Advanced Compressor Modeling (Compressors 102): Motors For Compressors

By Peter Wung PhD

July 15, 2012

REGAL

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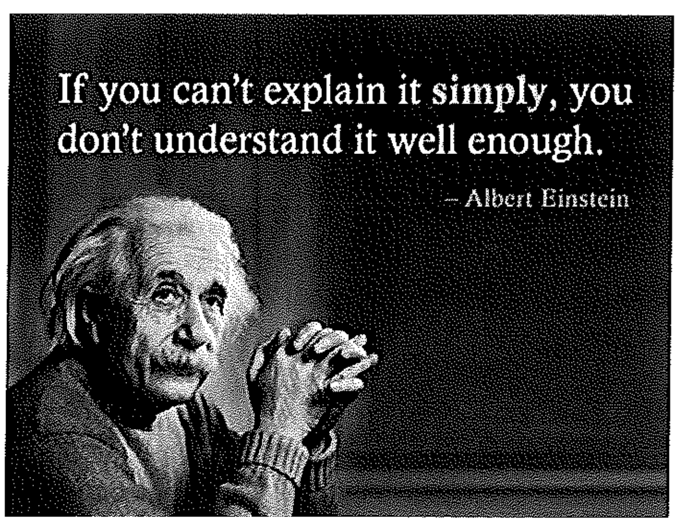
Occam's Razor (Principle of parsimony):

"The Simpler the explanation, the better."



Motivation

To elementary — Introduce fundamental concepts of electrical energy conversion, motor design, motor/drive technology, and testing by using heuristic explanations, i.e. no equations or very few equations.

Agenda

- ***Overview of Regal***
- **Electric Motors Primer**
- **Existing Motor Technologies**
- **Motor Drives**
- **Motor Design**
- **Testing**
- **"New" Motor Technologies**
- **Summary**
- Motor Model

$\eta = f(P_{shaft}, \omega_0, T, V)$

Overview of Regal

Regal History

- Founded and Headquartered in Beloit, WI in 1955.
- Consist of 2 major business segments
  - Electrical: Motors, Capacitors.
  - Mechanical: Gears.
- 28 acquisitions in 25 years.
  - Milwaukee Gear (2012)
  - A. O. Smith Electrical Products (August 2011) – Hermetic motor business
  - Ramu Inc. (2011) Prototyping
  - UNICO (2010) VFD

Regal Hermetic Business

(Part of the A. O. Smith EPC purchase)

AMERICAS

ASIA & EUROPE

Global Hermetic OEM Customer Base

4 Continents

10 Countries

70 Customers

REGAL Hermetic End Application

Residential Segment

Commercial Refrigeration
Walk-in Freezers &
Display Cases
Recip
(1-5 Ton 1Φ, 3 Φ)

Unitary A/C & Heat Pump
Recip & Scroll
(2-5 Ton 1Φ)

Light Commercial
A/C & Heat Pump
Recip & Scroll
(3-10 Ton 3Φ)

Commercial Segment

Commercial Chillers
Air-Cooled & Water-Cooled
Recip, Screw, & Centrifugal
(50 to 2000 Tons)

Commercial Refrigeration
Including Container Units
Recip & Scroll
(5-250 Ton)

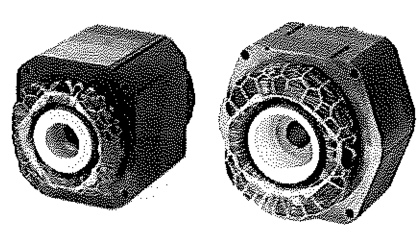
Light Commercial
A/C & Heat Pump
Recip & Scroll
(5-20 Ton)

REGAL Hermetic Products Manufactured in NA

Hecho en Mexico

genteq®

HERMETIC



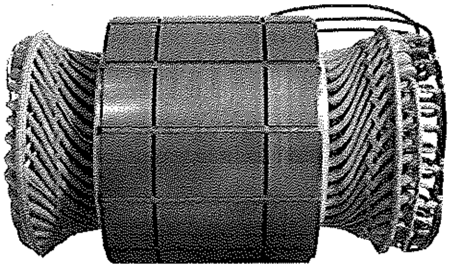
- 55 Frame through 88 Frame
- 115 to 690 Volt (1PH & 3PH)

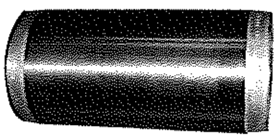
Commercial Hermetic Products Manufactured in NA & China

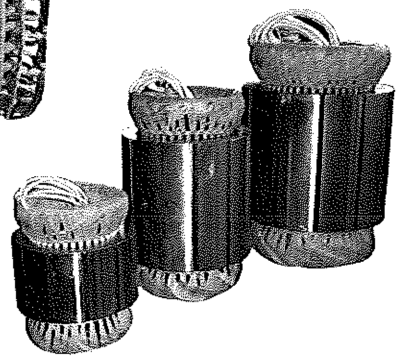
Stator rotor sets

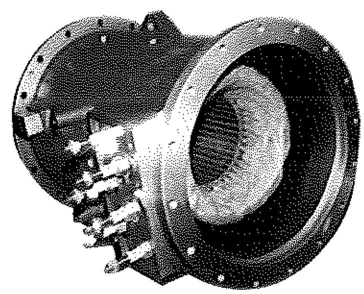
genteq®

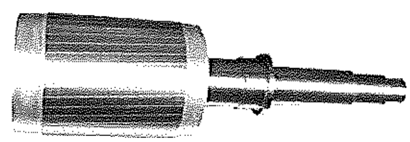
HERMETIC











- 63 Frame through 305 Frame
- Up to 13.8KV (Up to 1,800HP)

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What is a motor? Physical View

- Energy Conversion device.
- Think of Electric Machine as a three port black box.
  1 Mechanical Port: Torque
  2 Electrical Ports: Current and magnetic field.
- One port has to be the output port, the other two ports has to be input ports.

