Vehicle Design Summit Electric Hub Motor (V2)

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Motivation

- The AHPV from VDS 1.0 used an expensive, NGM electric hub motor, costing roughly $8000. (picture on right)
- VDS 1.0 required a new electric hub motor to serve as both a replacement for the NGM motor, and as a stepping stone design for VDS 2.0.

Requirements (Preliminary)

- 10 kW continuous Power
- 90%+ efficiency optimized for 45 miles an hour.
- Motor weight less than 30 kg
- Must interface with EV-C200 controller
- Acceleration from 0-60 mph in less than 15 s.
- Solar/Battery power must be used
- Constant Torque with speed variation

Constraints

- Motor must fit between wheel and suspension arm, not interfere with other components
- Motor cannot draw more power then controller can supply

- Torque must not surpass limit of suspension arm bolt hole

Preliminary Design Choices

- Design Choices → Why did we decide to design a 3-phase, axial gap, double sided, slotted, surface mounted brushless DC motor? Note, these design choices were made based on research, not simulated optimization.
- Brushless Hub Motor → Comparison to Brush Hub Motor
  - higher efficiency and reliability (reduction of electromagnetic interference)
  - reduced noise
  - longer lifetime (no brush erosion)
  - However, more difficult to control (resolved by digital control)
- Why 3-phase?
  - Excellent starting conditions with smooth rotation and low torque ripple → No structural resonance and induced mechanical stress
  - Flexible → Work with large variety of magnet configurations, winding configurations, and coil winding
  - Good conductor utilization → Higher phases give better utilization but are offset by increased numbers of leads and transistors

Preliminary Design Choices (Continued)

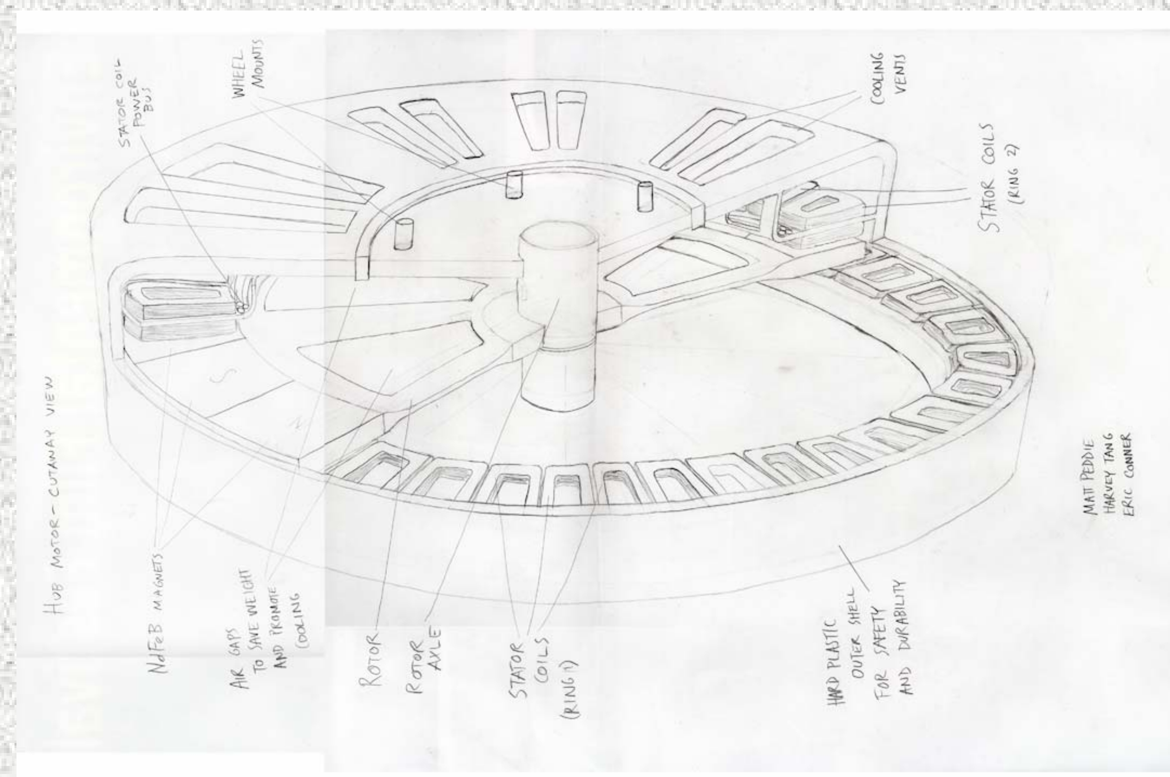
- Why axial gap?
  - Spatial limitations → Motor must interface with suspension arm; fixed dimensions.
  - Axial Gap gives compact machine construction and short frame with much shorter rotor in axial direction, and thus less overall thickness
  - High power density.
  - High efficiency; no rotor copper losses due to permanent-magnet excitation.
- Why double sided air gap?
  - The high attractive force between the rotor and the stator is counterbalanced by the use of a second stator.
  - Reduced copper and iron losses
  - Increased power density.
  - Increased cooling characteristics

