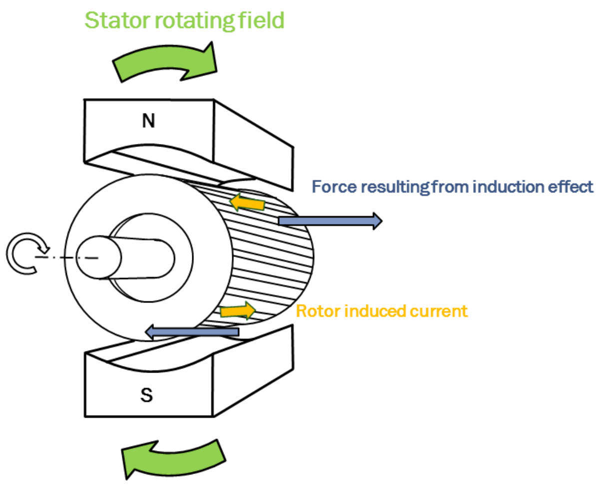
Asynchronous motor cut www.alphadrives.ie

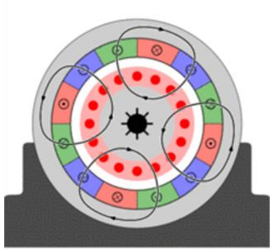
Used for pumps, cranes, fans, ...

Water pump motor and inverter application www.abb.com

Induction Machine / Asynchronous Motor

- Stator has a 3 phase winding Y or Δ connection
- Has to be fed with 3 phase current shifted by 120°
- Rotating field is created in the air gap
- Rotor has a squirrel cage (bars of Cu or Al connected on the end)
- Rotating field induces currents in the rotor
- Tourque as a result of an interaction between stator and rotor field

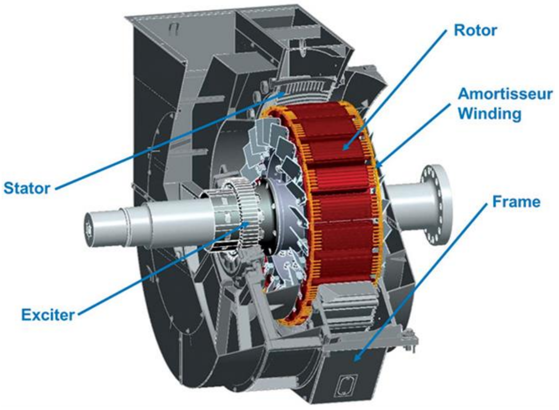




www.en.wikipedia.org/wiki/Induction_motor

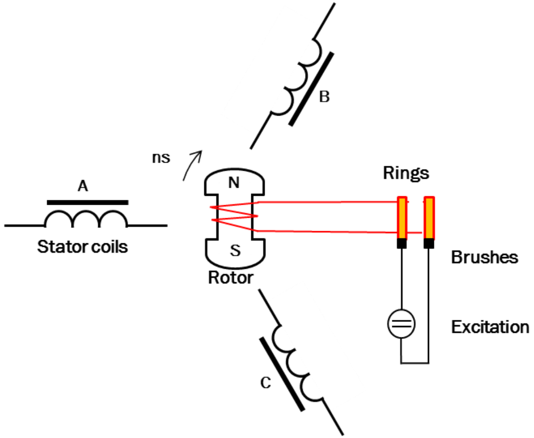
Synchronous Machine

- Stator has the same construction as IM
- Motor operates only at synchronous speed



Synchronous motor cut www.pumpsandsystems.com

- Rotor needs DC excitation
- Rings , Brushes and DC source add complexity



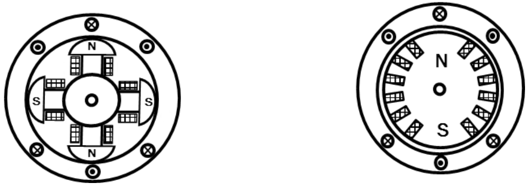
Synchronous Machine

- Motor operates only at synchronous speed
- Used for high power drives with constant speed in paper or steel industry
- Synchronous generator in power plants
- Start-up without Inverter need effort

http://www.varspeedhydro.com

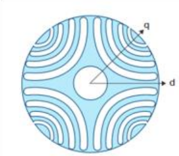
http://www.starterandalternator.com

- Two types of rotor exist – with salient poles and with cylindrical rotor



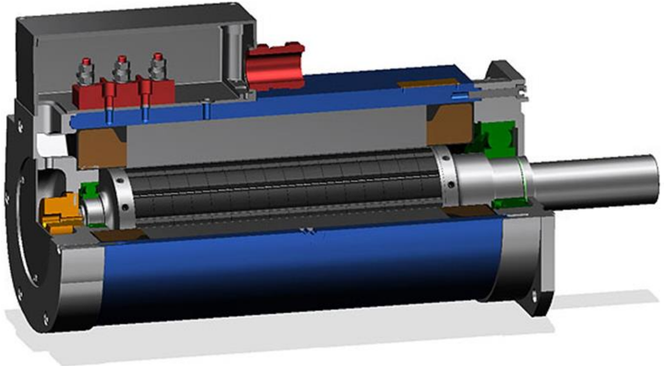
- Reluctance synchronous motor – has no rotor winding

