Design, Engineering, and Manufacturing of Motors for Electric Vehicle Applications

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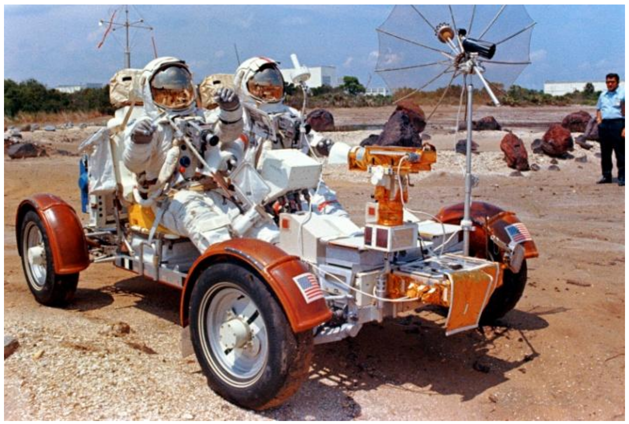
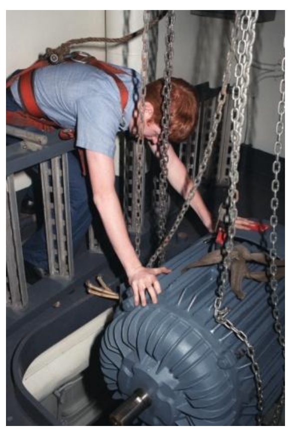
History of Electric Drives in Transportation





Why Use Electric Drives?

- Advances in power electronics as well as motor design and manufacturing have made electric drives very attractive.
- Benefits of electric drives include high efficiency with lower mass.
- By using AC induction motors, adjustable/variable speeds can be obtained by using variable frequency drive (ASD/VSD/VFD) motor current.

Motor Design Factors

- Typical motor design factors that need to be comprehended include:

Application	Environment
Commutation method	Duty cycle
No-load speed	Weight
Stall torque	Lifetime
Load (operating) point	Torque ripple
Power source	Controllability
Envelope (volume)	Heat dissipation

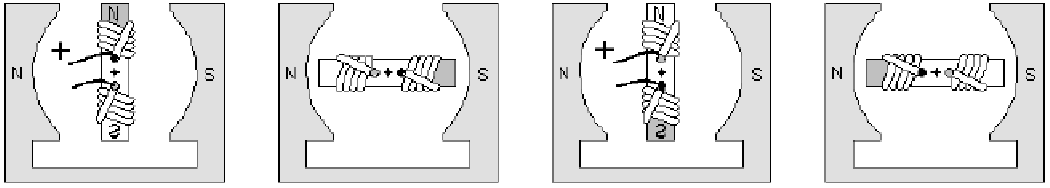
System Engineering Aspects of Electric Drives

- EMC: Goal is to minimize both conducted and radiated emissions.

- Safety:
  - *Safety aspects TAKE PRIORITY in the design of any high voltage / high current electric drive system.*
  - *Requirements for system integration (such as grounding for safety) MUST BE ADHERED TO.*
  - *If a "Best Practice" for EMC conflicts with a safety requirements – the safety requirements take precedence!*

DC Motor Construction

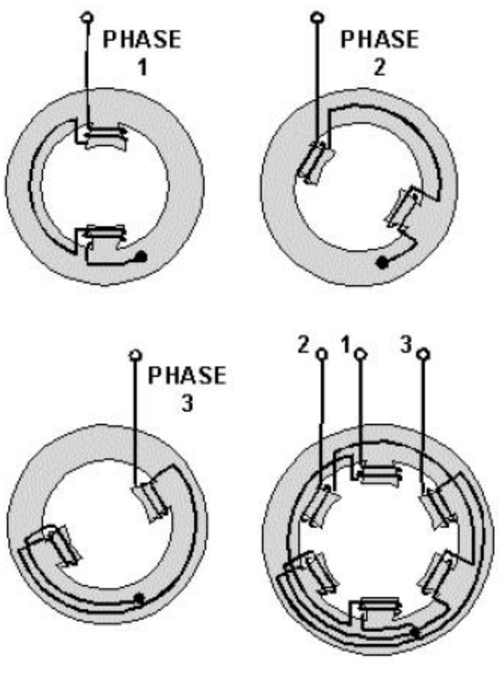
- Small DC motors (those with a wire-wound rotor contained within a magnetic field generated by permanent magnets) – operate as shown below.



