Series-Wound Heteropolar Inductor Motor for Automotive Applications

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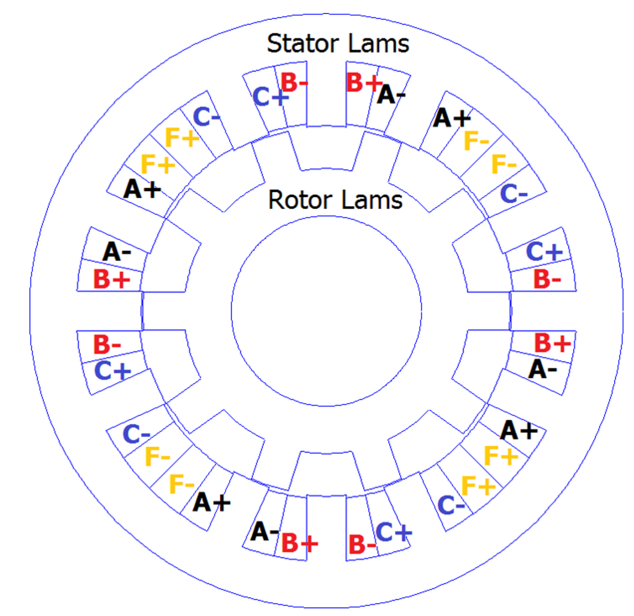
Introduction

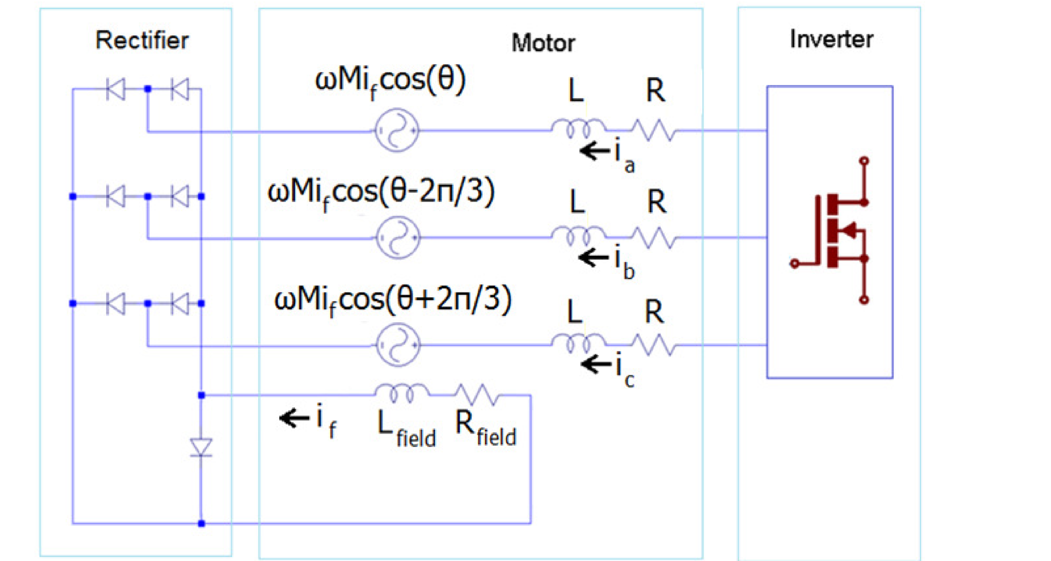
- Wound Field Heteropolar Inductor Machines
  - Simple construction reminiscent of Switched Reluctance machine
  - But can be driven by sinusoidal varying voltages, currents
  - And do not require any permanent magnets
- Previously, Heteropolar Inductor machines have been largely overlooked for automotive applications due to perceptions of poor power factor
- The present work considers a method of driving a specific Heteropolar Inductor design to:
  - Eliminate the need for a separate drive for the field winding
  - Realize high power factor operation
  - Accommodate voltage and current limits in the field weakening regime