Synchronous reluctance motor
www.abb.com



Synchronous Machine with Permanent Magnets (PMSM)

- Construction similar as SM



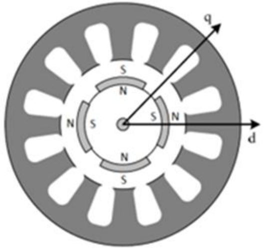
www.servax.com

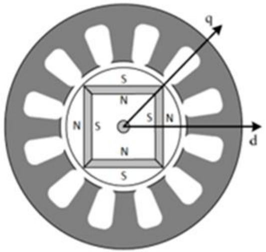
- Permanent magnets instead of rotor-winding
- High reliability due to brushless operation
- High efficiency (no dc losses in the rotor)
- High compactness
- Higher price (expensive magnets needed)
- Risk of demagnetization of the permanent magnets
- Rotor magnetic field cannot be changed

Synchronous Machine with Permanent Magnets (PMSM)

- Rotor with surface mounted magnets
- Best utilization of the magnets
- Mechanically less robust
- Magnets are more sensible to demagnetization
- eddy current losses are present in them

- Rotor with interior mounted magnets (embedded magnets)
- Magnets are mechanically and electrically protected
- Higher leakage flux (typically ¼ of the total flux)



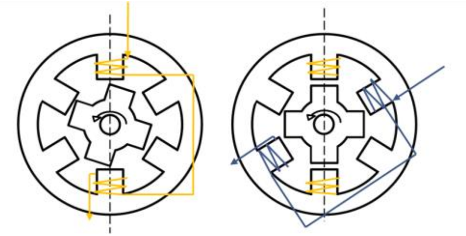


Switched Reluctance Motor (SRM)

- Cost effective
- High reliability due to robust structure
- High starting torque
- Fault tolerant operation possible
- High-speed operation (>100 000 RPM)
- Higher Torque ripple (reducable by more phases + advanced control)

www.copper.org

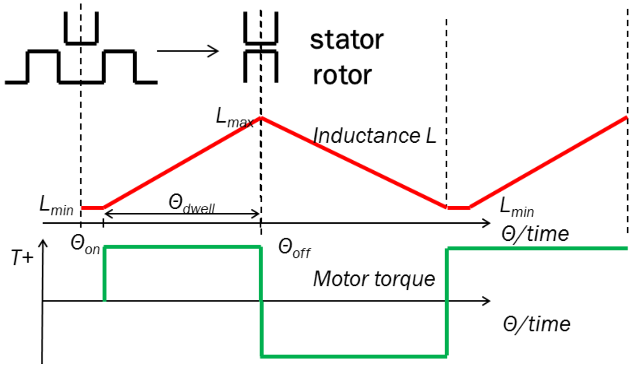
- Rotor and stator have salient poles
- No winding on rotor
- Torque is created only by the reluctance effect
- Every stator tooth has its own winding
- The motor has to be excited by a sequence of consequent pulses



6/4 poles SRM

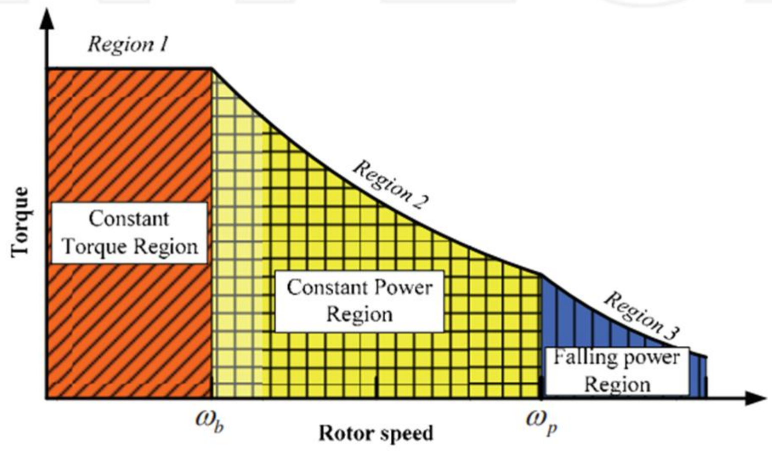
Switched Reluctance Motor (SRM)

- When current flows through the stator phase, torque is created in the direction of the increasing inductance
- Direction of the coil current does not play a role



