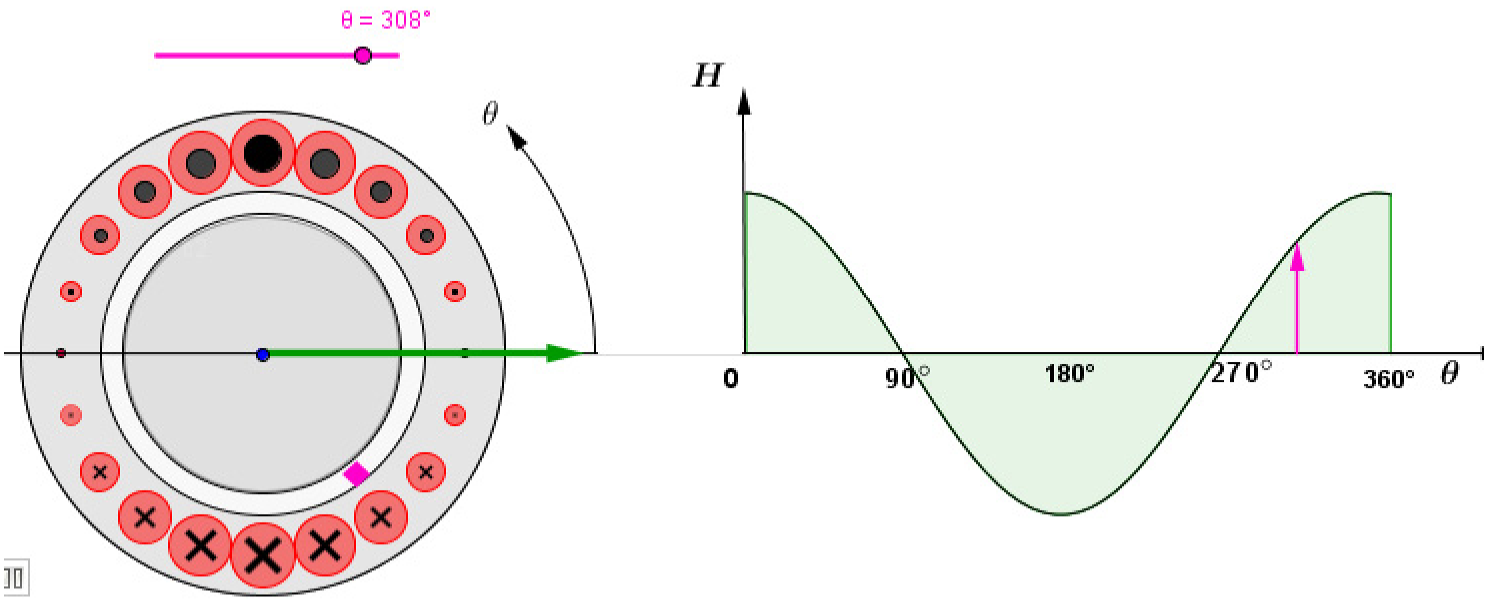
Supplemental Materials

PM Motor Design

BLDC-vs-PMSM

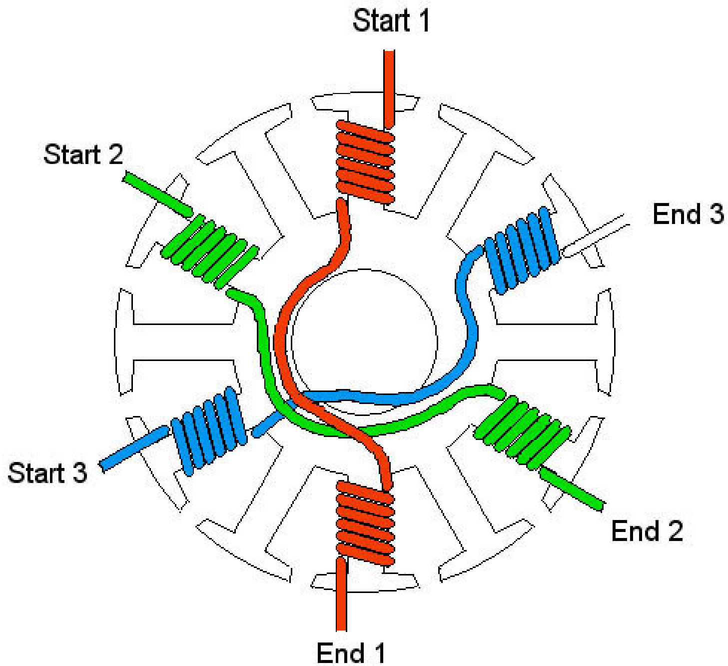
Shape of Back EMF – PMSM Winding

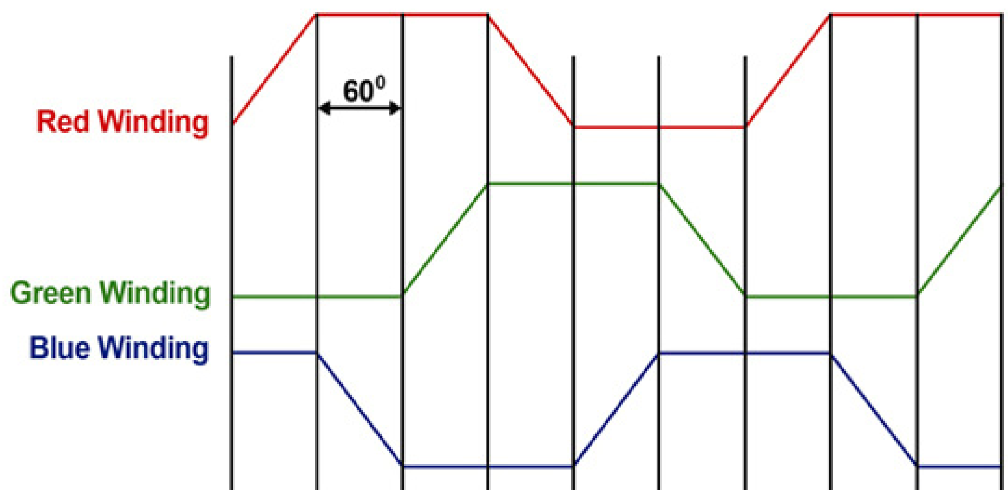


- Sinusoidal back EMF achieved with sinusoidal winding distribution
- Generally termed Permanent Magnet Synchronous Motor (PMSM)