Drive Motor Construction

- “Reverse” of small DC motors.
- Motor winding (“Stator”) surrounds rotor constructed with permanent magnets.
- Stator generates changing magnetic field due to AC current.
- Rotor turns as it “follows” the magnetic field that circles around the internal of the stator.

Steps in the Construction of A Stator

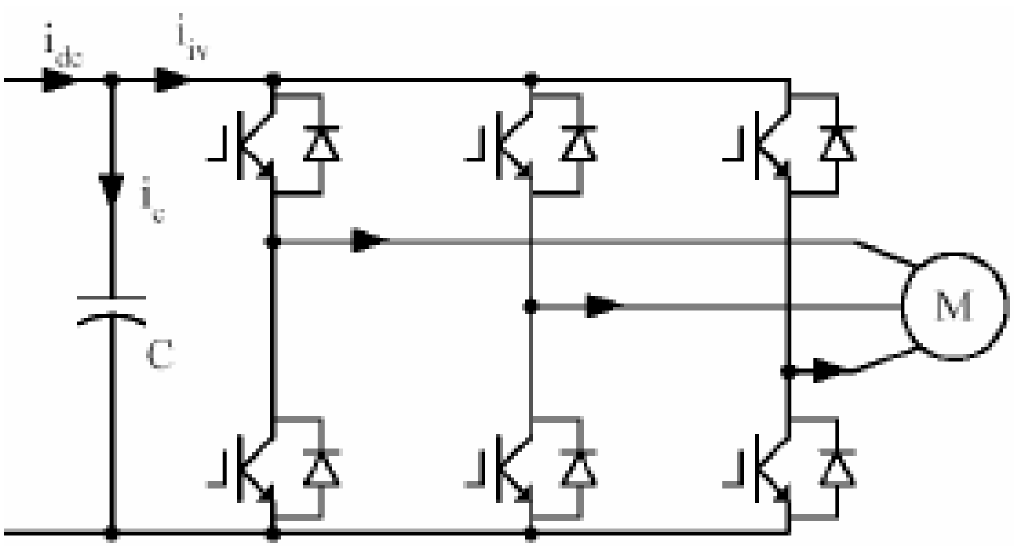


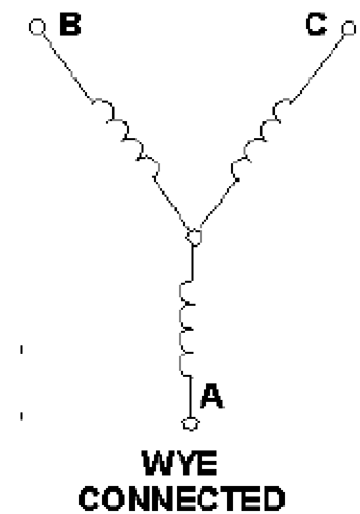
- A stator is produced that contains a number of “poles” that are used to hold the windings.
- Application of drive current for each phase generates magnetic field.

Stator Characteristics

- Results in a three-phase induction motor that operates on the principle of the rotating magnetic field.
- Windings for each phase are located 120 degrees apart around the stator.
- Phase windings are connected in a “Wye” configuration.

Schematic of Three Phase Controller and Motor Circuit





- IGBT’s generate three-phase motor drive current which is supplied to “Wye” stator windings.

Stator Winding Techniques

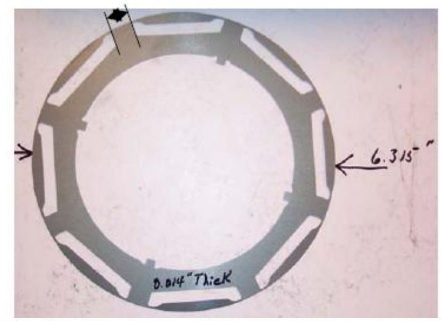
- Traditional design is parallel stator windings.
- Can also connect winding in series – this boosts torque that can be obtained (for a given current) due to doubling the turns of the that interact with the fixed flux of the permanent magnets (although it requires twice the voltage of parallel windings).