- The motor has to be excited by a sequence of consequent pulses
- When rotor poles are leaving the aligned position and approach the unaligned position, the torque is negative
- Feedback position sensors or sensorless control approach is needed
- Torque ripple depends on the number of poles
- High accoustic noise
- Driving – reducing the current in the point of maximum Torque – reduces torque ripple
- Animation:https://www.youtube.com/watch?v=LXJUYumwh-k

Switched Reluctance Motor (SRM)



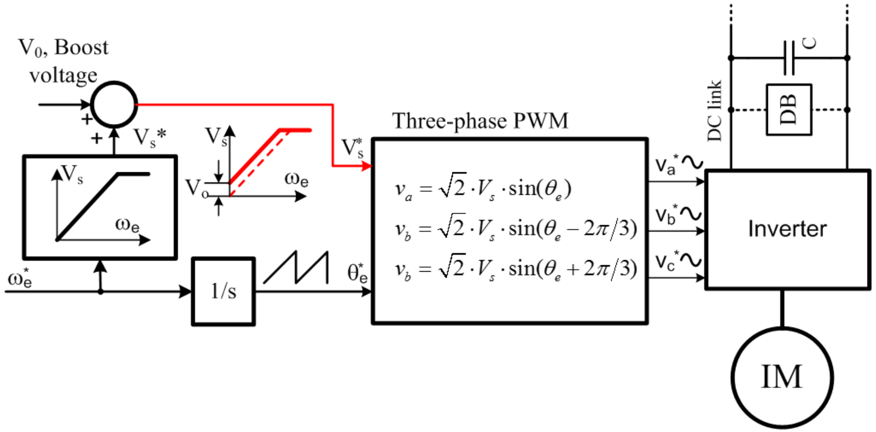
Jln-Woo Ahn (2011). Switched Reluctance Motor, Torque Control, Prof. Moulay Tahar Lamchich (Ed.), InTech, DOI: 10.5772/10520. Available from: https://www.intechopen.com/books/torque-control/switched-reluctance-motor

- High torque at low speed
- Const. Torque due to I-limit
- Due to BEMF, torque reduces proportional to speed -> const. Power
- In high-speed the torque decreases proportional to square of speed (BEMF)
- Speed limited by available voltage
- Ratio between max-speed and base-speed is up to 10
- Wie range of constant power makes SRM useful for EV application

Basic and Advanced Control Techniques

Open-loop Control Structures for IM

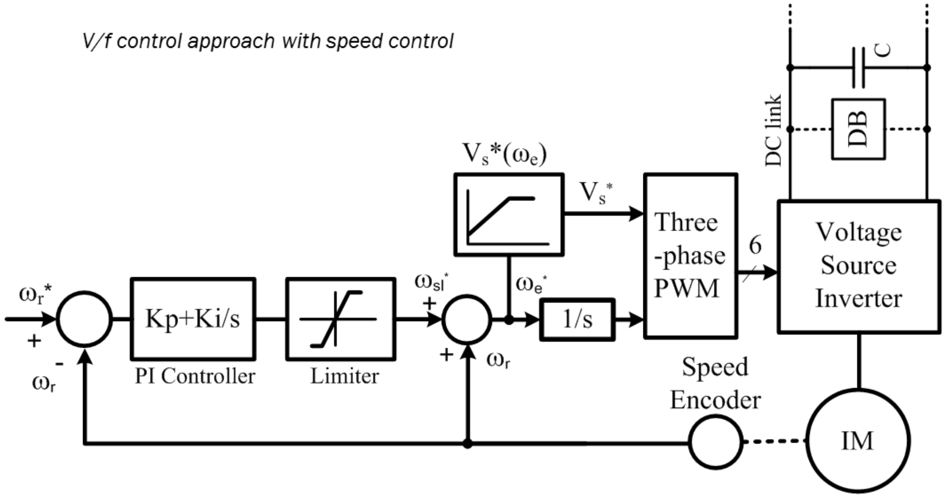
Open-loop V/f control approach



- Called V/f control technique due to keep the flux constant V_s/W_e = ψ=const
  - Stator voltage depends on required speed
- Rotor speed is less then requested due to the slip presence
- V_o called boost voltage is added to overcome the voltage drop across stator resistance R_s.
- Very simple control-method with weak response.
- Applications: pumps, fans or simple drives.