BLDC Motor Winding

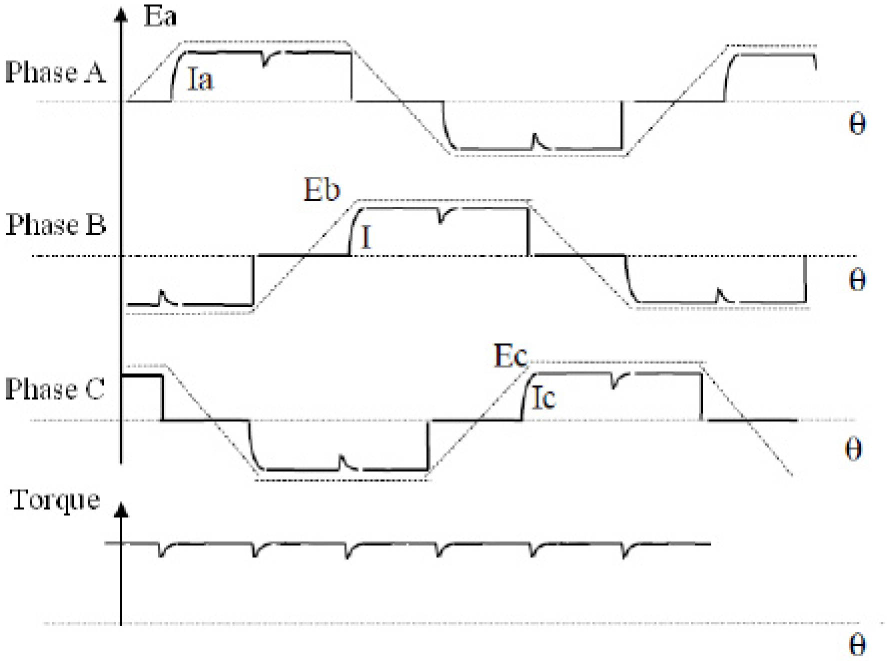
http://web.eecs.utk.edu/courses/spring2015/ece482/materials/brushless-motor.swf

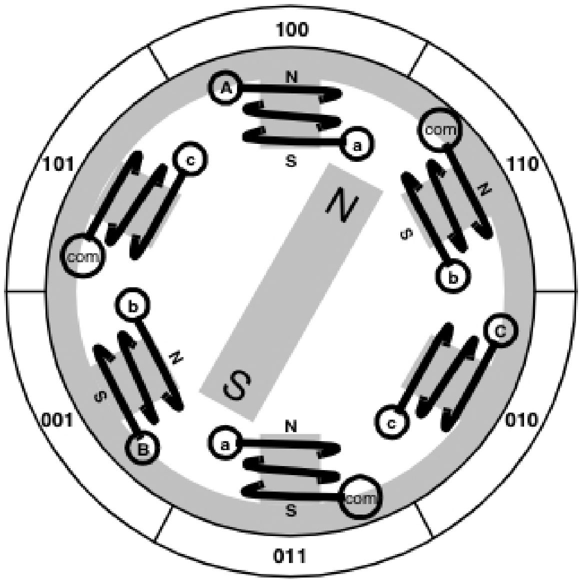




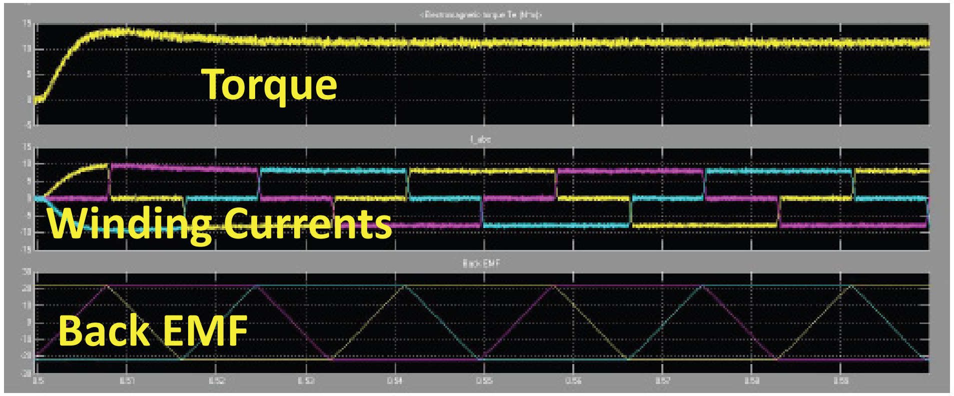
- Brushless DC (BLDC) Motors are not wound sinusoidally
- This results in Trapezoidal back emf, rather than sinusoidal
- Can be driven simply with Square-waves to achieve relatively low torque ripple