Cross-section of a Doubly Salient Synchronous Machine

- A specific example of a Heteropolar Inductor machine is the "Doubly Salient Synchronous Motor" (DSSM)
- All field windings in the stator; no on the rotor
- Consists of 4 X 3Φ groups
  - Each phase is wound around a single tooth in the 3Φ group
  - A field coil is wrapped around each group
  - Neighboring groups staggered to eliminate even-numbered harmonics and create a bipolar net flux linkage
- Skew in rotor teeth makes BEMF relatively sinusoidal



Proposed Configuration



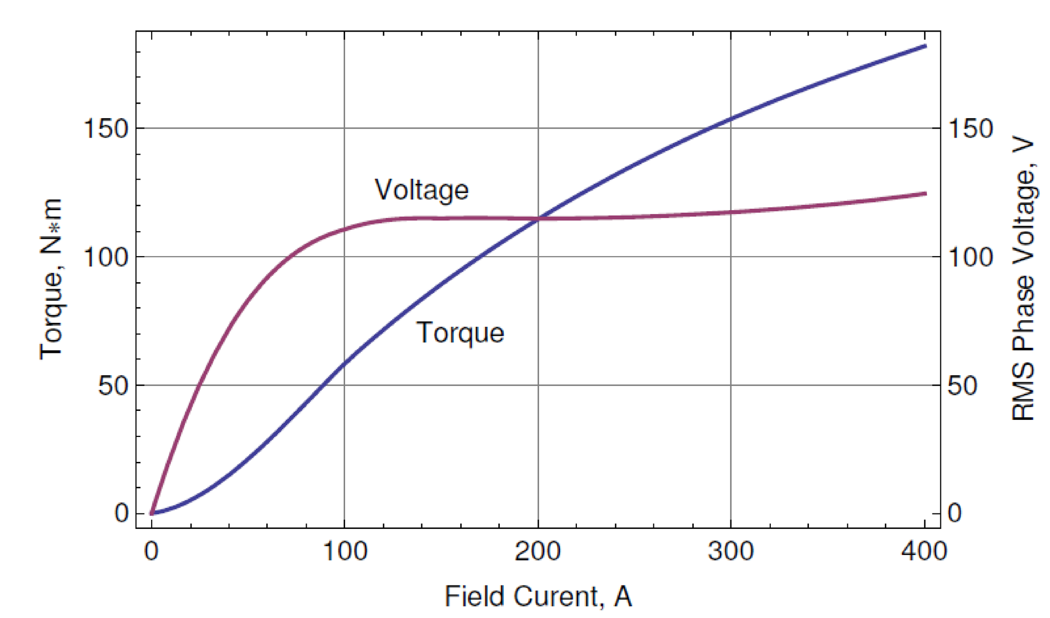
- Field current obtained by rectifying the phase current.
- Field current is approximately the same as phase current amplitude.

Comparison of DSSM to Representative Automotive IM Design

- Induction Motors are presently the dominant non-PM technology for automotive applications
- To assess the feasibility of DSSM for automotive applications, it is instructive to compare against published IM designs for automotive applications from the literature (ref [6] in full paper)
- DSSM and IM essentially the same size for a ~50kW machine.
- In simulation, DSSM has:
  - Simpler construction
  - Slightly better efficiency
  - Better power factor

Parameter	Units	DSSM	IM [6]
Pole Pairs		10 (effective)	2
Stator Teeth		12	48
Stator OD	mm	216	216
Stator Bore Dia.	mm	134.5	142
Stack Length	mm	170	170
Air Gap	mm	0.5	0.7
Number of Turns		7 (phase coils) 10 (field coils)	5
Copper fill factor		0.41 (phase) 0.45 (field)	0.4
End Connections (per side)	mm	35 (phase) 150 (field)	150
Max Speed	rpm	12,000	12,000
Continuous Torque @ 3.2kW loss	N*m	110	110
Speed at Cont. Torque	rpm	4000	4000
Current at Cont. Torque	A_{pk}	185	200
Current Density at Continuous Torque (in Cu cross-section)	$\frac{A_{rms}}{mm^2}$	10.1 (phase) 14.1 (field)	12 (est.)
Overload Torque	N*m	180	210
Overload Current	A_{pk}	360	360
Rated Phase Voltage	V_{pk}	173	173
Stator Resist. (130°C)	Ω	0.0222 (phase) 0.0495 (field)	0.027
Rotor Resist. (180°C)	Ω	N/A	0.018
Steel Grade		DI-MAX HF-10	M250-35A
Rotor Temperature	°C	150	150