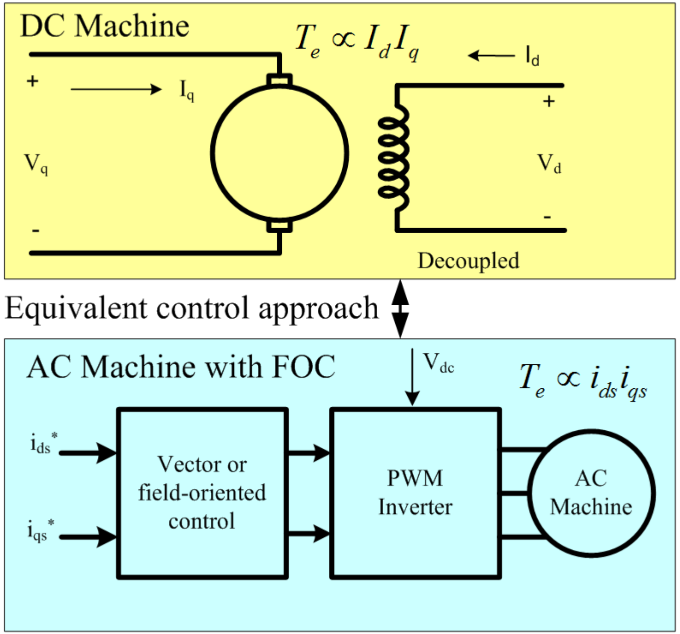
Closed-loop Control Structures for IM

V/f control approach with speed control



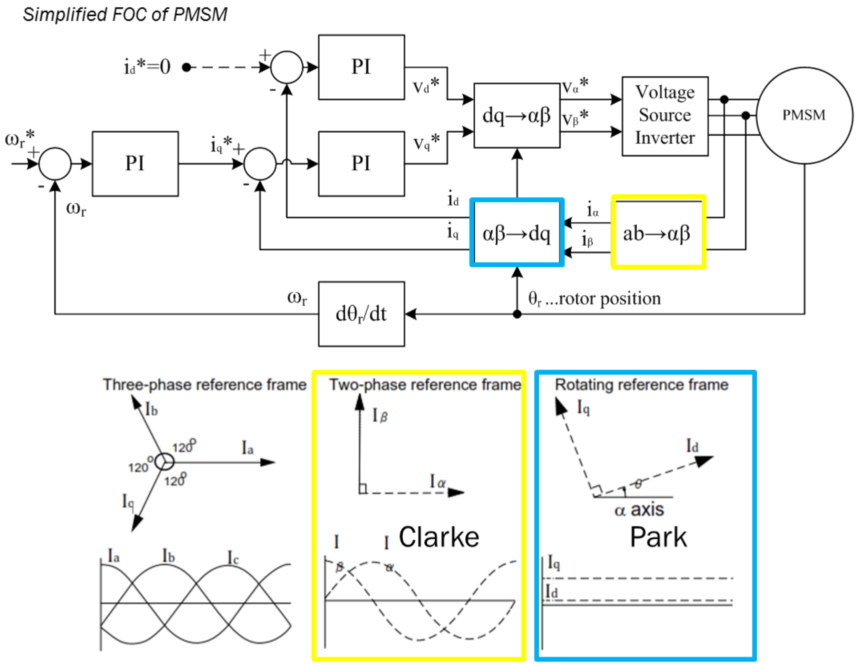
- Closed loop always means that an encoder is needed
- The feedback provide information about $\omega_{sl} = \omega_e - \omega_r$
- The electromagnetic torque of an IM is directly proportional to slip frequency ω_{sl}
- The method can be considered as an open-loop torque control within a speed control loop
- The structure contains V/f function to keep machine with rated magnetic flux
- Convenient for all application where good transient is required and accurate speed regulation.

Field Oriented Control (FOC)



- Previous control methods have sluggish control response.
- Better : vector- or field-oriented control
- With FOC an ac motor can be controlled like a separately excited dc motor
- In a dc motor, the field flux and armature flux, established by the respective field current I_d and armature I_q
- torque component of current I_d is orthogonal in space so when torque is controlled by I_q, the field flux is not affected which result in fast torque response
- Similarly, in ac machine vector control, the synchronous reference frame currents i_{ds} and i_{qs} are analogous to I_d and I_q, respectively

Field-Oriented Control Structure for a PMSM



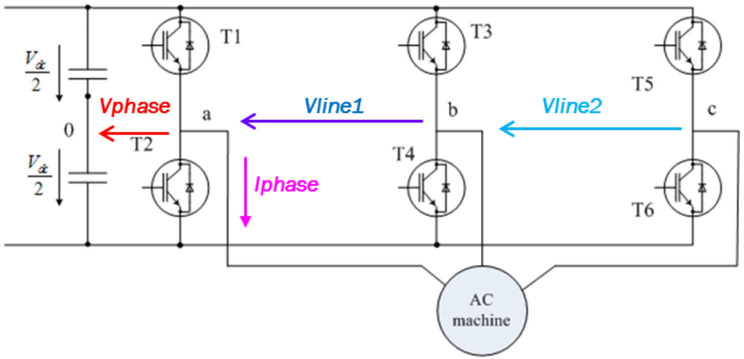
Source:Microsemi: park-inverse-park-and-clarke-inverse-clarke-transformations-mss-software-implementation-user-guide

- The vector transformations makes the control of an AC machine very straightforward
- It removes dependencies on rotor position
- The structure handles DC and no AC (easy close-loop design)
- It makes possible to control AC machine as DC by independent regulation id (excitation current) and iq (torque)
- FOC provides excellent time response
- FOC is more complex and need rotor position information.