DC machine is clear I + B

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What is motor? Black Box View

Electrical Current	Input	Output	Input
Field	Input	Input	Output
Mechanical	Output	Input	Input
Classification	*Motor*	*Generator*	*Synchronous Condenser (Big capacitor)*

Energy Conversion

- Lorenz Force Law: Force on a current carrying wire:

$$\underbrace{\vec{F}}_{\text{Force}} = \underbrace{\vec{Il}}_{\text{Current}} \times \underbrace{\vec{B}}_{\text{Magnetic Field}}$$

current sheet on stator (ideal)
vs. cogging torque from slots (reality)
↳ esp PM machines with reluctance torque

Electrical Current

- Windings used to supply a "smooth" current sheet in the stator to supply current (torque) and sometimes magnetic flux (field) to the motor.
- Smooth current sheet not physically possible, so windings are placed in slots (Compromise).
  - Having slots disturb the assumed smoothness of the air gap, introducing:
    - Air gap variations-> Inductance variations-> higher space frequencies
    - PM machines-Cogging torque, radial forces, noise and vibrations.
    - Induction Machines-Crawling, parasitic torques, locking torques.
- Windings can be:
  - Single Phase, two-phase, or three phase.
  - Connected Wye or Delta for three phase motors.
  - Made from copper or aluminum.

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Magnetic Field

- Magnetic Field can be Supplied from:
  - Stator terminals, as a component of the supply current (induction motors, switched reluctance motors, synchronous reluctance motors, and to some extent IPM motors). Brushless AC
  - DC current to rotor connections (synchronous machines). Separately supplied from the AC terminal current but must be taken into account for efficiency considerations.
  - Magnets on the rotor (PM machines).

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Torque: Alignment Torque

- *Two magnetic fields residing on freely moving parts attempt to align with each other.*
  - Induction motor:
    - the rotor magnetic field induced in the short circuited cage rotor by the stator magnetic field.
    - The rotor fields attempts to align with the stator field.
    - Rotor field moving at a speed less than the stator field; the difference in speed is defined as the slip of the motor.
    - Slip must exist since the induced rotor field ceases to exist if the rotor is turning at the same speed as the stator field.
  - Permanent magnet motor:
    - Rotor magnetic field is supplied by the permanent magnets present in the rotor.
    - Stator field comes from the windings.
    - No steady state speed difference between the stator and rotor.

What are losses (hysteresis) how to analyze, what magnitude

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Torque: Reluctance Torque

- *Reluctance torque is derived from the saliency of the motor structure. Rotor turns in order to maintain the path of least reluctance.*
  - Salient pole structure of the reluctance machine rotor causes a preferred magnetic position of least reluctance path to align with the stator magnetic field.
  - Stator field is a periodic traveling wave that has the same number of poles as the rotor.
  - The rotor lock in with the stator field and the rotor turns in order to maintain the minimum air gap reluctance,
  - Stator field pulls the rotor along as it travels around the periphery.
  - Operating principle behind the synchronous reluctance motor and switched reluctance motor.

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Motor Technologies

	AC or DC	Speed	Line Start	Air gap	Torque Mechanism	Speed Range	Drive	Phase Count
Induction Motor	AC	Asynch. slip	Yes	Smooth	Alignment	Wide	Vector and Scalar	N=1, 2, 3. N>3 possible
Brushless AC (SurfacePM)	AC	Synch.	No	Smooth straightfwd	Alignment	Limited	Vector and Scalar	N=1, 2, 3. N>3 possible
Brushless AC (IPM) Interior PM machine	AC	Synch.	Yes (With cage)	Smooth (Saliency inside rotor)	Alignment and Reluctance	Less limited	Vector (Special)	N=1, 2, 3. N>3 possible
Synchronous Reluctance	AC	Synch.	Yes (With Cage)	Single saliency. saliency inside Rotor	Reluctance	Wide	Vector and Scalar	N=1, 2, 3. N>3 possible
Switched Reluctance	Switched DC	Synch.	No	Double saliency	Reluctance	Wide	Unique	N=1, 2, 3, …

VFD drive to control field

like stepper motor

noisy

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Power Factor

- The power factor of an AC electrical power system is defined as the ratio of the real power (P) flowing to the load to the apparent power (S).
- PF = P/S $\phi = \text{atan}\frac{Q}{P}$ + PF = cos ϕ
- For sinusoidal waveforms, PF = cosΦ where Φ is the angle between the voltage and current
- S=P+jQ
- S=Apparent power (measured in VA)
- P=Real power (measured in W)
- Q=Reactive power (measured in Var)