DSSM Voltage and Torque vs. Field Current at Base Speed



Vector control Approach (I)

- In saturating regime:
  - Torque roughly linear with current
  - Voltage is relatively flat vs. load
- Behavior looks reminiscent of a PM machine
- Amenable to a vector control strategy similar to PM machine that realizes:
  - Good power factor across a wide range of operating conditions
  - Field weakening above the base speed to accommodate voltage limits while simultaneously accommodating current limits
- Machine is designed so that field winding has about $\sqrt{2}$ times as many turns as the phase windings to give the machine the right level of excitation for high power factor operation when field driven in series with the phase windings.
- Then, D-Q currents specified in a rotor-fixed reference frame as:

$$i_d = -i_f \cos\phi$$
$$i_q = i_f \sin\phi * \mathrm{sgn}(\tau_{des})$$

Vector Control Approach (II)

Define:

- Base Torque, τ_o
- Base Speed, Ω_o
- Base Field Current, i_{fo}
- Base Phase Angle, φ_o
- Base Phase Angle, φ_{max}

  Biggest possible value below base speed
- Base Phase Angle, φ_{min}

  Minimum phase angle approached at high speed

At any speed, the max. allowable torque is

$$\tau_{lim} = \tau_o \min\left(1, \left|\frac{\Omega_o}{\Omega}\right|\right)$$

Then, the required field current is:

$$i_f = i_{fo}\left|\frac{\tau_{des}}{\tau_{lim}}\right|$$

Phase angle then selected so that above base speed, phase angle drops:

$$\phi = \min\left(\phi_{max}, \phi_{min} + (\phi_o - \phi_{min})\left(\frac{\Omega_o}{\Omega}\right)^2\right)$$

- φ_{min} carefully selected so that desired torque is achieved and voltage limits are not exceeded
- The $(\Omega_o/\Omega)^2$ form was empirically determined based on quality of the inversion of curves from FEA.

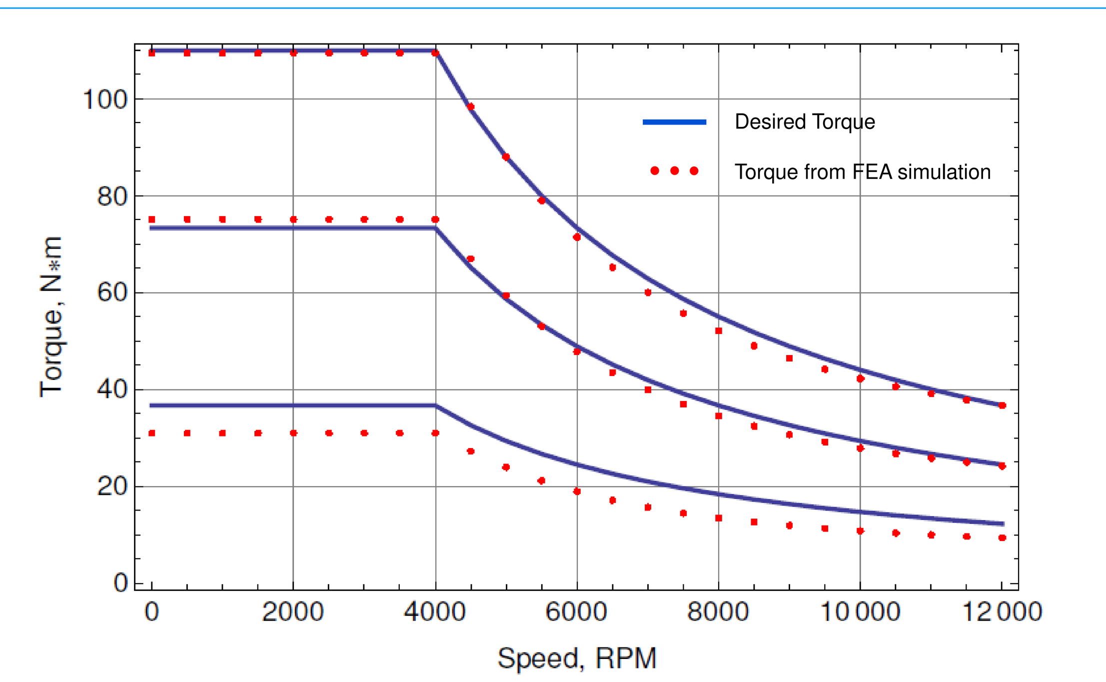
Vector Control Application to Example Machine