Preliminary Design Choices (Continued)

- Why slotted armature?
  - A motor with armature slots is more robust
  - Allowance for different winding structures
  - Although the slotted armature implies increased losses from flux ripple and tooth iron losses, the increased robustness is necessary to combat the mechanical stress.
  - Slotted armatures give higher airgap flux density levels using fewer permanent magnets.
- Why surface mounted permanent magnets?
  - Much easier construction and manufacturing compared to interior permanent magnets

Design Variables

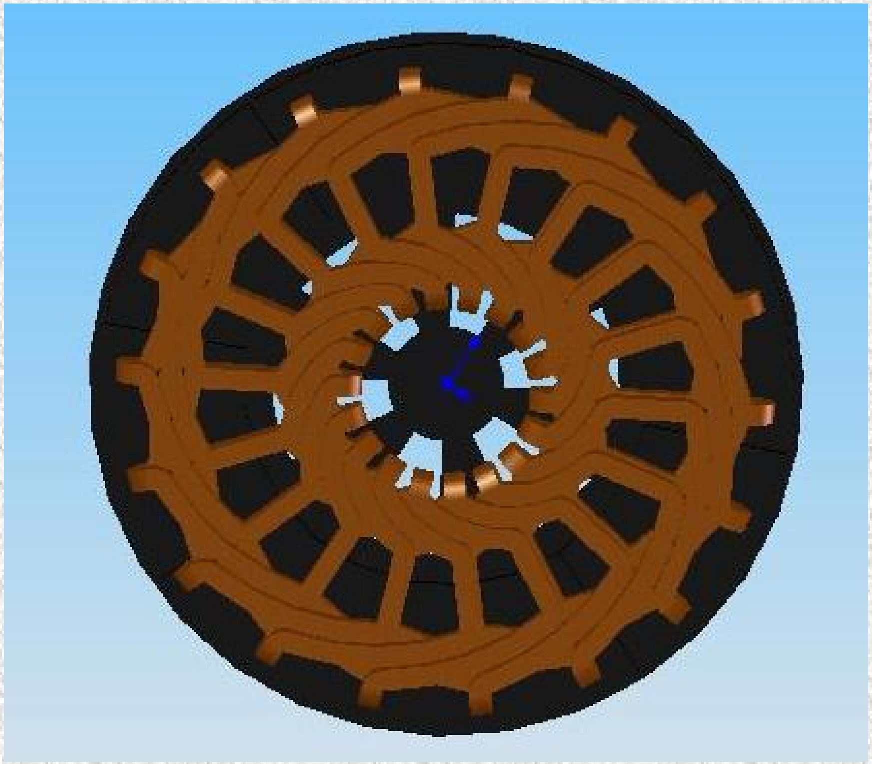
- How did we optimize our motors number of poles, stator slots, magnet span, coil turns, magnet grade, magnet skew and air gap length?
- Maxwell3D was used as a means of running dynamic optimization → Program errors would not allow use of Maxwell's optimization toolbox → Several configurations were analyzed separately so that various trends could be analyzed for an optimized engine