Power Inverters and Semiconductor Requirements

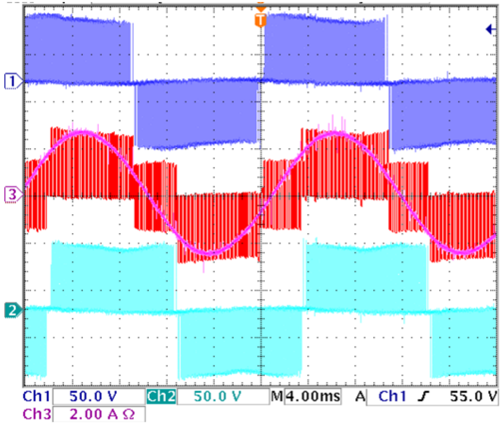
Standard Voltage Source Inverters for AC Machines

3-phase half-bridge topology

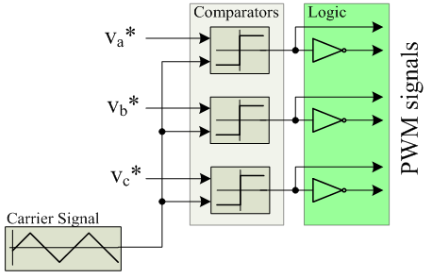


Output waveforms

Vline1, Vline2
Vphase, Iphase



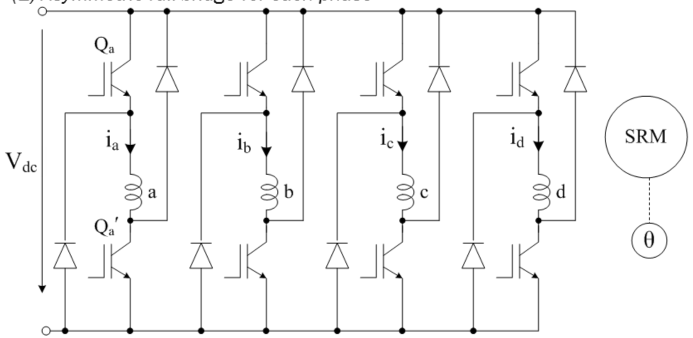
Easy PWM modulation



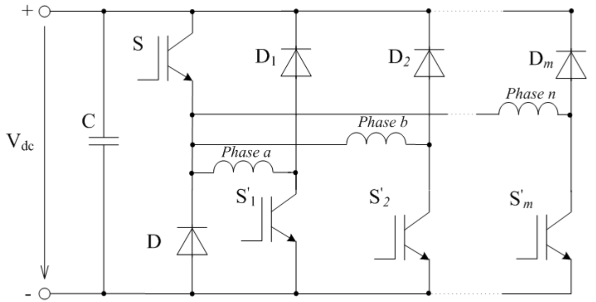
- Most common topology widely used in the industry
- 3 halfbridges of switching-devices like IGBTs or MOSFETs to generate a 3phase voltage source.
- Useable for all machines except SRM or stepper motor where more suitable topologies exist

Voltage Source Inverters for SRM

(1) Asymmetric full bridge for each phase



(2) One switch for all phases topology



- The electromagnetic torque doesn't depend on current direction but on inductance slope (page13)
- There are couple of topologies for SRM differentiating in number of power devices and degree of phase independency
- Asymmetric full bridges for each phase (1)
  - minimize SC probability
  - No dead times needed
  - Completely independent phase control
  - More semiconductor devices
- One switching device for all phases (2)
  - Less semiconductor devices
  - No independent phase control

Key Requirements to Semiconductors

Electric drives require Robustness and Reliability

Definition of Robustness, Ruggedness and Reliability is complex.
Here a couple of parameters which influence Reliability:

- Short Circuit Safe Operating Area (SCSOA) or SC withstand time)
- Maximum junction temperature, low R_{thjc} and high P_D rating.
- Wide and Squared Reverse Bias Safe Operating Area (RBSOA)
- Wide Forward Bias Safe Operating Area (FBSOA).
- Self clamping capability –Avalanche rating in Unclamped Inductive Switching (UIS).
- Positive $\Delta V_{ce(sat)}/\Delta T_j$ and tight distribution of parameters (Vge(th), Vce(sat))
- Low ratio of C_{res}/C_{ies}, this provides excellent ΔV/Δt immunity, short delay times and simple gate drive (low Miller capacity)