To demonstrate inversion of current-torque and current-to-voltage curves from FEA, control of the Slide 5 example machine is considered.

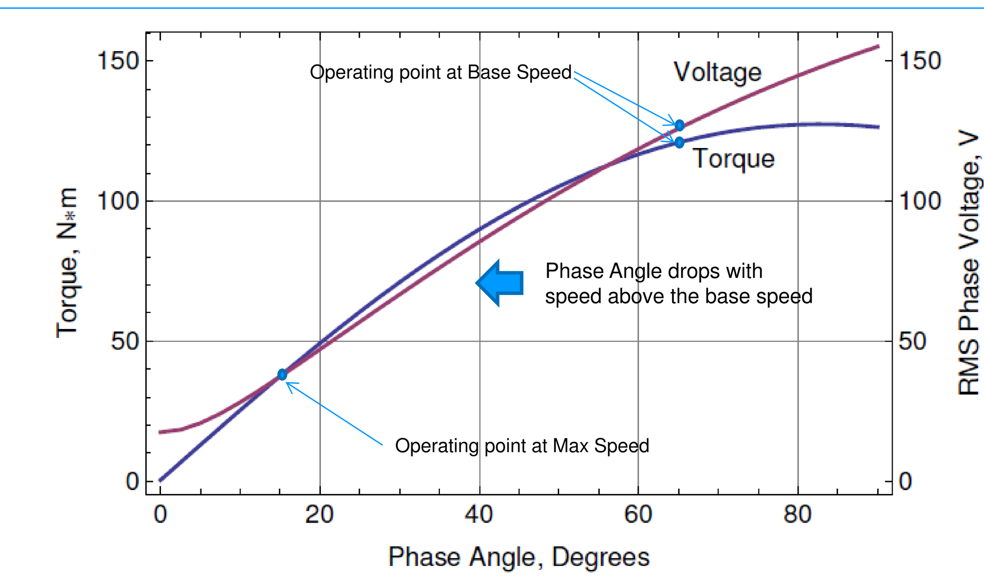
VECTOR CONTROL PARAMETERS FOR EXAMPLE MACHINE.

Parameter	Value
Base Field Current i_{fo}	200A
Base Speed Ω_o	4000 RPM
Base Phase Angle ϕ_o	62°
Base Torque τ_o	118.65 N*m
Maximum Phase Angle ϕ_{max}	62°
Minimum Phase Angle ϕ_{min}	10.25°