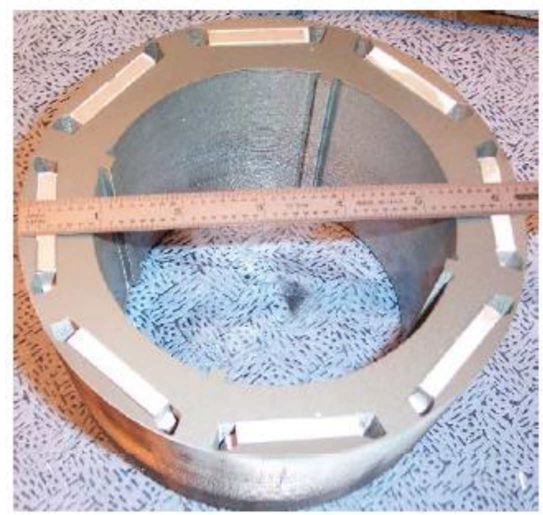
Actual Stator Construction

- Figure at right shows a typical stator from a variable speed drive motor.
- Significant portion of the stator (and it's mass) is due to the large number of windings required.

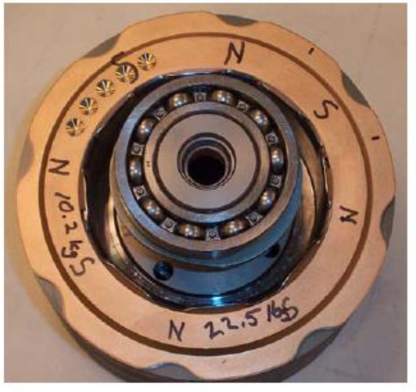
Construction of Permanent Magnet (PM) Rotor

- Rotor “layers” are produced and then “stacked”.
- High strength permanent magnets are inserted into rotor stack.





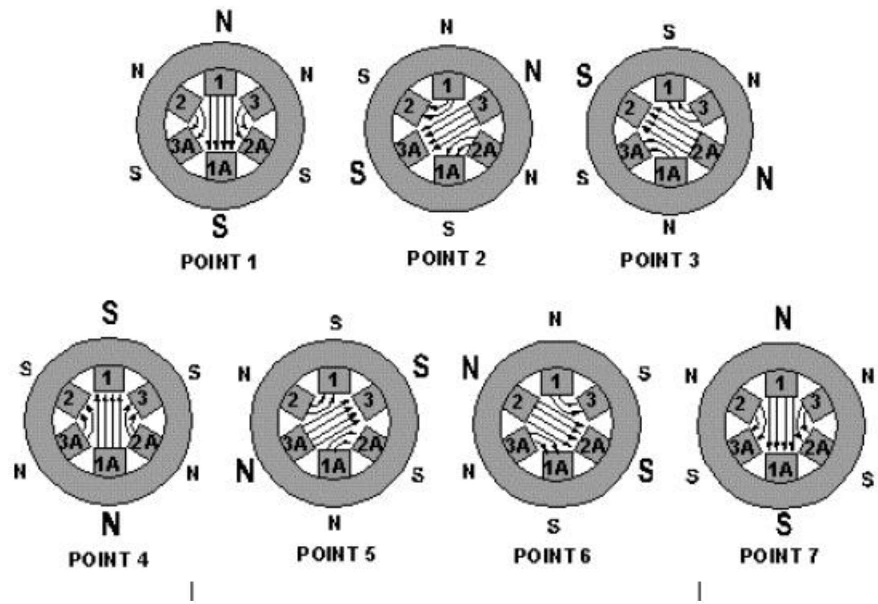
Complete PM Rotor Assembly



- Result is that the rotor contains high-strength permanent magnets arranged around the shaft.
- “Movement” of field in stator causes magnets to try to track the field – resulting in rotation.

Example of Rotor Positioning

- Magnetic field polarity from poles causes rotor to move in an attempt to align permanent magnets with field from stator.
- As field moves from pole to pole – rotor turns.



Motor Speed Control

- Speed of induction motor is dependant on the motor design.
- The motor operates at “synchronous” speed – which is the speed that the stator magnetic field rotates.
- Determined by the frequency of the AC input *and* the number of poles in the stator.
  - As the poles increase – the speed decreases.
  - As the frequency increases – the speed increases.