BLDC Waveforms During Rotation

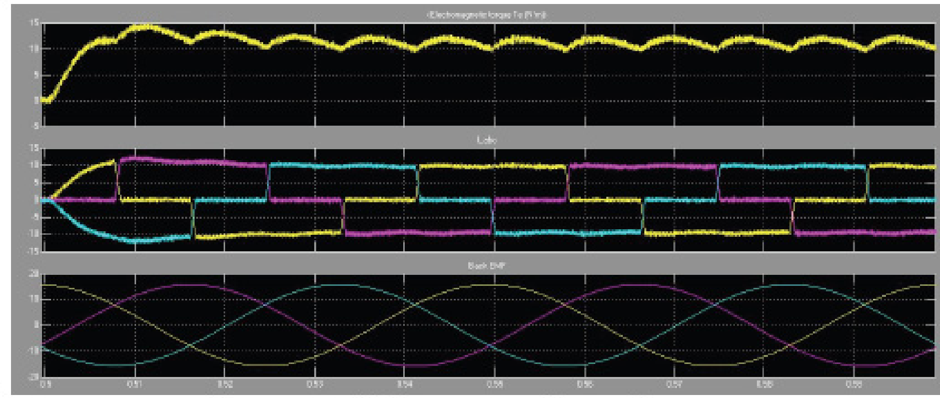




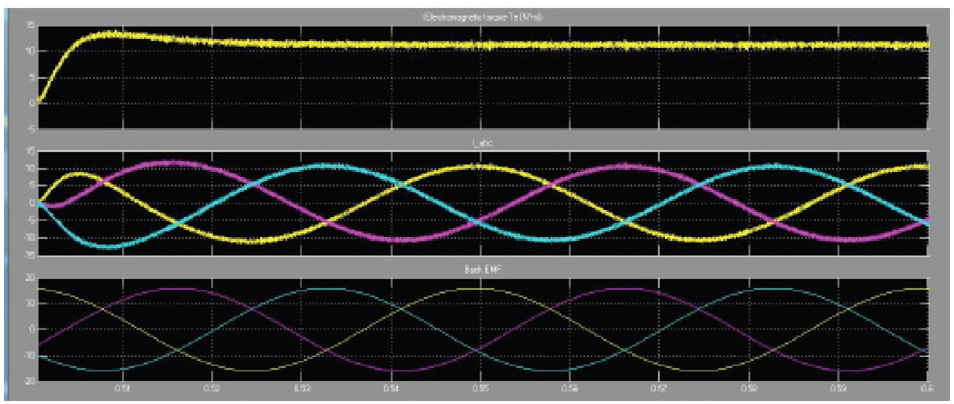
Simulation of BLDC and PMSM



(a) Trapezoidal commutation with BLDC



(b) Trapezoidal commutation with PMSM



(c) Sinusoidal Commutation with PMSM

- Low Torque ripple when BLDC driven by square waves or PMSM driven by sinusoid
- Moderate torque ripple when PMSM driven by square waves

Outer- vs. Inner-Rotor

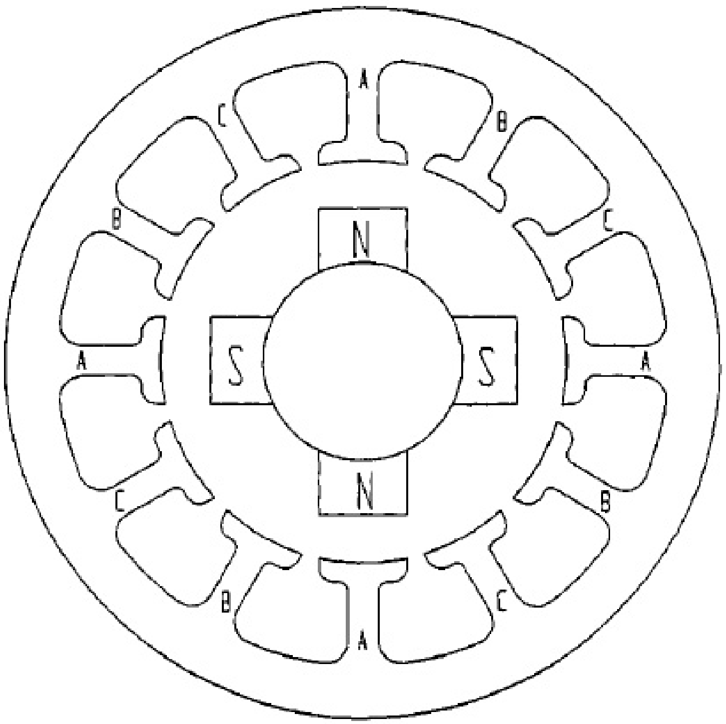


FIGURE 5.15 Multiphase inner-rotor motor.

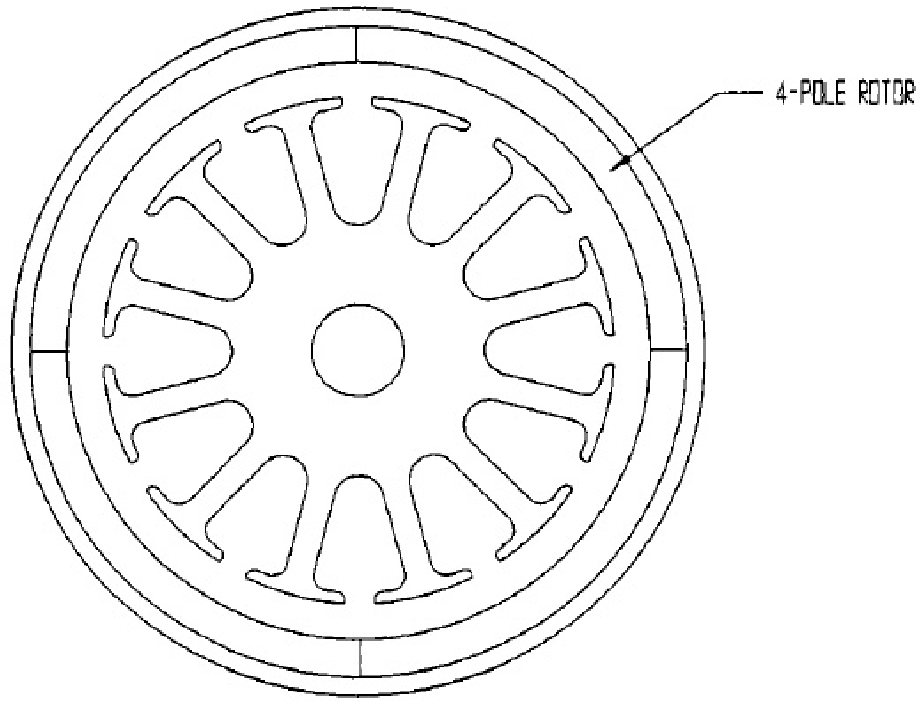


FIGURE 5.13 Multiphase outer-rotor motor.