FEA torque vs. Desired Torque using Vector Control Scheme

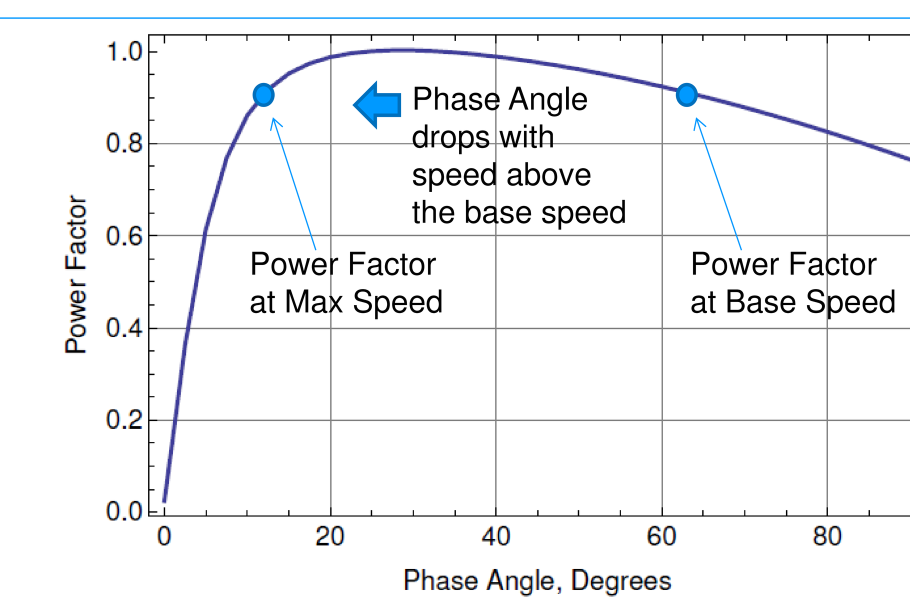


Voltage and Torque vs. Phase Angle at Base Current & Speed



Can achieve field weakening by maintaining same current amplitude and changing phase angle to get reduced torque with constant voltage as speed increases.

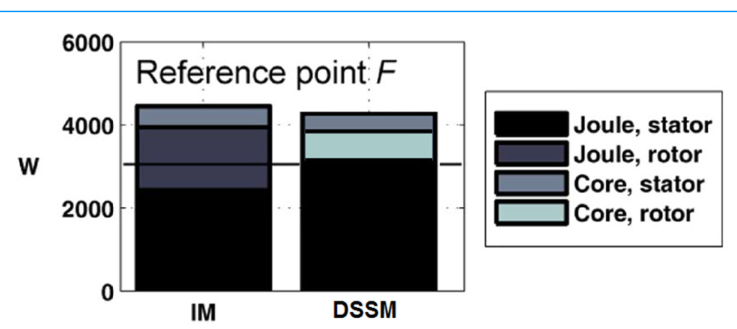
Variation of Phase Angle vs. Speed



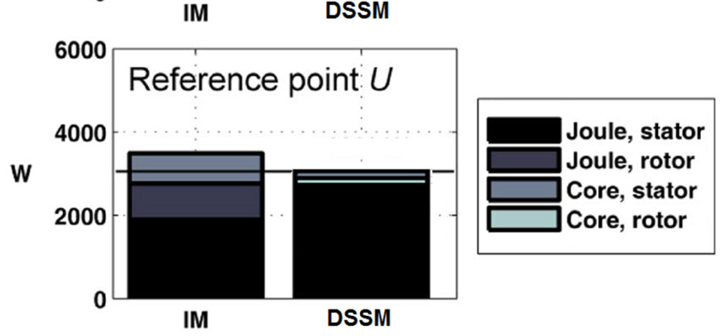
Good Power Factor Realized over Entire Field-Weakening Regime

DSSM vs IM Performance Comparison

Base Power at Max Speed



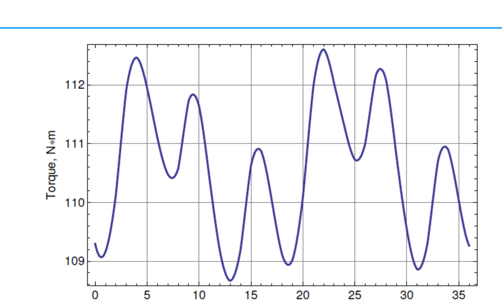
Base Power at Base Speed



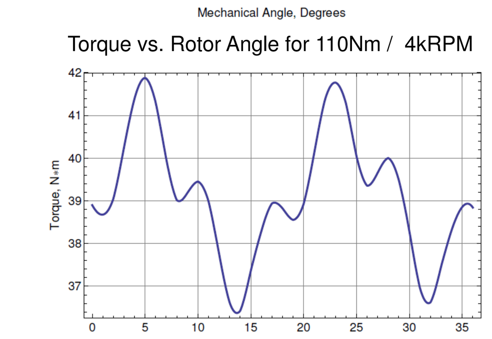
Losses at 110N*m/4kRPM (U) and 39N*m/12kRPM (F).