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Efficiency: Losses

- Losses=(Energy In) –(Energy Out)
- Losses=Electrical losses+Mechanical losses
- **Electrical losses usually dominate.**
  - Mechanical losses=Windage losses+Bearing losses
  - Electrical losses=Copper losses+Core losses.
    - Copper losses: Direct losses due to current flowing through wires. I^2R losses.
    - Core losses: Two components: Hysteresis and eddy current
      - Hysteresis losses: Nonlinear loss mechanism in the steel. (is Hyst loss proportional to mass?) $B = \alpha I N$ α is fn of steel
      - Eddy current losses: due to high frequency ? swirling eddy currents in the steel. (This is why motors are laminated structures)
    - **Copper losses dominate at low speeds,**
    - **Core losses dominate at high speed.**
    - There are also core losses associated with magnets. → laminated magnets for high speed PM machines

Noise and Vibration

- Noise and vibration comes from a myriad of sources
  - Interaction of forcing function with housing mechanical resonance
    - Radial forces (r, Θ) Plane
    - Solenoidal forces (Z-Axis)
    - Slot passing noises
    - Forces comes from non-ideal situations (violation of assumptions)
  - Airborne noises
- Reasons for non-ideal situations?
  - Design compromises
  - Physics
  - Manufacturing variations
  - Concentricity/eccentricity, F ∝ B² airgap

Temperature and Cooling

- Need to be limited due to material thermal limits
- Directly related to electrical losses and ability to disperse the electrical losses

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- System Testing
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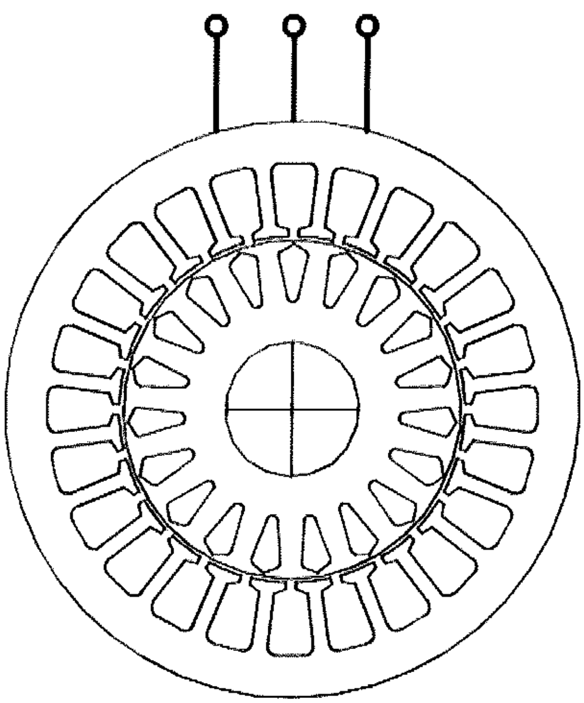
Farari (Italy)
Nicola Tesla

Induction Motor

N slot [stator rotor

- Smooth air gap motor (No saliency)
- Distributed winding
- AC excitation
- Alignment torque
- Asynchronous machine
- Wide speed range
- Most common motor in industry today.
- Rotor cage can be aluminum (prevalent in most machines) or copper (mostly in very large machines).
- Most induction motors in the field are line start machines.

CDA
Amer Copper inst
Die cast copper



From SPEED Consortium Electric Motors Manual.

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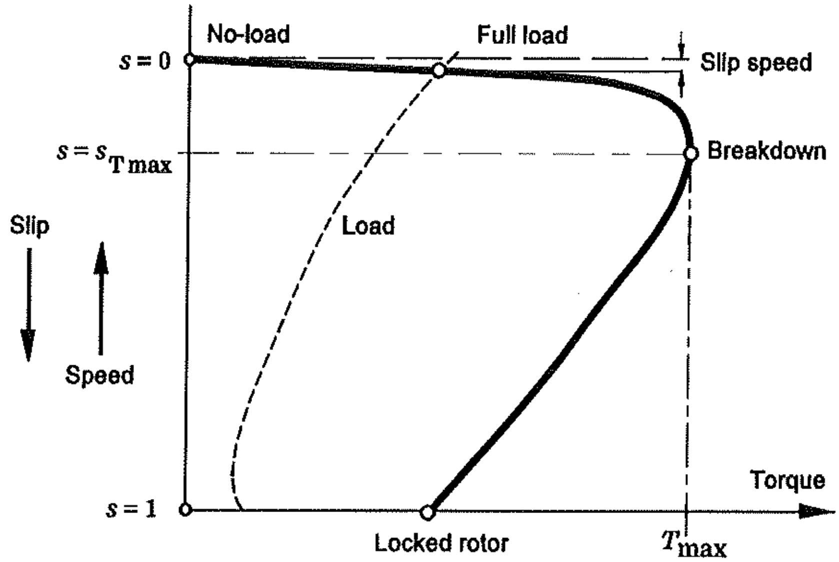
Induction Motor Torque Speed Curve



From SPEED Consortium Electric Motors Manual.