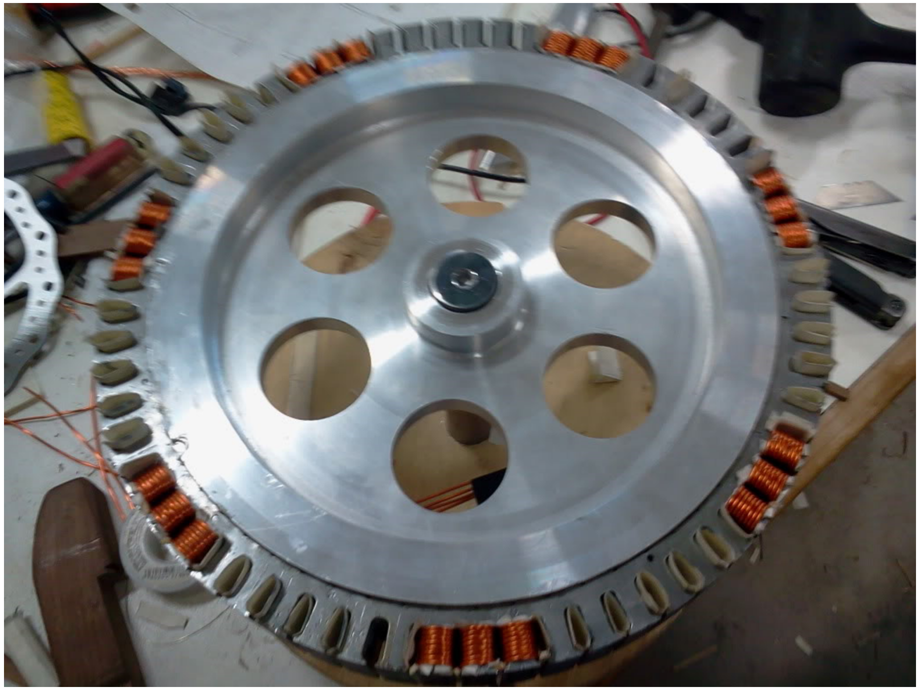
- Traditional motors are inner-rotor
- On e-bike, need hub to remain stationary and outer wheel to spin

Example Front Wheel Hub Motor

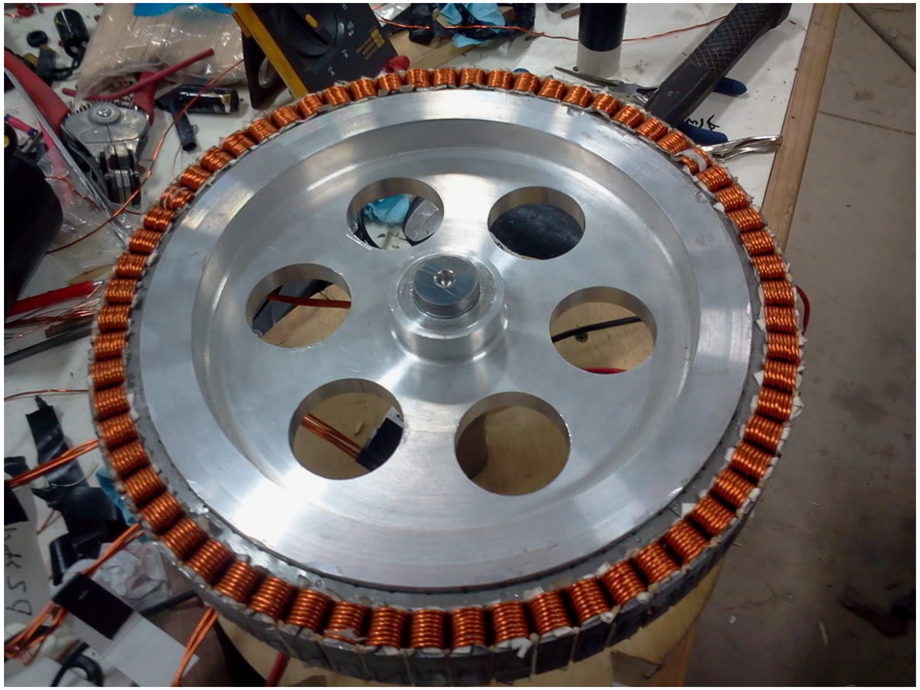
E-bike hub (stator)