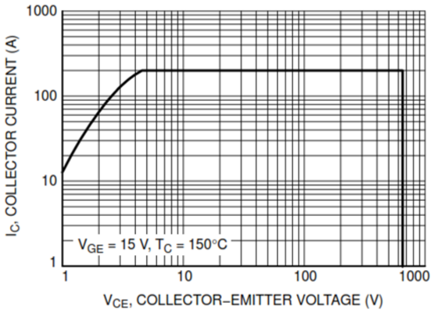


Figure 18. Reverse Bias Safe Operating Area

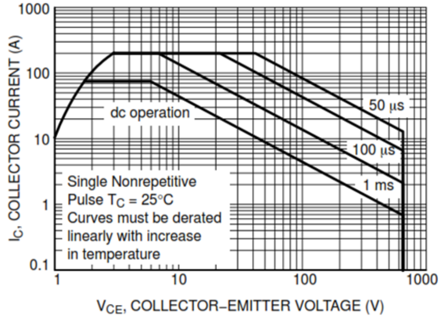


Figure 17. Safe Operating Area

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Key Requirements to Semiconductors

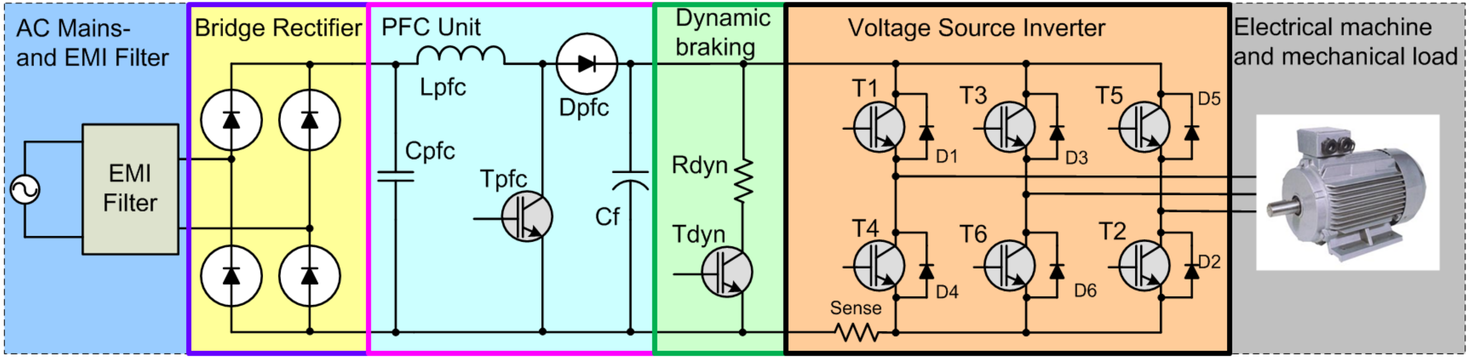
Diode bridge rectifier:
1φ-600V. .1000V
3φ-1200V..1600V
surge capability, low VF
Active PWM rectifier:
(PFC, recuperation, regulate DC=const):
1φ-600V/650V typ. -> 400 VDC,
3φ-1200V typ.-> 600 VDC)
Fast IGBTs/FWDs, full rated diode

Boost (PFC regulate to VDC=const typ. 400V.
Fast IGBT/MOSFET 600/650V.
Fast Diode 600V (low trr)
SiC plays perfect

Dynamic brake
(breaking power dissipation)
400VDC: 600/650V,
600VDC: 1200V
low VCEsat IGBT.

Inverter: (DC to AC conversion)
400 VDC: 600V/650V,
600 VDC: 1200V optimized based on fsw (white goods fsw ≈ 16 kHz, industry 1-10 kHz), robust and Short-circuit rated IGBTs/MOSFETs with fast Diodes.
Full or half rated diodes depends on motor/generator modes with high dynamic robustness

Typical low power (up to 3kW) motor drive topology



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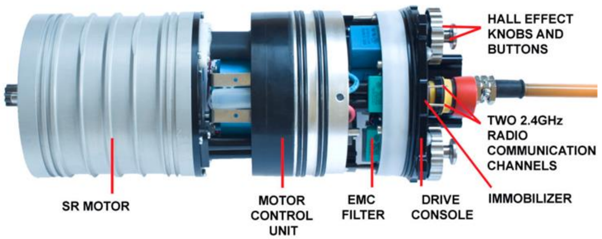
Trends in Electric Drives

SRM becomes important in Industrial High Power

- Lowest manufacturing price of the motor
- High efficiency over a wide speed range
- Low inertia of the rotor
- Fault tolerant (overload)
- Wide supply range voltage
- Suitable for high temperature operation
- Applications Industry drills
- HEV drives, train motors etc…



9kw Drill motor unit with integrated inverter http://kaskod.ee

260kW SRM http://www.usmotors.com

Integrated Inverter (Inverter goes to motor)