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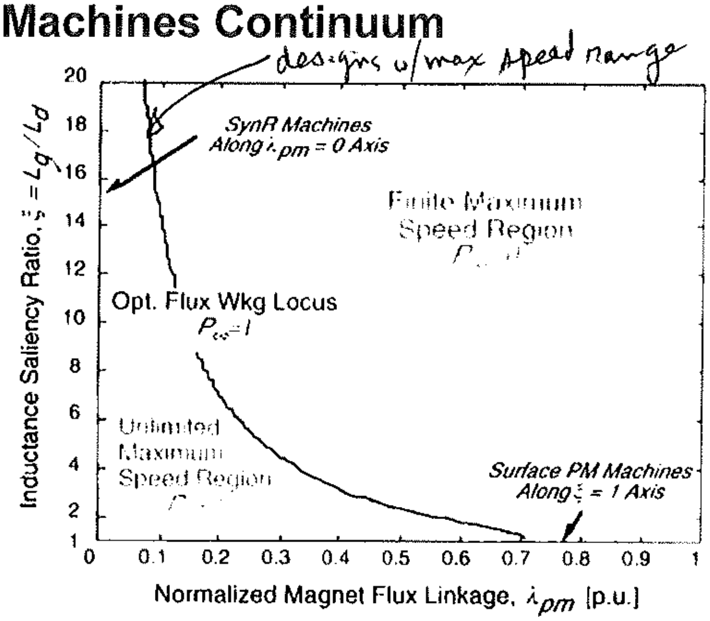
Motor Technologies: PM and Reluctance Machines Continuum



Design space for the IPM as the plane of flux linkage vs inductance saliency ratio. *From "Design, Analysis and Control of Interior PM Synchronous Machines" A tutorial from the 2004 IAS Annual Meeting, Organized by Nicola Bianchi of University of Padova and Thomas M. Jahns of University of Wisconsin-Madison.*

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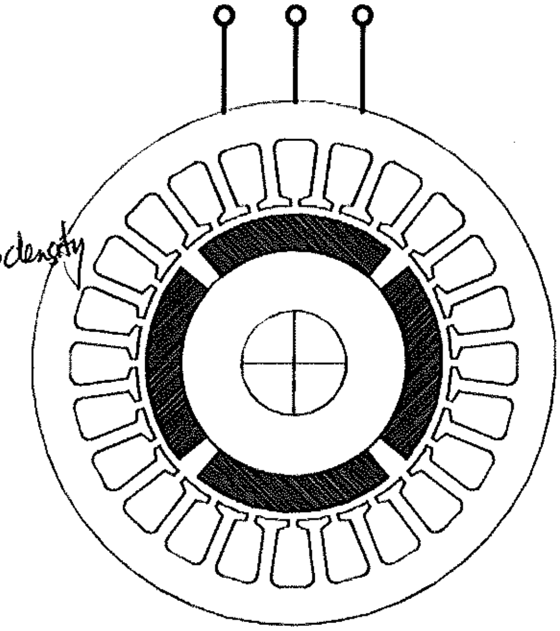
Surface Permanent Magnet Motor

- Smooth air gap motor (No saliency)
- Distributed winding
- AC excitation
- Alignment torque
- Synchronous machine
- Can use both ferrites and rare earth magnet. 10x better power density Difference is in the torque density.
- Limited speed range (limited field weakening)
- Lower right of the design space.
- Not line started.



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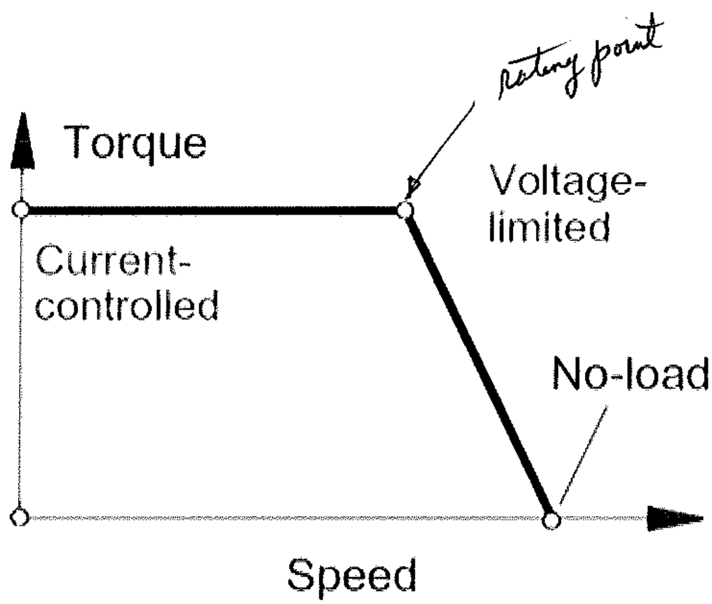
Surface Permanent Magnet Motor



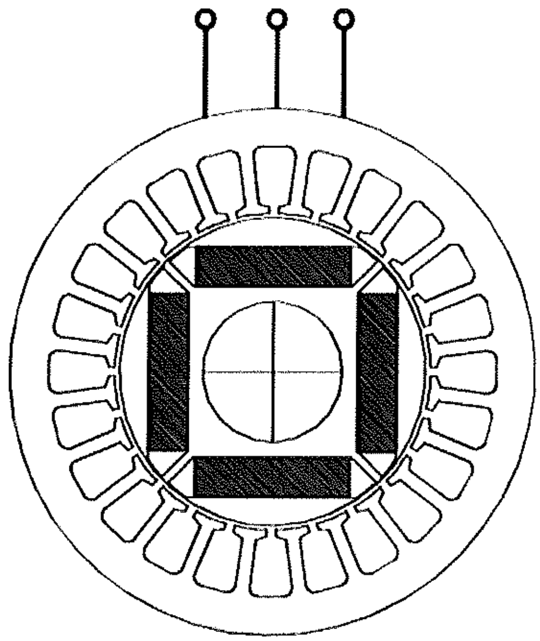
From SPEED Consortium Electric Motors Manual.