Single phase wound per tooth

Stator Winding



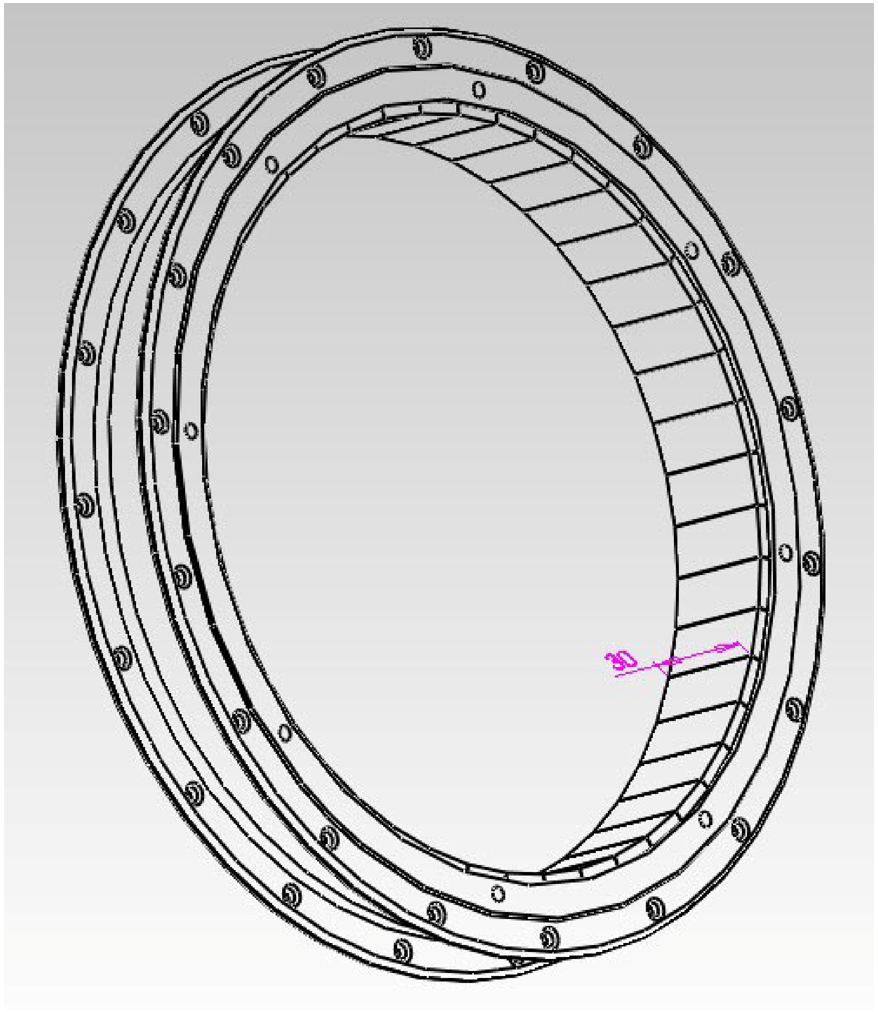
Complete winding of Phase A



Complete winding of all phases

56 pole
63 teeth

Rotor and Poles



- Outer rotor (to which spokes/wheel are attached)
- Magnets alternate N-S

Example Comparison of Inner/Outer Rotor

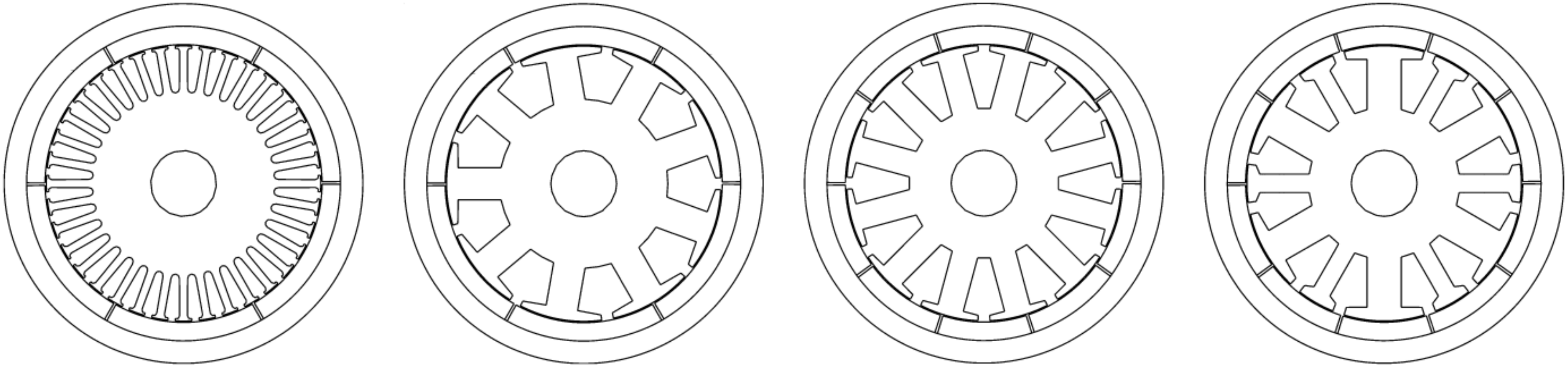
TABLE 5.1 Comparison of Outer-Rotor and Inner-Rotor Motors

Outer rotor	Inner rotor
Shorter end turns yield lower inductance and less copper loss.	Longer end turns yield higher inductance and more copper loss.
Greater rotor inertia.	Lower rotor inertia.
Less torque perturbation.	More torque perturbation.
Slower acceleration.	Fast acceleration.
Lower-energy magnets can be used.	Higher-energy magnets required.

TABLE 5.2 Inner-Rotor Versus Outer-Rotor Motor Applications

Requirement	Inner rotor	Outer rotor
Rapid acceleration	Very good	Poor
Heat dissipation	Very good	Poor
Low cogging	Okay	Good
Pump application	Okay	Good
Disk-drive application	Poor	Very good
Fan application	Poor	Very good
High side load	Good	Poor
Use with speed reducers	Good	Poor to okay
Reversible	Very good	Poor

Motor Teeth/Poles Example



(a)
36-slot/6-pole

(b)
9-slot/6-pole

(c)
12–slot/10-pole
(all teeth wound)

(d)
12-pole/10-pole
(alternate teeth wound)

Number of Phases

- Single:
  - Poor conductor utilization
  - High torque ripple
  - Unable to start from stall reliably

  + Easy to wind
  + few power switches

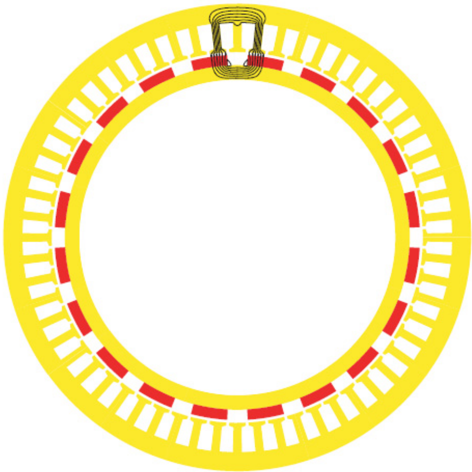
- Two:
  - Poor conductor utilization
  - Minimum 4 power switches