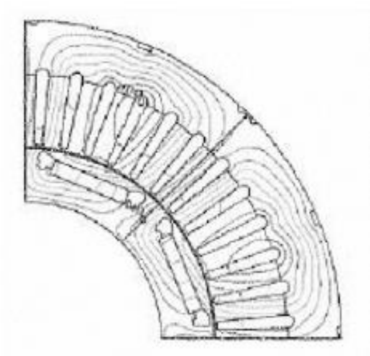
Induction Motor Speed Determination

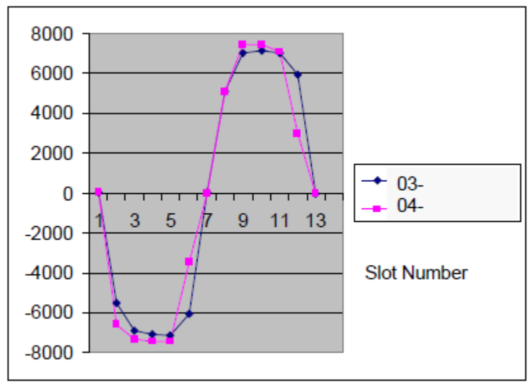
- The speed of a induction motor is known as the synchronous speed and is determined by the following relationship:

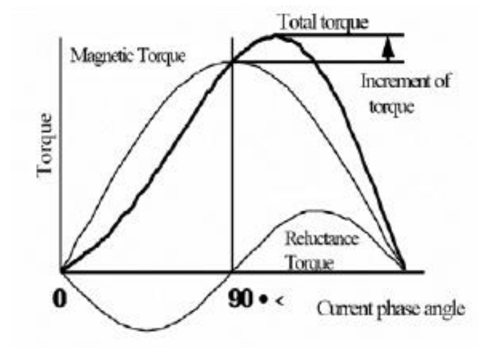
$$RPM = 120\ f\ /\ NP$$

- The speed is directly related to the applied frequency (f) in Hertz and inversely related to the number of poles (NP).

Simulation and Analysis







- For optimum design decisions – electromagnetic analysis can be done to determine torque and current phase-angle characteristics.

Actual Rotor Mechanical Speed

- Rotor mechanical rotation does not achieve same speed as magnetic field rotation.
- Rotor “lags” behind the magnetic field due to “slip” – which must occur in order for the motor to operate.
- Slip is typically a few percent of the field rotation.
- For synchronous speed of 3600 rpm – the rotor speed would be approximately 3400 to 3500 rpm.

Typical Electric Drive Motor Specifications

- The motor shown at left has an output capability at 1500 RPM of:
  - 50 kW (approximately 67 hp)
  - 400 NM (approximately 300 ft-pounds).

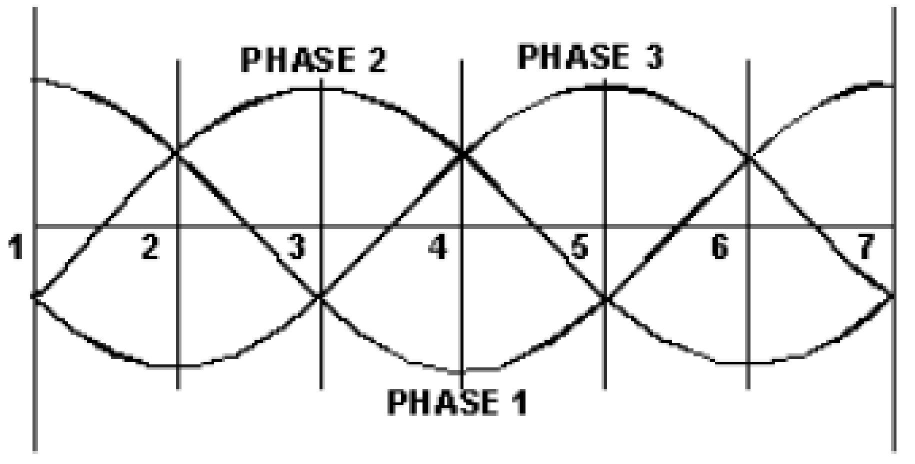
Electric Drive Control Systems

- Control systems for electric drives typically consist of active switching of the primary current for the motor (similar to basic switching power supply).

- Output voltage is determined by switching speed and "on" duration of the drive transistor's).