Interior PM Motor

Toyota Prius

- Single saliency
  - Rotor
- Distributed winding
- AC excitation
- Reluctance Torque and alignment torque
- Synchronous machine
- Trade off between high reluctance ratio rotor and high alignment torque rotor.
- Can use both ferrites and rare earth magnet. Difference is in the torque density.
- Depending on design has better speed range. (Better field weakening)
- Lower left of design space.
- Not line started.

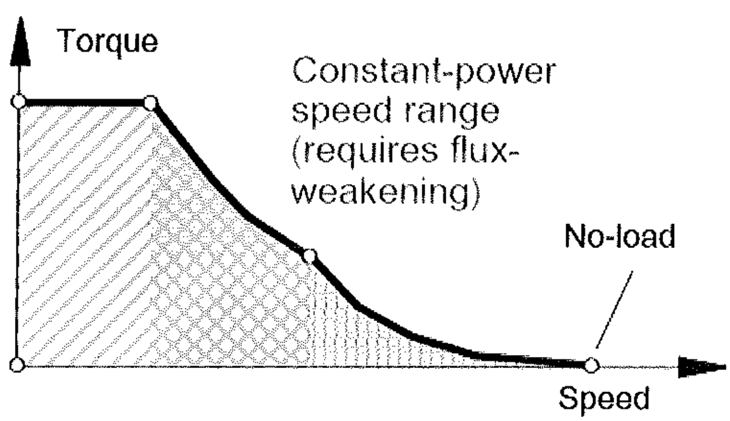
what is this tradeoff?



From SPEED Consortium Electric Motors Manual.

Interior Permanent Magnet Motor

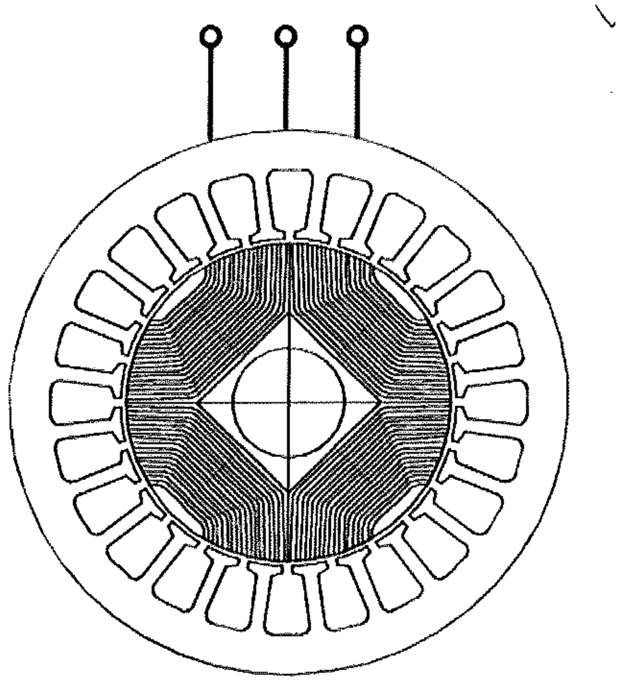
molycore Leadville, Co?
Mtn Pass CA?



From SPEED Consortium Electric Motors Manual.

Synchronous Reluctance Motor

- Single saliency
  - Rotor
- Low inertia rotor (High dynamic response
- Distributed winding
- AC excitation
- Reluctance Torque
- Synchronous machine
- Lower stability limit, depending on design
- High reluctance ratio rotor equals higher max. torque, but also more difficult to manufacture.
- Wide speed range.
- Upper left of design space.
- Could be line started, but needs to have induction rotor cage built into the rotor.



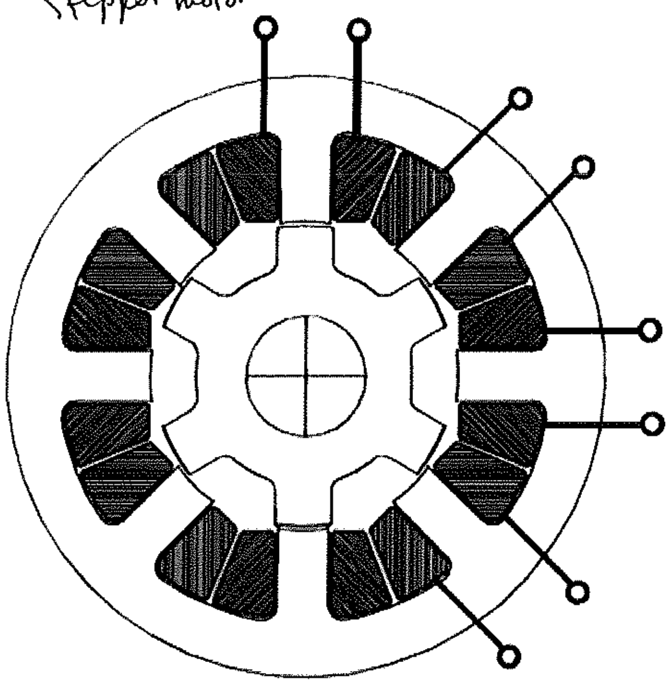
From SPEED Consortium Electric Motors Manual.