Computed Torque Ripple

- For a machine reminiscent of an SRM, ripple in torque is a common concern.
- Ripple in torque simulated via FEMM
  - Operating point dictated by vector control prescription is assumed
  - Balanced sinusoidal currents assumed
  - Resulting torque over one electrical cycle (36° mechanical) was considered
- Computed ripple seems reasonable
  - ~2% near Base Torque / Speed
  - ~8% near Max Speed



Torque vs. Rotor Angle for 110Nm / 4kRPM



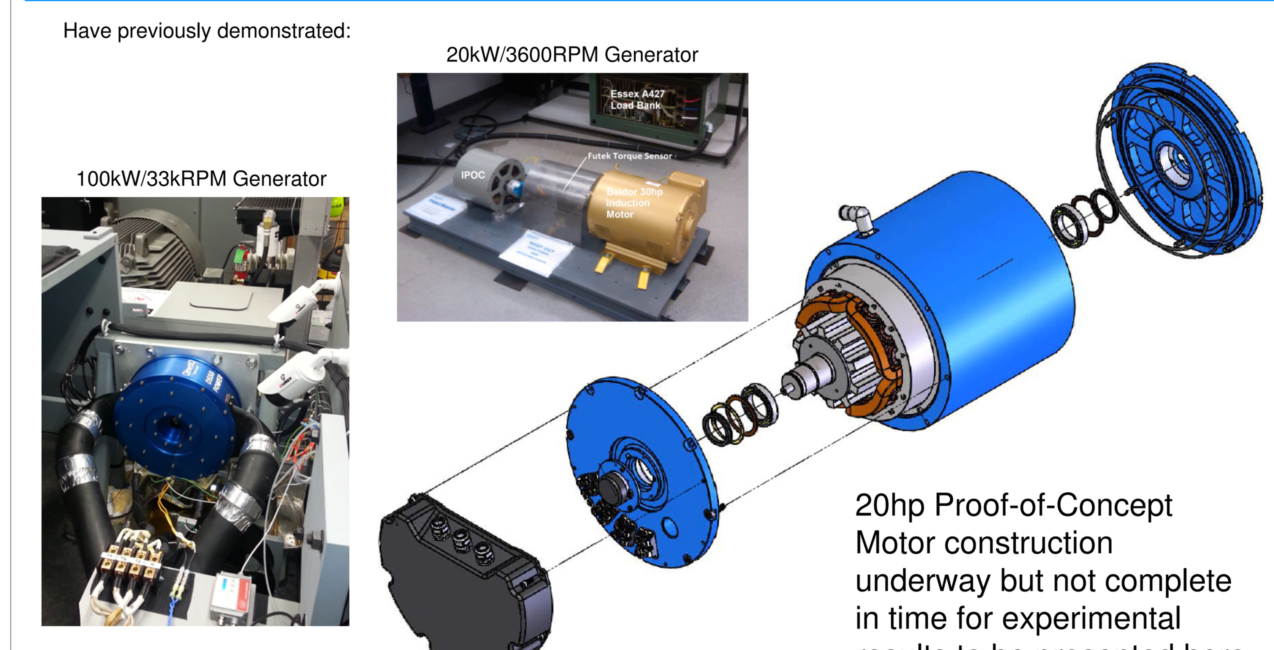
Torque vs. Rotor Angle for 39Nm / 12kRPM

Demonstration Machine Under Construction

Have previously demonstrated:

100kW/33kRPM Generator

20kW/3600RPM Generator



20hp Proof-of-Concept Motor construction underway but not complete in time for experimental results to be presented here

Conclusions

- A novel Heteropolar Inductor machine and control approach have been proposed
- Allows machine with a structure reminiscent of an SRM to be driven with a standard automotive voltage source inverter
- Power density predicted to be on a par with IMs used in automotive applications
- Power factor is better than an IM
- Easier to cool than IM since no current flows on the rotor.
- Construction of a liquid-cooled proof-of-concept machine is in process, but results not ready in time for this presentation.