  + reliable starting
  + reduced torque ripple

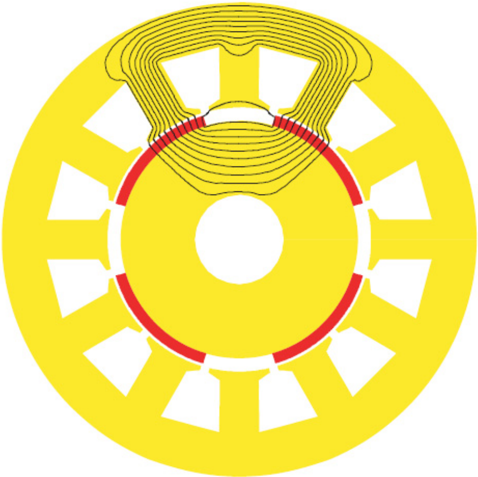
- Three
  - costly to wind

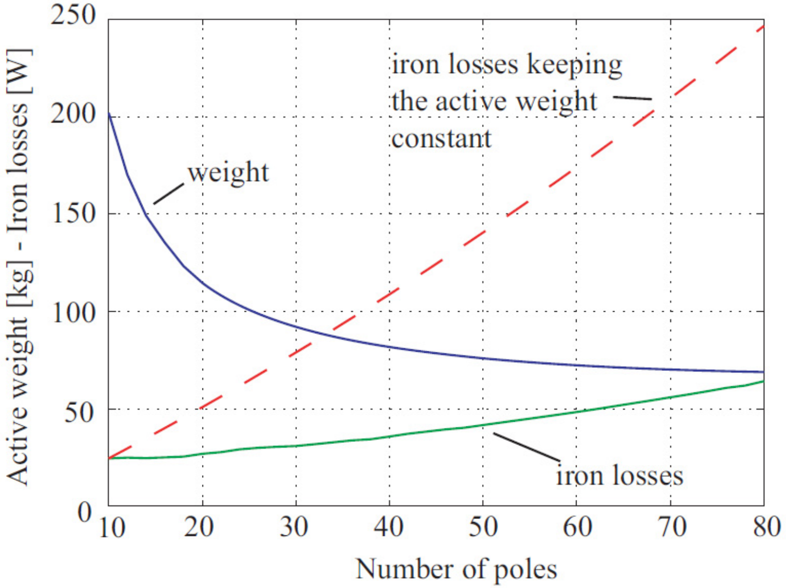
  + Good conductor utilization
  + as few as three switches

Number of Poles



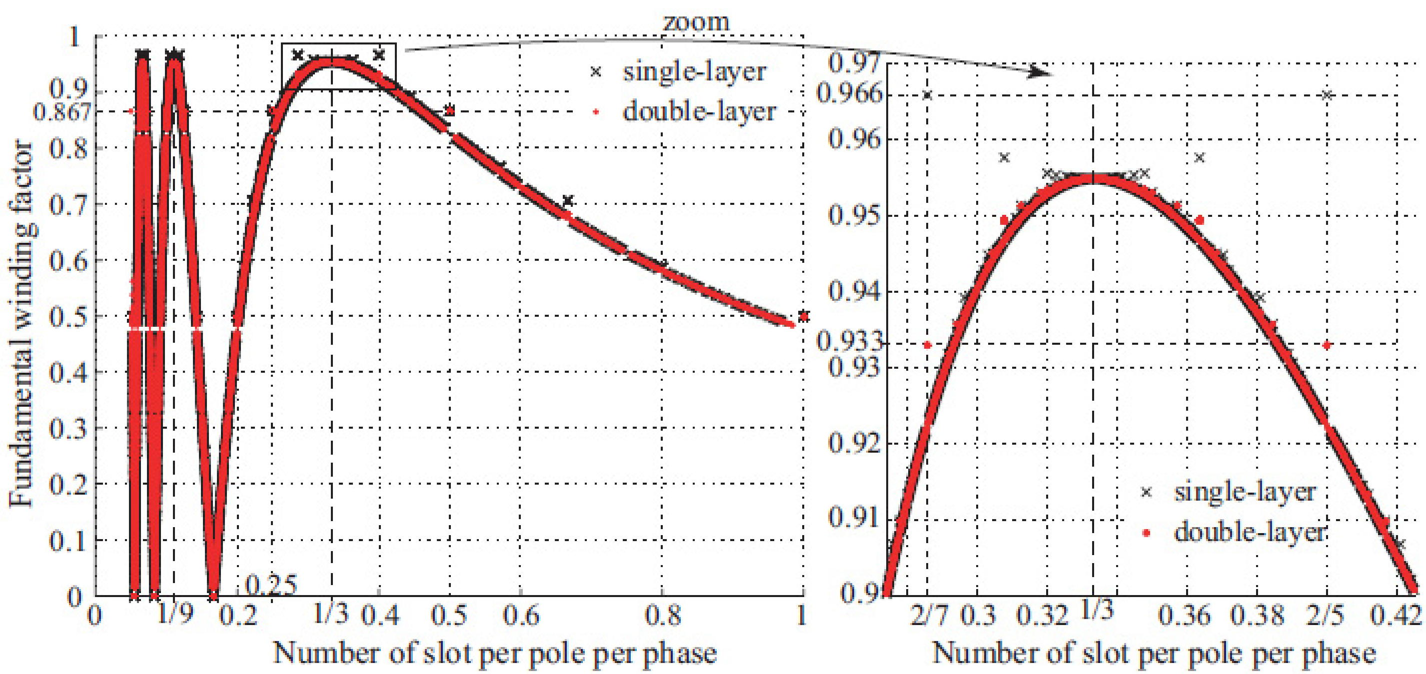
- flux spread over more poles, reducing flux density
- less magnetic material required on stator to prevent saturation
- Higher part count and assembly time
- Higher electrical frequency