- On the right is the sketch of the engine prior to the optimization of the design variables

Design Variables (Continued)

- The table on the right shows our final optimized engine and the values for each design variable



Design Variable	Optimized Value
Pole Number	8
Stator Slots	18
Magnet Grade	NeFeB
Coil Span	2
Air Gap	1 mm
Stator Offset	15 Deg.
Magnet Span	150 Deg.
Magnet Skew	1 slot pitch
Wire Diameter	.82 mm

Design Variables (Continued)

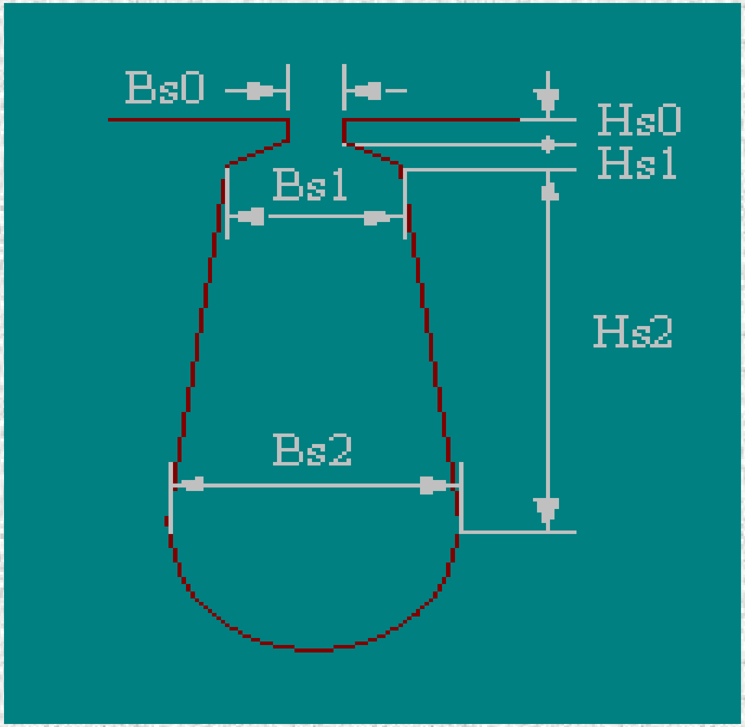
- Pole Number → Smooth torque coupled with low speed generally implies large pole count
- 8 poles decreases thickness of rotor yoke/stator yoke, decreasing overall diameter.
- 8 poles minimizes flux leakage inside rotor
- 8 poles increases the axial length of the stator and the end windings which reduces copper losses and increases efficiency
- Stator Slots → Related to pole number; slot/pole number must be fraction to reduce cogging and skewing of poles or lamination stack.
- 18 slots gives coil span of 2 → easier to manufacture
- 18 slots reduces cogging torque
- 18 slots reduces the length of the end windings and consequently the copper losses.
- Air Gap Length → Increased length results in more overall losses while too small of a gap results in decreased power density

Design Variables (Continued)

- Magnet Grade → NeFeB has a larger energy-density then other magnets at a reasonable cost, increasing overall power density and torque
- Stator offset → 15 degree offset of stators with each other was arrived at; compromise between elimination of some higher order harmonic components (decreases overall losses) and axial asymmetry which can cause pulsating axial force and create losses.
- Magnet Skew → Skew can eliminate cogging torque as well as high-frequency components related to flux losses
- Magnet Span → Span minimizes the pulsating torque, and in turn, cogging torque.
- Wire Diameter → Optimized to turns per coil in the motor. Larger diameter gives less losses, however, less turns per coil.
- Coil Span → Given by slot/poles, rounded down for short-pitching; gives an increased machine efficiency by reducing the end-turn lengths.

Stator Slot Design

- Previously defined Maxwell3D slot configuration for axial gap hub motors was used
- Slot too deep or narrow → increased leakage
- Slot width too large → slot tooth saturation
- Slot top too open → cogging torque increases
- Slot top too closed →leakage will increase.