Nidek? Nidek? Natick? Niles Motor

Switched Reluctance Motor

stepper motor

- Double saliency
  - Stator
  - Rotor
- Low inertia rotor (High dynamic response
- Concentrate tooth winding
- ***Switched DC excitation***
- Reluctance Torque
- Synchronous machine
- High torque possible at low speed.
- High torque ripple.
- Noise and vibration issues.
- Fault tolerant
- Wide speed range.
- Not line started.



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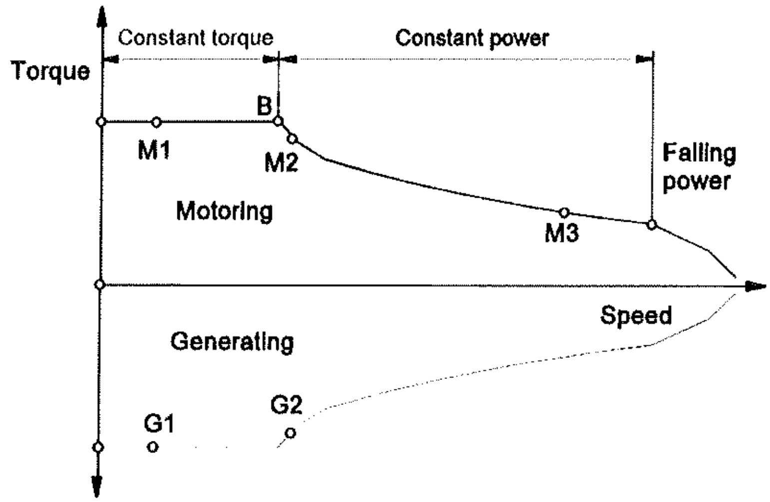
Switched Reluctance Motor



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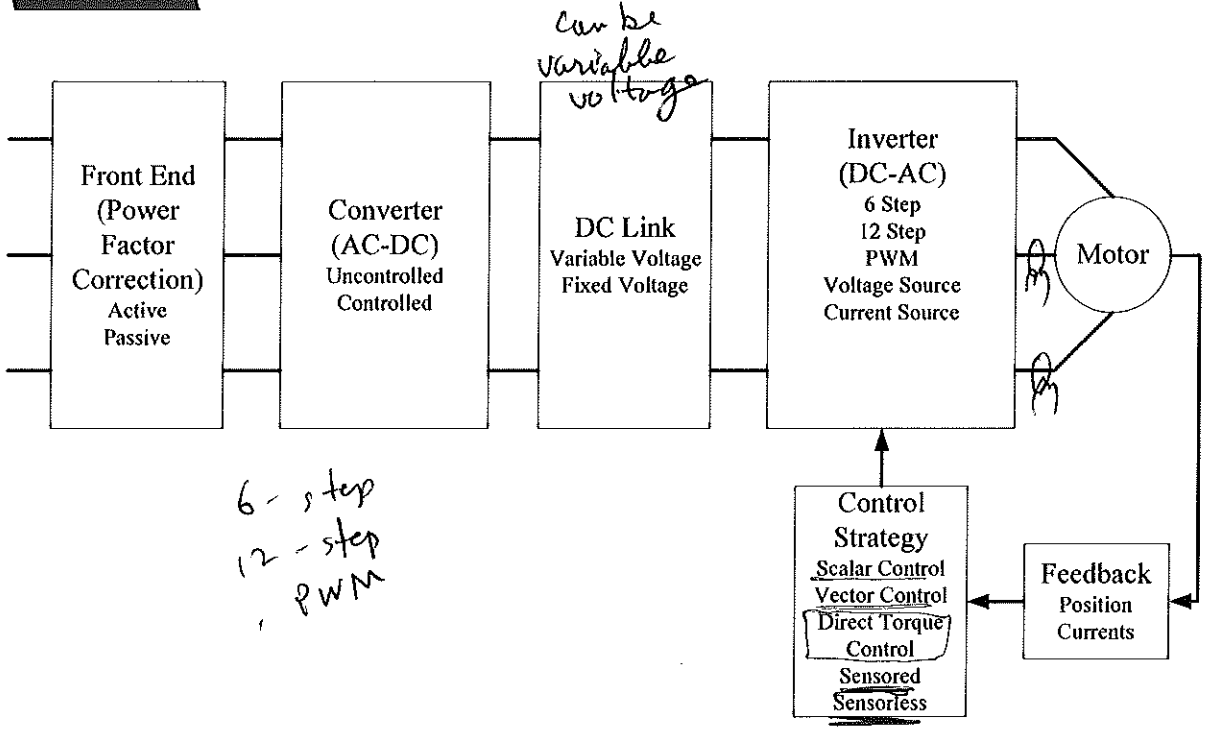
Simple AC Drive Configuration



Power Factor Correction

At. RAC terminals

- Why?
  - Lower RMS input current (up to 50% reduction compared to standard bridge rectifier)
    - Lowers energy bill
    - Enables more load capability for a given breaker
  - Lower peak input current (up to 60% reduction compared to standard bridge rectifier)
    - Reduces voltage distortion
    - Reduces stress on power lines and magnetics
    - Reduces losses in transmission equipment
    - How?
  - Passive Techniques
    - Capacitor/Inductor banks (entire facility compensation)
    - Low pass filter (single load compensation)
  - Active Techniques
    - Boost (CCM, DCM, Bridgeless)
    - Buck
    - Buck-Boost
    - Single stage, Multi-stage

Show some Typical waveforms

AC Motor Drive Nomenclature

- Scalar Control-Open Loop, Voltage and frequency of input is controlled. V/Hz → const flux
- Vector Control-Controlling the current vectors, (amplitude and phase) through controlling the input voltage and frequency.
- Field Oriented Control-Special case of vector control. Current vectors are oriented to the field.
- Field weakening-Special case of vector control, current vector directed towards countering the field component.
- Inverter duty motor-Motors specially constructed with:
  - Triple build insulation coated wires
  - Anti-shaft current provisions
  - Provisions to protect against high neutral to ground voltages.