Pro

- Reduced volume
- Less cabling, connectors, housing
- Less manufacturing effort for assembling into the EV or in factory installation
- Sealed in one housing
- Lower EMI effects (better defined)
- Drive is optimized to motor attached

Con

- High thermal /mech. stress of electronics
- Cooling system more complex
- High level of miniaturization needed
- Reliability

Explosion proof on site inverter
www.dietzelectric.com

750W integrated Servo motor
www.jvl.dk

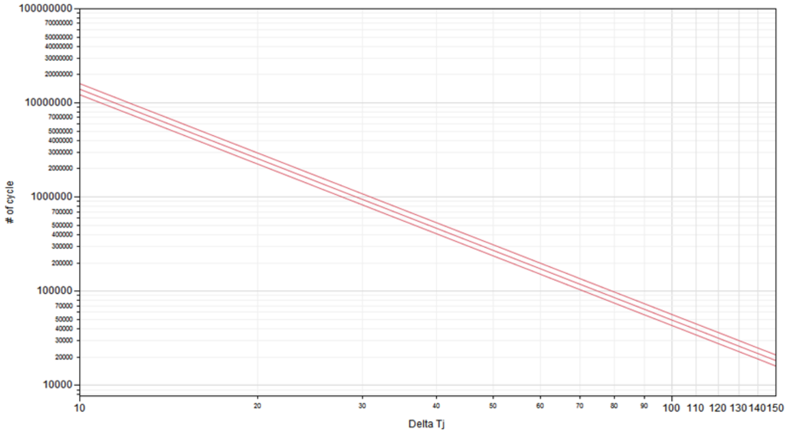
75kw In wheel motor unit
www.proteanelectric.com

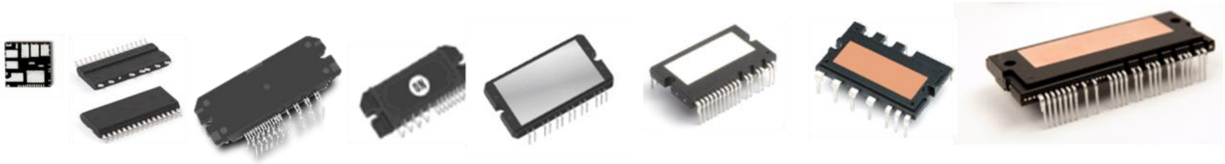
Integrated Inverter (Inverter goes to motor)

Integration-challenges can be solved by IPMs:

- excellent mechanical strength against vibration through moulded package
- High compactness, through integrated Gate-Driver and protection-functionality
- high reliability proven (power-cycling)
- Wide portfolio of power-level, size and functionality available (e.g. with PFC)

  500V/600V/1200V up to 10kW





Fast Switching with SiC and GaN in Motor Control?

Pro

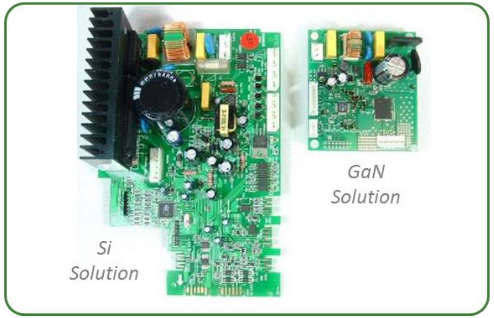
- Reduced switching losses
- Higher Efficiency reachable
  - Compactness (weight/size)
  - Reliability
  - Fullfil requirements high Eff.class
- Audible noise > 16kHz
- Fast regulation-loop

Con

- EMI more critical (PCB, wiring)
- Reliability of Motor (winding/bearings)
- Today cost of SiC/GaN devices