Section	Size
Wedge Height	1 mm
Body Height	8 mm
Opening Width	2.5 mm
Wedge Max Width	6 mm
Bottom Width	6 mm
Bottom Fillet	3 mm
Opening Height	1 mm

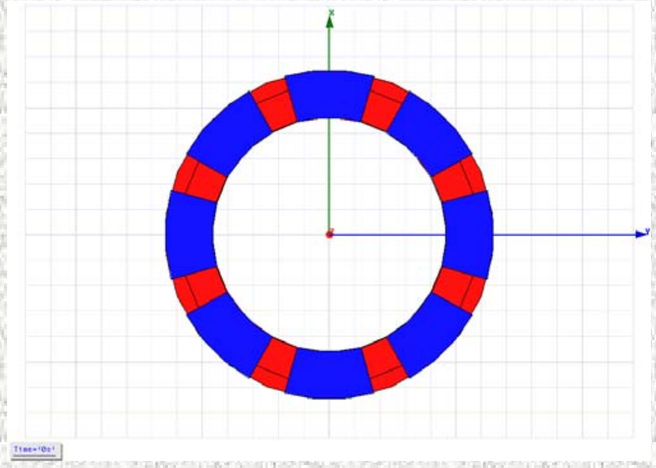
Motor Geometry

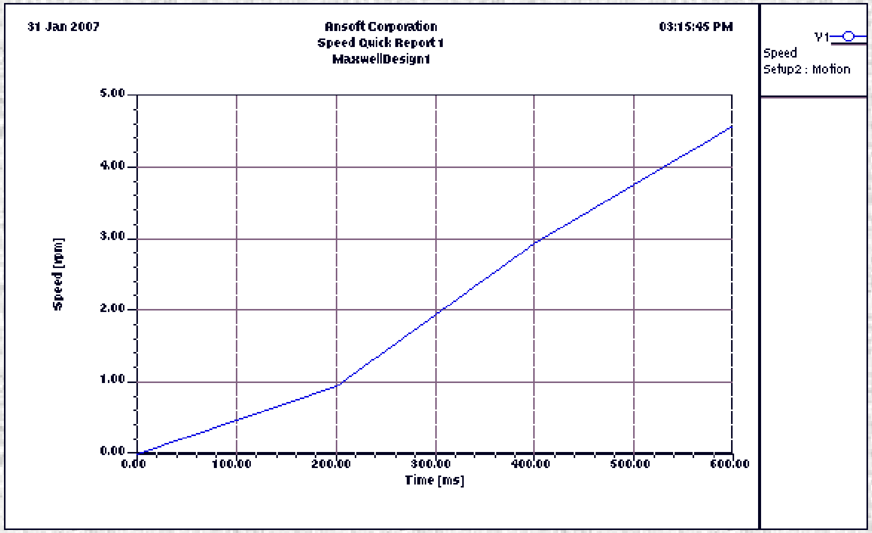
Component	Size (mm)
Inner Diameter	252 mm
Outer Diameter	360 mm
Rotor Thickness	36 mm
Air Gap (x2)	1 mm
Stator Thickness (x2)	8 mm
Frame Thickness (x2)	16 mm
Overall Thickness	86 mm

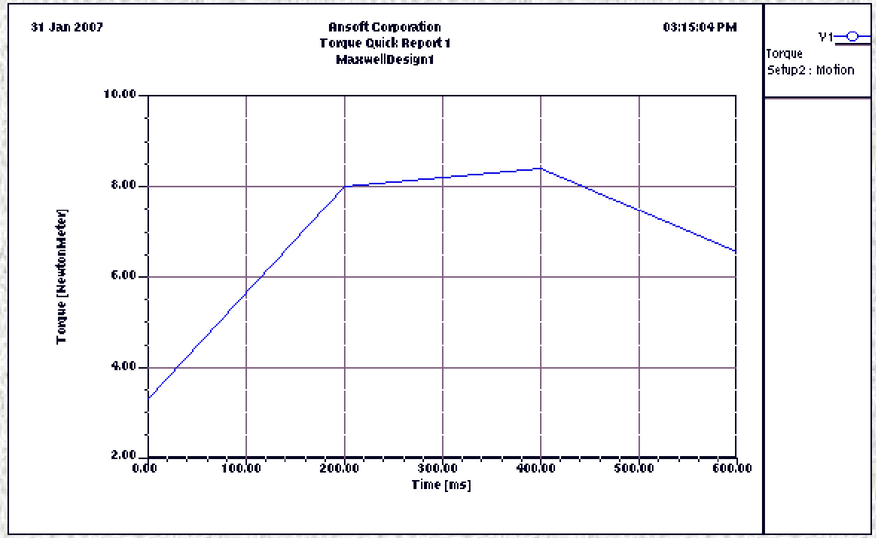
- Although inner and outer radius are good design variables, in our case, we were limited by the given AHPV dimensions. We did, however, optimize the inner diameter within the given constraints.