Rotor demagnetization possibility

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Motor Design

- Initial Design Consideration From Customer Spec.
    - Power/Torque Rating
    - Speed Rating
    - Operating points
    - Efficiency Minimum
    - Class of Insulation
    - Type of load torque curve
- Translate to Design Variables
    - Magnetic loading
    - Electrical loading
    - Physical Envelope (Volume)-D^2L (Design from scratch)
    - Torque Density (Power Density)
    - Material consideration
    - Temperature rise
    - Cooling

Motor Design

- Translate to Heuristic Design Rules
    - D/L (Pancake motor Vs Submarine motor)
    - Stator/Rotor combinations:
        - Stator/rotor slot combination (induction machines),
        - Stator slot/rotor pole combination (PM and synchronous reluctance machines),
        - Stator pole/rotor pole combinations (switched reluctance machines).
    - Split ratio=Stator ID/Stator OD (Material ratio).
    - Number of wire turns
    - Winding-Concentrated Vs Distributed
    - Wire size Copper loss
    - Material choices (Copper Vs aluminum, rare earth Vs ferrites, low loss steel versus cheaper steel)

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Motor Design

- Calculate Motor Performance
  - Using circuit based motor models
    - Simple model, fast execution, less accurate*. (Induction Motors, PM, SynchRel))
  - Finite element based models
    - Complex model, slow execution, more accurate*. (All)
  - Performance at rated point.
  - Starting and maximum power performance.
  - Steady state temperature at rated and maximum points through use of current densities.
  - Flux density in the steel (Saturation).
- Compare Calculated and Desired Performance
- Adjust design to meet desired performance.
- Iterate

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Motor Design

- Complicating Factors
  - Variable speed motor designs-addition of a degree of freedom. From single rating point to numerous rating points.
  - Using variable speed drives also mean adding time harmonics. Implying additional higher harmonic torques, forces, and losses.
- Complications due to Hermetic Applications
  - Pulsating load
  - Periodic load variations. Introduces transient oscillations into the system if drive controls are not properly tuned.
  - Multiple operating point efficiency Vs. Single operating point efficiency. (EER)

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Hermetic Motor Design

light-start induction motors

- Take the desired compressor in output and multiply by a rule of thumb of X oz-in/(1000Btu). This will give the approximate torque needed to drive the compressor. This is a design point.
- Multiply the estimated maximum torque by 2.25 to get the desire breakdown torque usually defined at 5/6 synchronous speed.
- From the specification, determine the lower bound of the voltage magnitude at which the motor has to supply the desired torque . This is a design point.
- Find out from specification the amount of heat that the refrigerant and flow system can remove from the motor and that the temperature rise is consistent with the temperature class.
- From the Specification determine the minimum starting voltage.

What is a Hermetic Motor?

Characteristics

- High power density
  - Smaller package than air cooled due to refrigerant cooling
- Efficiency range (~80-96% product line dependent)
- Typically supplied to customer as Stator & Rotor "kits"
  - Some rotors supplied with shafts
  - Some stators supplied in "frames"
  - Some requests to supply bearings
- UL listing consists of material listing only
  - Materials must demonstrate compatibility with refrigerants & oils used in end application (UL984 and UL984a)
  - Customer is responsible for UL listing of compressor
- Appearance important (no loopy wires, no dings, no rust)
- Tight tolerances for mechanical interface with compressor
  - Example: Stator OD, Rotor ID

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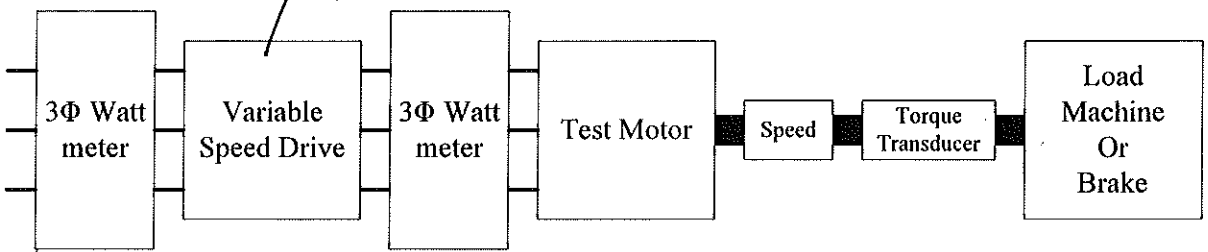
Motor Testing

- Motor Testing
  - Purpose: Verify calculated performance results, steady state thermal results, noise and vibration results.
  - Input-output testing. Voltage-frequency to Torque-speed.
  - If using drive and motor combination, separate performances for motor and drive.
- Errors
  - Metering
  - Manufacturing
  - Material
  - Thermal stability