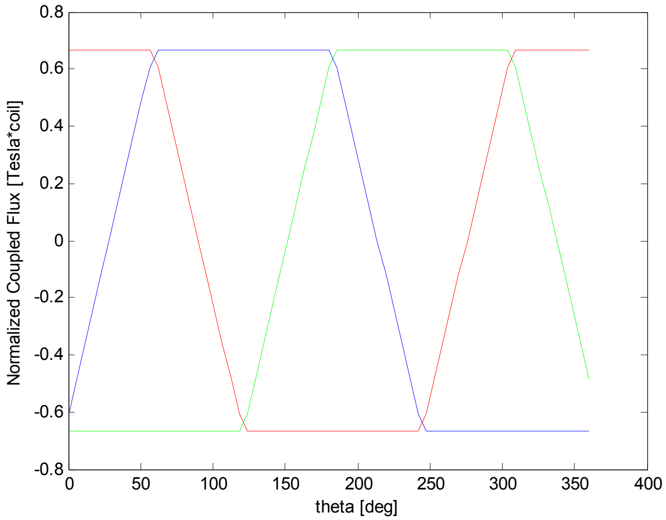


Number of Teeth

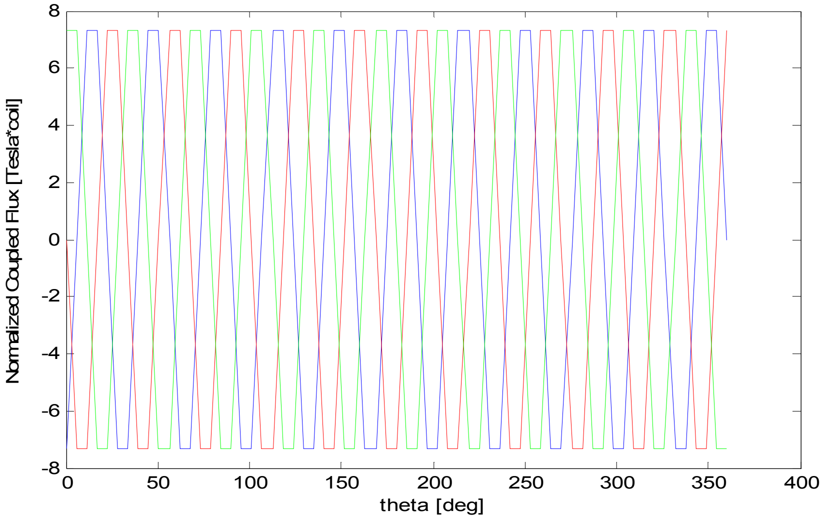
- Back EMF determined by "Teeth Per Pole Per Phase"
- Can be used to smooth out back EMF without sinusoidal winding