Performance Analysis

- Maxwell3D ran simulations on various inputs spanning several values for each design variable → Hybrid method of research and computer aided analysis was used to select final values. Below are torque and speed graphs, and to the right is our model representation within Maxwell







Manufacturing

- Materials
  - Copper – conductive
  - Steel – cheap, strong; placed to minimize magnetic losses and side effects
  - Polycarbonate – strong, light, impact-resistant and easy to machine
  - Automotive bearings for thrust and radial support

- Techniques
  - Milling
    - polycarbonate shell
    - smaller steel parts
  - Waterjetting steel frame and rotor disc
  - Epoxying
    - magnets to rotor disc
    - stator coils within polycarb shell
  - Welding rotor disc and support discs to axle

Assembly

- Overall Design Principles
  - Simple
  - Strong
  - Light
- Rotor disc attached to axle
- Polycarbonate safety shell doubles as stator structure
  - Coils and power buss embedded
- Axle held in place by huge bearings
- Steel arms lock two halves of safety shell together
- Assembles rapidly

Cost

Section	Rate	Qty	Total Cost
Design and Engineering			0
Engineer	$75*	40**	3000
CAD workstation	$55	10	550
Simulation workstation	$55	30	1650
Rotor Disc			
Magnets	$30	32	960
Disc	$35	1	35
Epoxy	$10	1	10
Assembly	$40	4	160
Driveshaft			
Steel Rod	$33	1	33
Bearings	$65	1	65
Steel Cylinders	$15	2	30
Bolts	$15	1	15
Machining	$50	2	100
Assembly	$40	2	80
Coils			
Copper wire	$12	36	432
Winding machine	$75	3	225
Lamination	$40	4	160
Epoxy	$10	3	30
Assembly	$40	5	200
Shell			
Polycarbonate	$500	2	1000
Steel	$150	1	150
Waterjetting	$75	2	150
Other Machining	$50	2	100
Assembly	$40	4	160
Electronics			
Hall Sensors	$2	9	18
Wiring and regulation	$40	1	40
Assembly	$40	1	40
Total Cost			9393

- Going for cheap
- This table includes labor
  - One-time costs of design
  - Non-bulk rates for materials
  - Machine-shop rates for machines

Future Work

- 1. Continuing Analysis Refinement
  - Moving from parameters chosen originally by “rules of thumb” to CAD models with finer detail resolution to capture these design decisions
  - FEA simulations that span full dynamic response of the motor system including startup acceleration and constant speed cruising

- 2. Motor Controller Design and Integration
  - Developing power electronics capable of supplying the minimum 10kW with sufficient scalability to accommodate future design demands
  - Baseline software interface to ease monitoring of motor and wheel interaction allowing programmable performance commands (ie. Anti-lock brakes)

- 3. Cost Reduction in Manufacturing Process
  - Expand supplier base and list of coil winding companies

Lessons Learned

- 1. Get expert advice from the start
  - Reduces confusion about basic design differences and nomenclature
- 2. Get proper simulation software
  - Having incompatible software made the optimization nearly possible
- 3. Constraint on overall design variables
  - Motor design offers more variables than can be accounted for, reduction of design variables preferable
- 4. Further research and time required for complex new design