Motor Testing

What about calorimeter MoM



How to increase $\eta_{mot\text{-}drive}$ at low speed

Application Testing

A O Smith in house

- Calorimeter Testing 85000 BTU calorimeter for residential compressor /motor testing
- System efficiency (EER) =(BTU/hour)/Input Watts
- Rule of thumb: Tons=12,000(BTU/hour)/Input Watts
- Rule of thumb: 1HP needed to drive 1 Ton.
- Plug reversal stands for reliability testing of the insulation and varnish systems.
- No Commercial testing available at Regal Beloit due to the size and complexity of the testing

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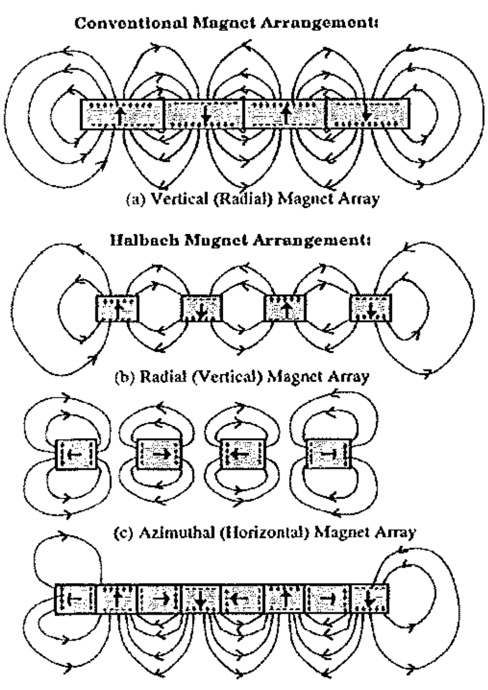
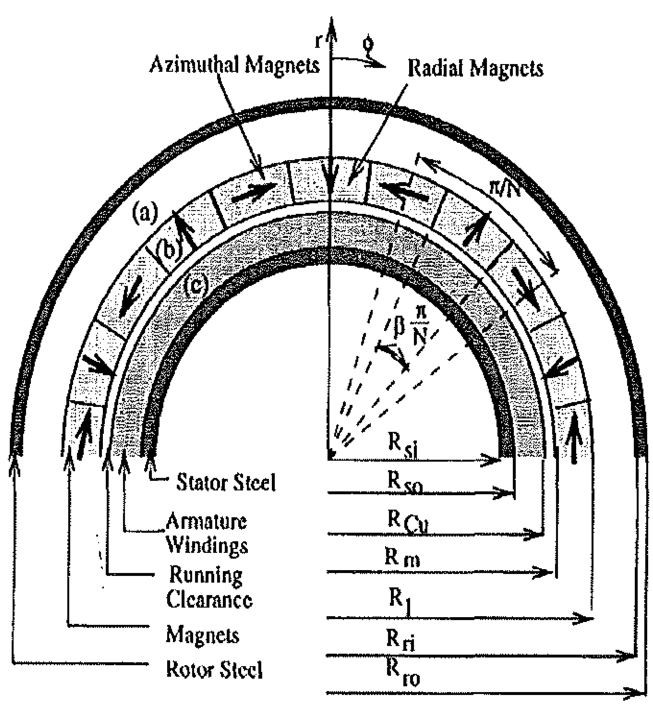
Unique Motor Topologies: Halbach Arrays





From 1995 IEEE Paper of Ofori-Tenkorang and Lang

Unique Motor Topologies: Axial Flux Motors

- Concentrate tooth winding
- Alignment Torque
- Synchronous machine
- Could be PM or could be induction.
- Same operational characteristics as radial flux except for physical envelope.
- Change in physical profile from radial flux.

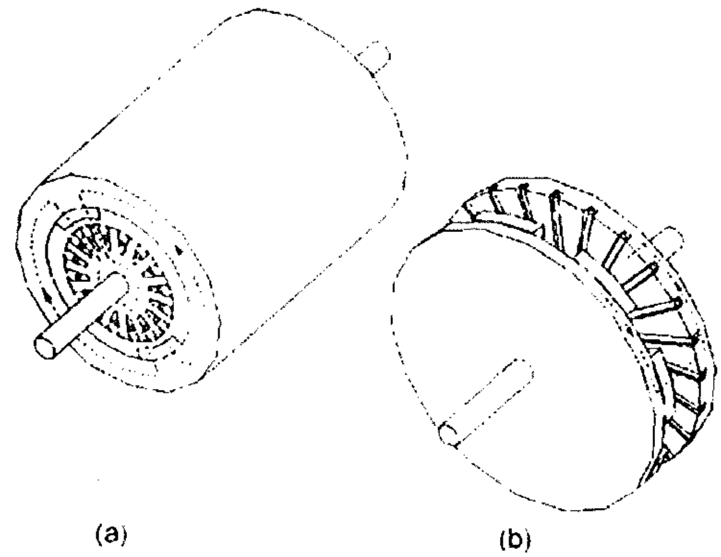


Figure 1.10. Topologies of (a) RFPM machine (b) AFPM machine.

From Axial Flux Permanent Magnet Brushless Machines By Gieras, Wang, and Kamper.

Summary

- Introduced Regal Beloit and its hermetic motor business
- Introduced fundamental relationships between Force, magnetic field and electrical current.
- Introduced existing motor technologies
- Brief introduction to motor drives.
- Brief consideration of motors, motor design, motor testing.
- Newer motor technologies.