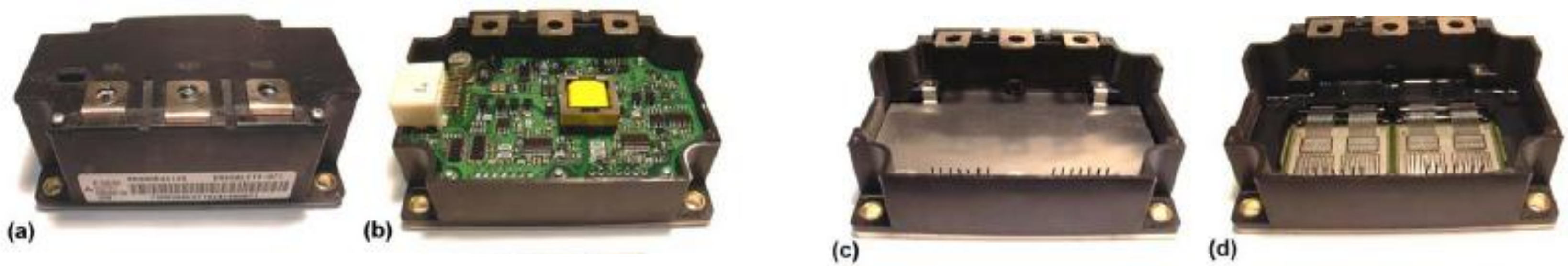
- Multiple phases can be obtained by utilizing multiple driver transistors with appropriate timing.

Motor Drive Waveform



- Three-phase waveform used for motor operation.
- Each vertical division represents 60 degrees.
- A voltage (current) maximum occurs at each 60 degree increment.

Examples of Electric Drive Controller

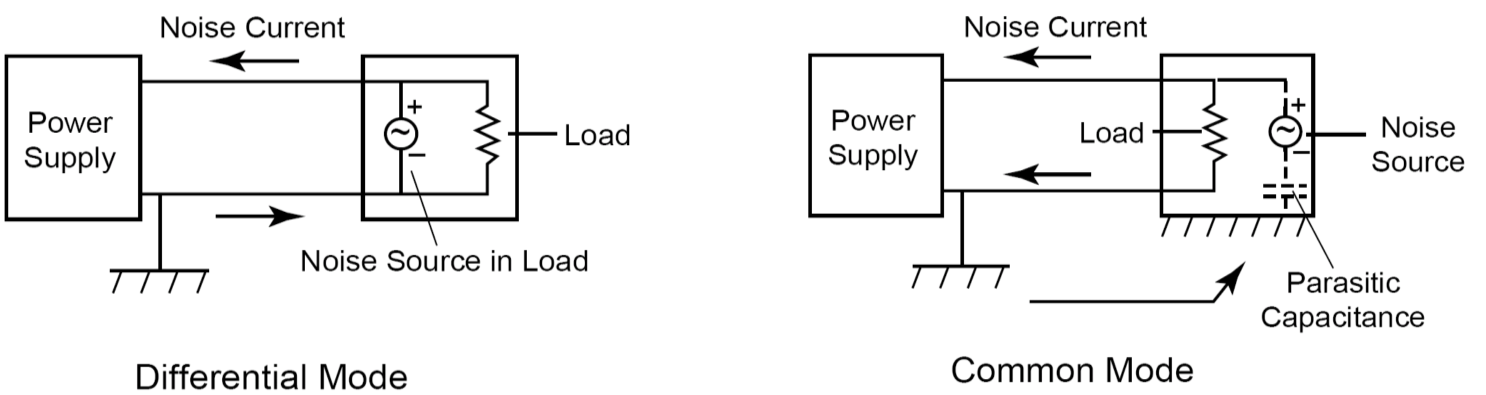


- Figures (a) and (b) show the control electronics.
- Figure (c) shows an EMC shield over the IGBT's to prevent noise from affecting low-level signals.
- Figure (d) shows the driver IGBT's.

Controller Design Goals

- The advantages are the following:
  – Changing the frequency and/or the duty cycle (pulse width) will change the motor speed.
  – High efficiency due to minimal time that the switching devices are in their linear operation condition.
- The trade-offs in order to achieve these advantages need to be understood to minimize resulting CE issues.

Causes of Electric Drive Conducted Emissions



- Differential Mode Current – Consequence of intentional motor drive current.
- Common Mode Current – Current “loops” by coupling through motor parasitic and structures.

Balancing EMC and Control System Requirements

- Important to understand the impact of fast “slew rate” operation with power drive devices such as Insulated Gate Bipolar Transistors (IGBT).
- The switching operation results in low power dissipation along with:
  - Possible of operation at an order of magnitude faster than the response time of electromechanical devices.
  - Causing radiated/conducted emission issues.

Summary

- Electric variable speed drives are becoming more common and have advantages over previous systems.
- Can have EMC issues due to:
  - CE and RE caused by common mode and differential mode current.
  - Important to understand motor actual characteristics and system architecture contribution to these currents.
- Understanding the process of drive motor design and manufacturing can minimize EMC issues!