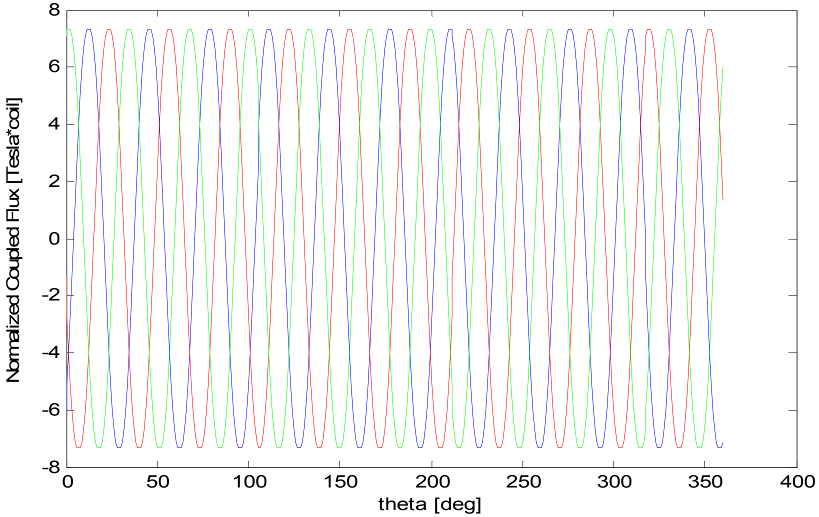
Teeth Per Pole Per Phase



- 33 Teeth, 2 Poles

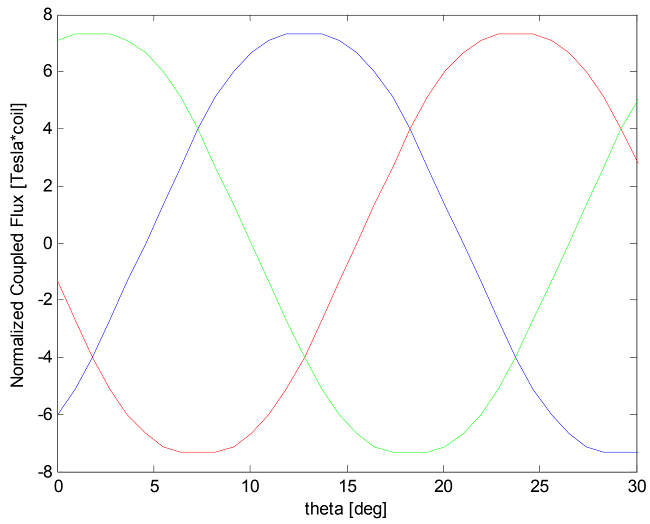


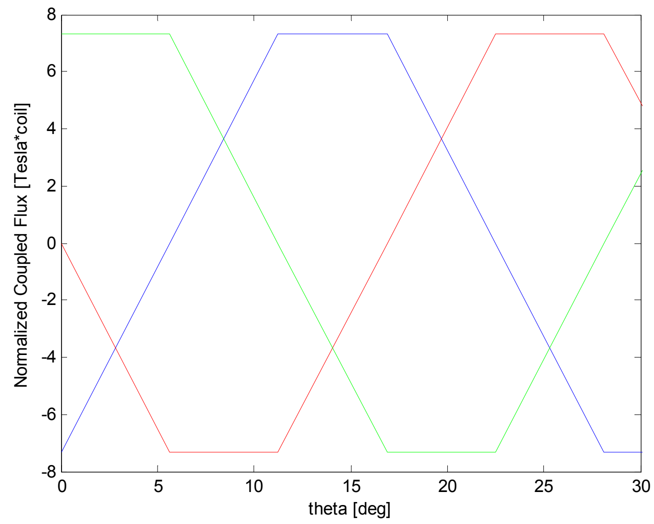
- 33 Teeth, 22 Poles



- 36 Teeth, 22 Poles

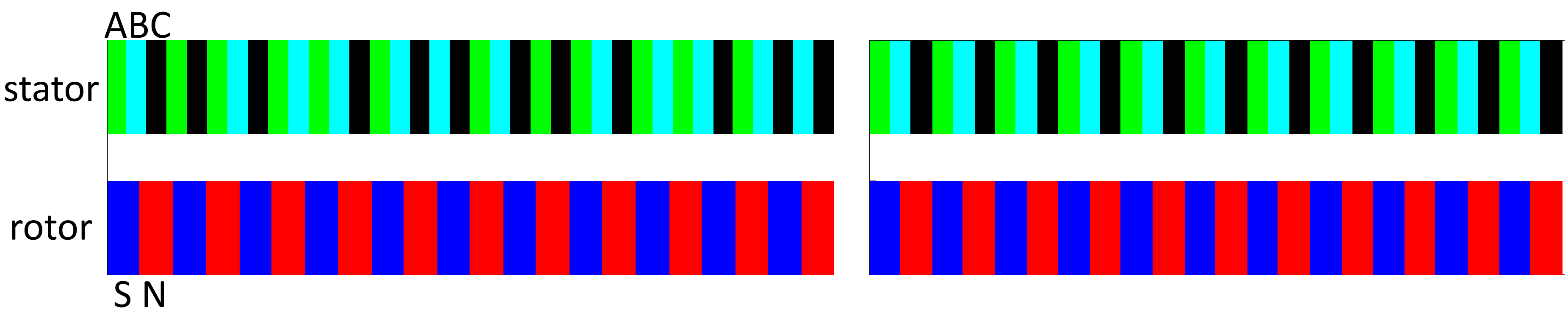
Shape of Back EMF





- 36 Teeth, 22 Poles
- Teeth/Pole/Phase = 0.5455

- 33 Teeth, 22 Poles
- Teeth/Pole/Phase = 0.5



General Effects of Design Alteration

TABLE 5.4 Effects of Changing Number of Poles, Teeth, and Phases

	Effect on design factors				
Change	Cogging	Speed	Torque	Active material utilization	Cost
Number of poles					
Increased	Decreases	Decreases	Increases	Increases	Increases
Decreased	Increases	Increases	Decreases	Decreases	Decreases
Number of teeth					
Increased	Decreases	No change	No change	Increases	Increases
Decreased	Increases	No change	No change	Decreases	Decreases
Number of phases					
Increased	Decreases	No change	No change	Increases	Increases
Decreased	Increases	No change	No change	Decreases	Decreases

Example Design Procedure

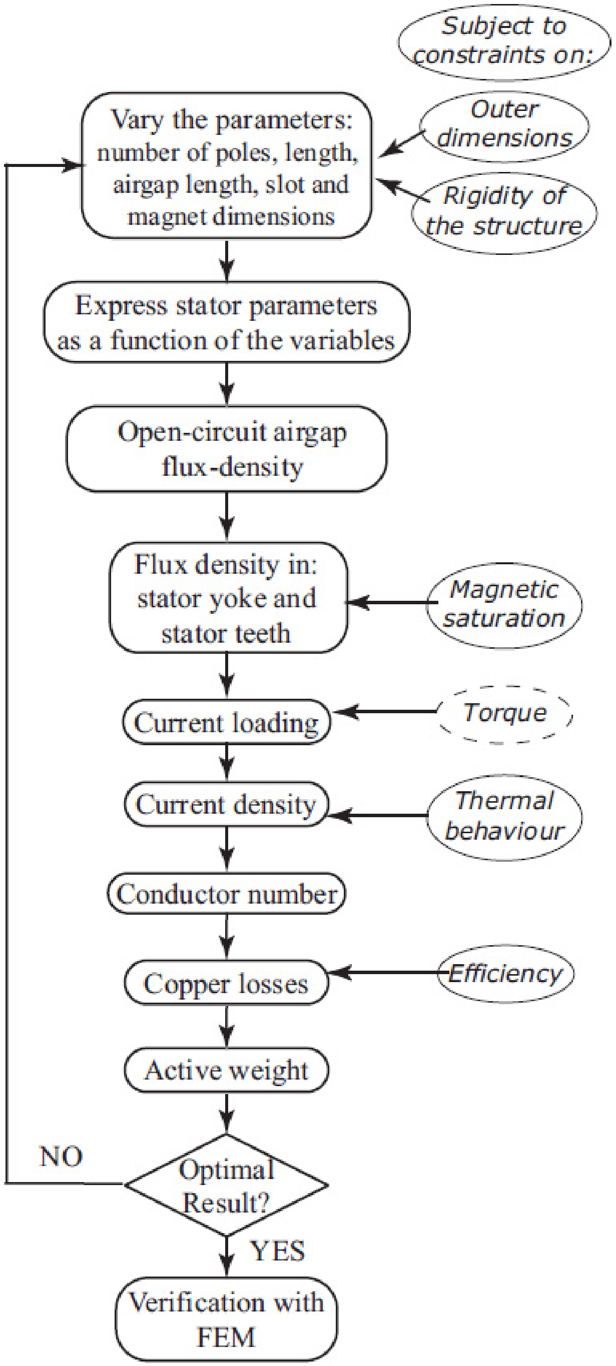


Figure 4.1: Optimization procedure.

FEM Simulation of Motor