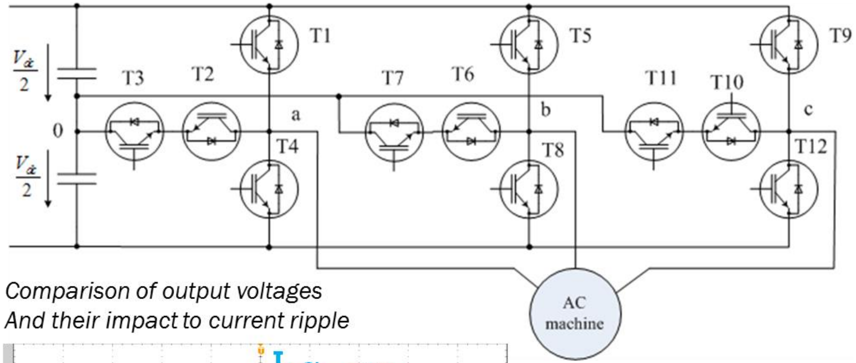
High Power Motor Drive System

Appliance Motor Drive System

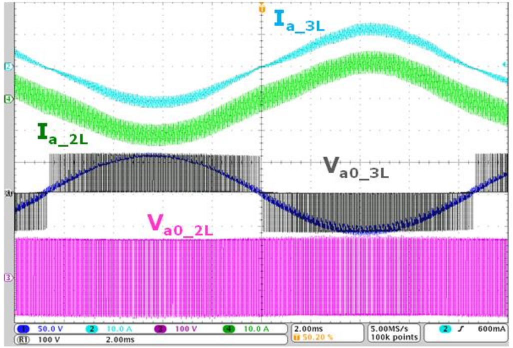


Advanced Voltage Source Inverters for AC Machines

3phases 3level neutral point clamp topology



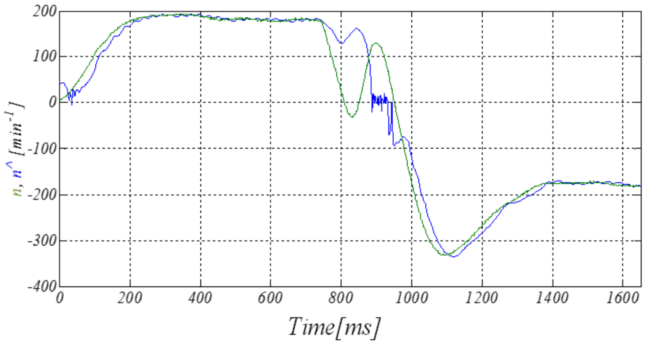
Comparison of output voltages
And their impact to current ripple



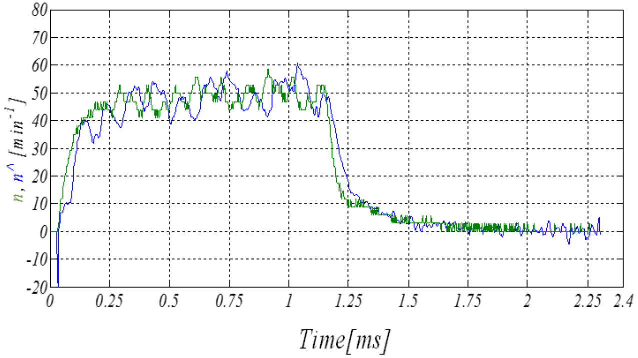
- Improving efficiency in DC-AC conversion.
- Output waveform with extremely low harmonic distortion (sinoidal)
- Switching frequency can be lower than that of a typical two-level application, allowing:
  - reduced silicon losses and reduced output filter results in a overall dimensions and costs reduction.
- More active devices, gate drivers and more complex PWM control.

Sensorless Control of AC Machines

Behavior of model based methods in higher, low and zero speed



Behavior of Non-model based methods in low and zero speed

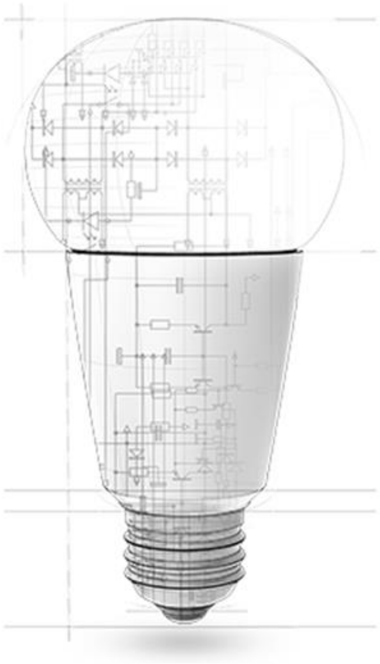


- Rotor position information required for vector control.
- Possible by sensors like encoders or resolvers
- Sensors increase cost, size, weight, cabling and reduces reliability
- Two different methods exist to estimate speed and rotor position
- Model-based method (using mathematical calculation based on measured voltage and currents).
  - Good for high speed range
- Non-model based – using HF voltage (around 1 kHz) signal injection and machines response in currents
  - good for low speed range or zero speed.

Green: how Processor sees the system
Blue: Reality

Conclusion

Conclusion



- SRM is an emerging alternative with simple construction, robustness, low cost and with good flat efficiency versus speed curve.
- FOC for PMSM, IM and SyRM (synchronous reluctance motor) is shown as state of the art alternative to simple control methods.
- Switched Reluctance Machines require special control techniques and different Inverter Topology.
- Also the Topology of 2- and 3-level-inverter is shown with the corresponding benefits.
- Various Trends are shown about System-level (Integration), Control-level (Sensorless control), Motors (SRM), Topology (3-level) down to Device-level (WBG-devices)

Thank You

For more information regarding these products or our complete portfolio of products, please contact your local sales person or authorized distributor.

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